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Power Quality
Implications at the Point of Connection

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof.dr.ir. C.J. van Duijn, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op dinsdag 12 juni 2007 om 14.00 uur

door

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Summary

There is a growing interest in the quality of voltage and current. This can be noticed most clearly in reports of the regulators and in discussions within national and international commissions for standardisation about the quality of voltage. Manufacturers insist on a tighter description of the voltage characteristics to optimise the design of their devices, which generally increases the sensitivity for voltage deviations. The grid operators resist against these adjustments because risk exists that the costs for the management and the operation of the grid will increase.

Discussions concerning the quality of the voltage are also conducted by the idea that the actual power quality might decrease because of the liberalisation and the need to reduce costs. Furthermore, there is the question to what extent making the energy supply more sustainable by implementing a lot of dispersed generation (DG) can influence the voltage quality. To deal with these problems, more insight in the actual quality of the voltage is needed and possibilities must be there to steer the management and operation of the grid in this respect.

Insight in the actual power quality is insufficient. The national measuring campaigns only deliver global information. Intensification of the measurements shall produce a huge amount of data which must be analysed and transferred into useful information for customers and regulators. For incorporating the quality of the voltage in the management of the grid the measurements must be made more specific and the data have to be analysed faster and presented more conveniently.

The classification method described in this thesis, is very suitable for this purpose. The advantage of the method is the simple presentation of the results with the “ABCDEF” classification directly showing the quality of the voltage. Therefore in the example described the quality of the voltage is classified from very high quality to very poor quality. To obtain this classification the data can be processed locally with as result the classification and a reduction of the amount of data which has to be communicated to a central location with a factor 300. Therefore, data transmission can be minimised and online PQ monitoring becomes possible.
The influence of dispersed generation on the voltage is unmistakable present. A simple example is the increase of voltage level at the end of the feeders in the low and medium voltage grid. The combination of load and generation in the medium and low voltage grid will lead to higher voltage variation in the grid. In several studies the possibilities are analysed to deal with this problem. Solutions which are considered are on demand control of the loads and the dispersed generators connected to the grids. In this thesis is concluded that in the Dutch situation several favourable circumstances occur that supports a large scale application of DG without the necessity of making use of complex control strategies. These circumstances are the adaptation of the upper limit of 230 V +10% for voltage level, the voltage regulation in the HV/MV substation and the relatively short length of the cables in the grids. If voltage regulating will be introduced on the MV/LV transformer, implementation of DG with a power equal or less then 70% of the nominal power of the transformer will be acceptable without additional controllers if only the voltage level is considered.

No requirements are described in the national Dutch grid code about dips. Since the year 2005, measurement devices are installed on points of connection in the Dutch high voltage grid to count the amount of dips. This information however is not enough to enable the regulator to develop good requirements on this aspect. In this thesis is analysed the average amount of dips, with depth and duration in low and medium voltage grids which can be used as basis to reach edge conditions for dips. Furthermore, also for dips a classification method based on the “ABCDEF” classification is made.

Another aspect is the problem with harmonic distortion. On this moment it is only a local problem because in general the level of harmonic distortion in the grid is rather small. However, it has been observed that on locations where a lot of DG is installed, connected to the grid by inverters, the level of harmonic distortion is significant higher. On some places the level of harmonic distortion is even higher than the acceptable level with disconnection of DG as consequence. In this thesis it has been analysed what the causes of this problem are, where the occurrence of oscillation is an important factor. Also the interaction of the inverters current with the voltage is of substantial importance. The “harmonic fingerprint” is developed to make this harmonic behaviour visible. This method has been further applied to other devices and is suitable for type test of devices and test results can give input for improving the standards for harmonic current limits of devices. By using this method also the capacitive behaviour of the devices is measured. This is important to predict the possibility of resonances in the grid. The capacitance of devices should be limited to prevent the occurrence of resonance frequencies in a domain where still a considerable harmonic background voltage exists.

From grid operators point of view it is desirable to have edge conditions for the current on the connection point (POC). On this moment only some requirements for
flicker are incorporated in the national Dutch grid code. For harmonic distortion and flicker there is an urgent need for additional requirements. In this thesis a proposal for such requirements is given based on work which is going on in several standardisation commissions and national research of the Dutch grid operators. These developed and in this thesis described requirements are depending on the current capacity of the connection and are related to the grid impedance. Since the flicker phenomena is of more importance for the grid design than the harmonic phenomena, in first instance the relation between the capacity of the point of connection, the flicker requirements and the grid impedance is determined. These new flicker requirements are simple and univocal to make easy grid design rules possible. Using the same grid impedances as determined for the flicker phenomena, requirements for the harmonic currents on the point of connection are developed.

In the final chapter the results of measurements on the location “Bronsbergen” will be presented. This is a Holiday Park where a micro grid situation will be realised in the coming years. Measurements in the existing situation with a considerable amount of PV-systems installed confirm the conclusions drawn before about the voltage level in relation to DG. Also the possible problems with harmonic distortion due to grid connected DG using inverters are underlined. A development of DG systems, which improve or at least does not deteriorate the voltage quality, is desirable.
Samenvatting

Er is in toenemende mate belangstelling voor de kwaliteit van de spanning en de stroom. Dit is het duidelijkst waarneembaar in de rapportages van toezichthouders en de discussies binnen diverse nationale en internationale normcommissies over de kwaliteit van de spanning.

Door fabrikanten wordt aangedrongen op een stringenter omschrijving van de spanningskenmerken om het ontwerp van hun toestellen te optimaliseren, wat de gevoeligheid voor spanningsafwijkingen meestal vergroot. De netbeheerders verzetten zich tegen deze aanscherpingen omdat het risico bestaat dat de kosten voor het beheer en de bedrijfsvoering van de netten zullen stijgen.

Discussies over de kwaliteit van de spanning worden ook gevoerd vanuit de gedachte dat de huidige kwaliteit wellicht aan het verslechteren is door de liberalisering en de behoefte om de kosten te verminderen. Verder is er de vraag in hoeverre een verduurzaming van de energievoorziening met veel decentrale opwekking (DG) de kwaliteit kan beïnvloeden. Om op een juiste manier met deze problematiek om te gaan moet er meer inzicht komen in de huidige kwaliteit van de spanning en moeten er ook mogelijkheden zijn om actiever in de bedrijfsvoering en het beheer van de netten te sturen op dit aspect.

Inzicht in de huidige kwaliteit is er onvoldoende. De landelijke meetcampagnes leveren slechts globale gegevens op. Intensivering van de metingen zal een gigantische hoeveelheid data opleveren die bewerkt moet worden en bruikbaar gemaakt moet worden voor communicatie met klanten en toezichthouders. Voor het meenemen van kwaliteit van de spanning in de bedrijfsvoering zal er meer specifiek gemeten moeten worden en moeten de gegevens sneller worden bewerkt en overzichtelijker gepresenteerd.

De in dit proefschrift beschreven classificatiemethode is hiervoor uitstekend geschikt. Het voordeel van deze methode is de eenvoudige presentatie van de resultaten, waarbij de “ABCDEF-classificatie” direct zichtbaar maakt wat de kwaliteit van de spanning is. In het beschreven voorbeeld is de kwaliteit van de spanning geclassificeerd van zeer hoge kwaliteit tot zeer slechte kwaliteit. Om deze classificatie te verkrijgen kan de data lokaal bewerkt worden met als resultaat de classificatie en een vermindering van de hoeveelheid data die naar een centrale locatie gestuurd moet worden met een factor 300. Hiermee kan het datatransport geminimaliseerd worden en is centrale PQ-monitoring te realiseren.

De invloed van decentrale opwekking op de spanning is onmiskenbaar aanwezig. Een eenvoudig voorbeeld is de stijging van het spanningsniveau in de uiteinden van het laag- en middenspanningsnet. De combinatie van belasting en opwekking zal tot
grote spanningsvariaties in de netten leiden. In diverse studies worden de
mogelijkheden bestudeerd om dit tegen te gaan. Oplossingen die hierbij worden
overwogen zijn het op afstand regelen en beïnvloeden van belastingen of opwekkers
die op het net zijn aangesloten.

In dit proefschrift wordt aangetoond dat er in de Nederlandse situatie diverse gunstige
omstandigheden zijn die een grootschalige toepassing van DG mogelijk maakt zonder
gebruik te hoeven maken van complexe regelingen. Deze omstandigheden zijn de
aanpassingen in de bovengrens van de acceptabele spanning naar 230 V +10%, de
spanningsregeling in de onderstations en de relatief korte lengte van de kabels in de
netten. Indien ook spansningsregeling op de transformator van midden naar
laagspanning wordt ingevoerd, kan gelet op het spanningsniveau, inpassing van DG
met een vermogen tot 70% van het transformatorvermogen plaatsvinden zonder
verdere aanvullende regelingen.

Ten aanzien van het aantal dips zijn in de netcode geen voorwaarden opgenomen.
Sinds 2005 zijn op de aansluitpunten in het Nederlandse hoogspanningsnet
meetapparaten opgesteld om het aantal dips te meten. Deze informatie is echter niet
voldoende om de toezichthouder in staat te stellen om goede voorwaarden te
ontwikkelen. In dit proefschrift is een analyse gemaakt van het gemiddelde aantal dips
in midden- en laagspanningsnetten, de diepte en tijdsduur van de dips wat als basis
gebruikt kan worden om te komen tot voorwaarden voor dips. Verder is ook voor
dips een classificatie-methode ontwikkeld gebaseerd op de “ABCDEF”-classificatie.

Een ander aspect is de problematiek met harmonische vervorming. Dit is thans alleen
op specifieke locaties in het net een probleem want in het algemeen is de harmonische
vervorming in het net beperkt. Wel is geconstateerd dat het niveau van vervuiling
significan topperkzelt waar veel opwekkers via inverters met het net
gekoppeld zijn. Op een aantal plaatsen is het niveau van de harmonische vervorming
zelfs hoger dan het acceptabele niveau met afschakeling van DG tot gevolg.

In dit proefschrift is onderzocht wat de oorzaken van dit fenomeen zijn, waarbij het
optreden van oscillaties een belangrijke factor is. Ook de interactie van de stromen
vanaf de inverter en de spanning is van wezenlijk belang. Om dit inzichtelijk te maken
is de “harmonische vingerafdruk” ontwikkeld. Deze methode is verder ook
toegepast op andere toestellen en geschikt voor type testen van toestellen. Resultaten
van de beproevingen kunnen gebruikt worden om te komen tot verbeterde normen
voor toestellen op het gebied van limitering van de harmonische stromen. Door
gebruik te maken van deze methodiek wordt verder ook het capacitiveve gedrag van
toestellen gemeten. Dit is van belang om mogelijk optredende oscillaties in het net te
c kunnen voorspellen. De capaciteit van toestellen zou beperkt moeten worden om
resonantiefrequenties te voorkomen in frequentiegeldien waarbij nog een
behoorlijke harmonische spanning in de netten aanwezig is.

Vanuit het oogpunt van de netbeheerder is het wenselijk om voorwaarden te hebben
voor de stromen op het aansluitpunt van de klant (POC). Thans zijn er alleen enkele voorwaarden voor flikker opgenomen in de netcode. Voor harmonischen en flikker is een grote behoefte aan aanvullende voorwaarden.

In dit proefschrift is hiervoor een voorstel opgenomen, gebaseerd op werk dat thans gaande is in diverse normalisatiecommissies en onderzoek van de gezamenlijke netbeheerders. De hier voorgestelde voorwaarden zijn gebaseerd op de aansluitwaarde van de klant en hebben een relatie met de netimpedantie. Omdat het netontwerp in eerste instantie wordt bepaald door de randvoorwaarden ten aanzien van flikker (eerder dan de randvoorwaarden voor harmonischen) is in eerste instantie de relatie tussen de netimpedantie, de aansluitwaarde en de mate van flikker vastgesteld. Deze nieuwe voorwaarden voor flikker zijn eenvoudig en eenduidig en maken eenvoudige ontwerprichtlijnen voor de netten mogelijk. Gebruikmakend van dezelfde netimpedanties als vastgesteld voor het aspect flikker zijn voorwaarden ontwikkeld voor de harmonische stromen op het aansluitpunt.

In een afsluitend hoofdstuk worden meetresultaten weergegeven van het net “Bronsbergen”. Dit is een vakantiepark waar de komende jaren een “microgrid” wordt gerealiseerd. Meetresultaten in de bestaande situatie met veel PV-systemen bevestigen de conclusies die eerder zijn getrokken ten aanzien van de relatie van DG en het spanningsniveau. Ook de mogelijke problemen met harmonische en via inverters met het net gekoppelde opwekkers wordt hierbij onderstreept. Een ontwikkeling van decentrale opwekkers, die de kwaliteit van de spanning niet verslechteren of zelfs verbeteren is wenselijk.
# Contents

Summary ........................................................................................................................................ iii  
Samenvatting ................................................................................................................................. vi  

Introduction ................................................................................................................................... 4  
1.1 Power Quality in general ........................................................................................................... 4  
1.2 Customers, manufacturers and grid operators ........................................................................ 6  
1.3 Power Quality monitoring program ......................................................................................... 8  
1.4 Statistics of power quality phenomena .................................................................................... 10  
1.5 Immunity and emission of devices ........................................................................................ 12  
1.6 Dispersed generation ............................................................................................................... 14  
1.7 Research objectives ................................................................................................................ 16  
  1.7.1 Classification of power quality phenomena ........................................................................ 16  
  1.7.2 Influence of dispersed generation ...................................................................................... 17  
  1.7.3 Interaction at customer’s connection point ......................................................................... 18  
1.8 The IOP project ...................................................................................................................... 19  
1.9 Thesis outline .......................................................................................................................... 21  

Power quality monitoring and classification ............................................................................... 23  
2.1 Power quality monitoring ........................................................................................................ 23  
2.2 Power quality indices ............................................................................................................... 26  
2.3 Voltage quality levels ............................................................................................................. 27  
2.4 Normalising and classifying power quality .......................................................................... 29  
  2.4.1 Normalising ....................................................................................................................... 29  
  2.4.2 The Percentile Method ...................................................................................................... 31  
  2.4.3 The STAV Method ........................................................................................................... 32  
2.5 Monitoring Power Quality in substations and transforming substations .................................. 38  
2.6 Summary and conclusions ...................................................................................................... 41  

Voltage level and dispersed generation ....................................................................................... 42  
3.1 Voltage magnitude variations, requirements .......................................................................... 42  
3.2 Grid design ............................................................................................................................. 44  
  3.2.1 Voltage level calculations ................................................................................................. 44  
  3.2.2 Dispersed generation in the grid ..................................................................................... 46  
3.3 Voltage level variation with reactive power ........................................................................... 53  
3.4 Voltage regulation concepts .................................................................................................. 57  
  3.4.1 Existing voltage regulation methods ................................................................................. 58  
  3.4.2 New voltage regulation methods ...................................................................................... 59  
3.5 Summary and conclusions ...................................................................................................... 61  

Voltage dip profiles and classification ....................................................................................... 63  
4.1 Origin of dips .......................................................................................................................... 63  

-1-
4.1.1 The definition of a dip.................................................................64
4.1.2 The low voltage network..........................................................65
4.1.3 The medium voltage network....................................................66
4.1.4 The high voltage network..........................................................68
4.2 The dip profile..............................................................................70
4.3 Cost of dips.................................................................................73
4.4 Mitigation of dips..........................................................................75
4.5 Classification of dips.....................................................................78
4.6 Summary and conclusions...............................................................82

Harmonic distortion...........................................................................84
5.1 Standards for harmonic distortion..................................................84
  5.1.1 The voltage...............................................................................84
  5.1.2 The harmonic currents..............................................................86
5.2 Interaction between voltage and currents......................................87
  5.2.1 Principle of defining interaction...............................................87
  5.2.2 Resistor and capacitor as example...........................................90
  5.2.3 Linearity................................................................................92
  5.2.4 Cross interference................................................................95
  5.2.5 PV inverter...........................................................................95
  5.2.6 Energy-saving light bulb.......................................................98
  5.2.7 Personal computer..............................................................100
  5.2.8 Behaviour of a rectifier.........................................................100
5.3 Resonance problems...................................................................105
5.4 Calculation of harmonic currents and voltages.............................107
  5.4.1 Grid components................................................................107
  5.4.2 Harmonic load flow calculations...........................................109
5.5 Currents at the connection point....................................................111
  5.5.1 Harmonic current of devices according to IEC 61000-3-12........112
  5.5.2 Current criteria for the POC....................................................115
  5.5.3 Possible solutions..............................................................123
5.6 Summary and conclusions.............................................................124

Flicker.................................................................................................127
6.1 Standards for flicker..................................................................127
  6.1.1 The voltage............................................................................127
  6.1.2 The flicker contribution at the POC.......................................128
6.2 The meaning of $P_f$ and $P_{net}$......................................................128
6.3 The flicker level in the network.....................................................132
6.4 Origin of flicker problems............................................................135
6.5 Calculation of flicker levels.........................................................136
  6.5.1 Propagation within the same voltage level.............................136
  6.5.2 Propagation through transformers........................................138
6.6 Requirements at the connection point ........................................141
  6.6.1 The general connection procedure ..................................142
  6.6.2 Additional requirements at the POC ..................................144
6.7 The lamp type and its influence ........................................149
6.8 Mitigation of flicker ........................................................150
6.9 Summary and conclusions ..................................................152

Bronsbergen micro grid ..................................................................154
7.1 Bronsbergen connected to the public grid ..............................154
  7.1.1 Voltage level ......................................................................157
  7.1.2 Dips .................................................................................158
  7.1.3 Flicker .................................................................................159
  7.1.4 Harmonic distortion ..........................................................159
  7.1.5 Unbalance .........................................................................165
7.2 Bronsbergen operated autonomously ......................................166
7.3 Influence of the micro grid on PQ ..........................................168
  7.3.1 Voltage level ......................................................................168
  7.3.2. Dips ..................................................................................169
  7.3.3 Flicker .................................................................................170
  7.3.4. Harmonic distortion and unbalance ...................................170
7.4 Summary and conclusions ......................................................171

Conclusions and recommendations ..............................................173
8.1 Conclusions ............................................................................173
  8.1.1 Standards .........................................................................174
  8.1.2 Classification .................................................................176
  8.1.3 Responsibilities .............................................................177
  8.1.4 Dispersed generation .......................................................178
8.2 Recommendations ....................................................................179
  8.2.1 General remarks .............................................................180
  8.2.2 Solving practical problems .............................................180
  8.2.3 Future research ...............................................................181

REFERENCES .............................................................................183

Appendix A: Classification and distribution .................................189
Appendix B: Dip calculations .......................................................193
Appendix C: Impedances of cables in relation with frequency ....208
Appendix D: Bronsbergen micro grid ...........................................212
Appendix E: Abbreviations and symbols ....................................215
Dankwoord ................................................................................218
List of publications .....................................................................220
Curriculum vitae .........................................................................222
Introduction

The quality of the product “electricity” has to be well defined. Manufacturers of devices will use this information for designing their devices, grid operators for network planning, and the customer making the installation suited for his purposes. There are standards for the quality of the supply voltage [Sta01, Sta03] and the quality of the current, [Sta02, Sta05, Sta06, Sta07], but in spite of the long time existence the characteristics of for example the voltage are not strict enough defined. And for some characteristics there is a lot of discussion about the limits which are too vague or even do not exist (e.g. for dips there are no limits). European regulators are evaluating the power quality issues and have concluded that the EN5160 [Sta01] should be revised, taking into account the actual levels of voltage quality in European transmission and distribution networks and the evolution of customers needs. To get more information about the actual power quality level an extended power monitoring program should be started.

So, there are still several problems to face and new developments such as dispersed generation, new equipment and devices in the customer's and grid operator's installation are providing new opportunities and challenges. Dispersed generation is able to influence the power quality in many ways. It can be negative by introducing a too high voltage level, more harmonic distortion or higher flicker levels. It can, certainly combined with storage, also improve the power quality by mitigating dips, harmonic voltages and restoring low voltage levels. All depends on the requirements set up for this type of generation. The most important new developments, having an impact on power quality, will be described in this chapter.

1.1 Power Quality in general

Quality of supply is mostly coupled to characteristics of the voltage (voltage level, flicker, unbalance, harmonics, dips, etc.) and for EMC this is an important feature [Cig01]. Electromagnetic compatibility (EMC) is concerned with the possible degradation of the performance of electrical and electronic equipment due to the disturbances present in the electromagnetic environment in which the equipment operates. For compatibility, there are two essential requirements:
The emission of disturbances into the electromagnetic environment must be maintained below a level that would cause an unacceptable degradation of the performance of equipment operating in that environment. All equipment operating in the electromagnetic environment must have sufficient immunity for all disturbances at the levels at which they exist in the environment.

Translated to the quality of the “supply” voltage it means that the emission of disturbances on all characteristics of the voltage must be maintained below a level that would cause a malfunctioning of equipment. All equipment operating connected to the voltage must have sufficient immunity for all disturbances at the level at which they occur.

The compatibility level, as shown in figure 1.1 line 1, is intended to represent a measure for the cumulative disturbance level on a given voltage, which is expected to be exceeded quite rarely (probability < 5 %). It is the specified voltage disturbance level used as a reference level for coordination of the setting of emission and immunity limits.

For each voltage disturbance phenomenon, the compatibility level must be recognised as the level of severity, which can exist. All equipment intended for being connected to that voltage requires having immunity at least to that level of disturbance. Normally a margin will be provided between the immunity level and the compatibility level, appropriate to the equipment concerned.

The planning level, line 2 in figure 1.1, is a level of a particular disturbance adopted as a reference value for the limits to be set for the emissions from large loads and
installations, in order to coordinate those limits with all the limits adopted for equipment intended to be connected to the power supply system. The planning level is lower than the compatibility level by a margin, which depends on factors such as the structure and electrical characteristics of the supply network, possibility of resonance etc. The main objective is to ensure that the predicted level of disturbance does not exceed the compatibility level.

The service level is the highest disturbance level allowed for a certain phenomenon, which is normally lower than the compatibility level. The allowed service level could be a result of a special contract with the connected customer.

In almost every country there exist rules for compatibility levels or they are being developed. Often used is EN 50160, mostly with some addition in the national code or standard.

1.2 Customers, manufacturers and grid operators

The responsibility to supply electricity of adequate quality is a joint problem for manufacturers, customers and grid operators. The relationships between these parties are shown in the power quality triangle in figure 1.2.

![Power quality triangle](image)

*Figure 1.2: Power quality triangle*

The customer is the major player: he receives and uses the product (electricity) as consumer or he produces the product and sends it away; he can specify the limits within which the equipment that he wants to buy has to function. The manufacturer will supply the customer the required equipment within the given specifications. The customer will also make a contract with the grid operator, specifying his connection requirements and demands. It is the grid operator’s job to meet these demands and
ensure the necessary power quality performance. If the ‘supply’ voltage (voltage at the connection point) is not of the necessary quality, complaints will result, which have to be solved. However, the problem is that most (domestic) customers are not aware of the required quality or are not even familiar with different power quality phenomena (except interruptions which they know very well and which the customer does not like at all). To solve this problem we have a European standard for the supply voltage [Sta01] so manufacturers can construct their devices according this standard and in most cases the customers do not need to specify further their quality needs. And also more specific requirements are set by national regulators to accommodate customer wishes. Although this seems to be an adequate solution, there is a difference between the quality of the supply voltage on the point of connection (POC) and the place in the installation where the devices are connected. For example, according installation standards [Sta04] the permitted voltage drop in the installation of the customer is 5% of the nominal voltage. According to EN-50160 [Sta01] the voltage at the POC has to be within $\pm 10\%$ of the nominal voltage, for 95% of the time within one week. For 5% of the time the voltage may be according EN 50160 between $-10\%$ and $-15\%$ of the nominal voltage. In an extreme situation, but fulfilling all standards, the voltage at the input of the device can be $-20\%$ of the nominal voltage. Customers must be aware of this.

![Figure 1.3: Point of connection (POC) and installation of a customer](image)

A problem, especially seen from the point of view of a grid operator, is the uncertainty on the effect that the customer has on the quality of the supply voltage. Of course, there are standards for equipment and devices connected to the installation. These standards, for example for harmonic distortion, limit the harmonic current of the device. Test methods to check if the device fulfils the requirements of the standard use a pure sinusoidal voltage. The influence of a distorted voltage, which in practice is always the case, is not implemented in the standard. [Sta05, Sta06]. This of course is helpful for keeping the test method cheap but certainly for type test of devices (so, not for every single device) a test with “standardised harmonic distortion” should be advisable. Furthermore, using a lot of devices with a distortion within the limits of the IEC standards can give an unacceptable distortion at the point of connection (POC).
At this moment there are no standards and there is no regulation regarding what distortion the customer may produce at the POC. The short circuit power at the POC complicates this issue, for which the grid operator can be held responsible. In the national Dutch grid code a first step is made to put some restraints on the customers influence on the flicker level and the impedance of the grid [Sta03]. In IEEE519 [Iee01] requirements for harmonic currents on the POC are given. For all power quality phenomena these requirements on the POC have to be made, related to grid impedances.

Customers want to get more and more information on the quality of the service and the quality of the product. When there are problems with the quality of supply, they want to know the reason and who was responsible for the interruption or distortion. Another trend is the increasing tendency of customers to make claims against the grid operator. In cases of malfunction or damage of devices the grid operator is blamed. In one case a court in the Netherlands stated that the grid operator has to prove that an unacceptable distortion of the supply voltage did not occur [Ene04]. In the absence of any evidence that the quality of the supply voltage was not far outside the limits, half of the costs had to be paid by the grid operator. An intensive measuring program has to be started to get more information about the actual power quality levels in the networks. This has to be combined with a method to analyse the data on an easy and practical way. This method should give as result a representation of the power quality in the grid on such a manner that it is understandable and useful to communicate with the customers and the regulator.

1.3 Power Quality monitoring program

Due to the liberalisation of the energy market most utilities within Europe are being forced to unbundle their organisation into a supply company and a separate independent grid company. The grid operating company has to facilitate the transport of energy (mostly gas and electricity). Because of the natural monopoly of the grid operators, national governments have established national regulators. These regulators control the most important activities of the grid operators. To get an insight into the quality of the service, the grid operators have to inform the regulator yearly on the interruption statistics and the performance on other quality aspects. In 2006 a system has been introduced by the national Dutch regulator to reward grid operators whose reliability performance is good and to penalise grid operators whose performance is poor (bad performance in comparison with other Dutch grid operators). Such a financial trigger is not yet being used for the quality of the ‘supply’ voltage.

The information for the voltage quality is gathered using a measuring program with several different statistical approaches depending on the voltage level, as is shown in table 1.1.
The number of measurements at the various voltage levels are picked at random in the total population of customers, connected to the specific voltage level, without any specific relation to the grid operator. The results cannot be used to draw any conclusion about the quality of supply in relation to a grid operator. It can be used only to give an indication about the general quality of the supply voltage within the Dutch grids. Fixed measurement equipment is installed on high and extra high voltage grids which make it possible to measure continuously also dips (or voltage sags). There was a need to measure this phenomenon to give better insight in the Netherlands about the amount, duration and magnitude of dips. Before putting restraints on this phenomenon, which is not yet done in most standards, the regulator forced the grid operators to measure this phenomenon in the high and extra high voltage grids. Results of the PQ-measurement program over the last years, giving the momentary level of power quality phenomena, are shown in section 1.4.

### Table 1.1: Dutch power quality measuring program

<table>
<thead>
<tr>
<th>Voltage level</th>
<th>Connected customers</th>
<th>Number of measuring points</th>
<th>Approach</th>
<th>Results of approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>U&gt;220 kV</td>
<td>6</td>
<td>6</td>
<td>Fixed equipment at all locations</td>
<td>Gives total overview of quality</td>
</tr>
<tr>
<td>35 kV≤U≤220 kV</td>
<td>60</td>
<td>20</td>
<td>Fixed equipment at all points to be measured</td>
<td>Statistical results on all aspects of quality of supply voltage, incl. dips</td>
</tr>
<tr>
<td>1 kV&lt;U&lt;35 kV</td>
<td>≈ 600,000</td>
<td>60</td>
<td>Equipment placed at random locations</td>
<td>Statistical results on all aspects of quality of supply voltage, excl. dips</td>
</tr>
<tr>
<td>U≤1kV</td>
<td>≈ 6,000,000</td>
<td>60</td>
<td>Equipment placed at random locations</td>
<td>Statistical results on all aspects of quality of supply voltage, excl. dips</td>
</tr>
</tbody>
</table>

In the coming years the regulator will intensify its supervision on the grid operators and there will be a greater focus on the quality of the supply voltage. Setting up a new measuring program will be needed, with results that enable conclusions to be drawn for each individual grid operator. This will be needed to compare the possible difference in quality of supply, and hence the quality of the grids, between several grid operators. Grid operators themselves will need more information about power quality phenomena for a good assessment of the grid, so this joint interest will lead to an intensive measurement program in the coming years. An interesting challenge will be how to handle the enormous amount of data and how to give an easy to understand overview of all power quality phenomena to non-experts in this field.
### 1.4 Statistics of power quality phenomena

A general overview of the results of the measurement program during 1998 up to 2004 is shown in figures 1.4 to 1.6 for the low voltage level, flicker and total harmonic distortion, which are the main voltage quality phenomena besides dips. In the figures the minimum, maximum and averages values (dot) are given.

The voltage level in the low voltage grid (figure 1.4) increases slightly. The main reason for this increase is the European normalisation of the nominal voltage level on 230 V. In the Netherlands this conversion from 220 V (old nominal voltage) to the new nominal voltage has been realised within a period of 15 years, from 1989 until 2004. In this period the upper limit of the voltage level was 230 +6%, almost equal to the old limit of 220 V +10%. In 2004 this was changed, due to the requirements in the national grid code to 230 V +10%. It will be analysed to which extent this extra 4% can help to implement dispersed generation into the low voltage grid. The integration of DG into the grid will give rise to the voltage level, so a further increase of the voltage level in the coming decennia is expected.[Pro02, Pro03]

![Figure 1.4: Low voltage level during the years 1998-2004](image)

The most important conclusion that can be drawn from analysing figure 1.5 is the rising trend in the flicker level in the low voltage grid. Increasing use of high-power equipment and connecting new installations without any supervision on the low voltage grid are important factors for the increasing level of the \( P_f \) which is a measure for flicker [Ene02]. Countermeasures have to be taken to stop this development and serious requirements on the connection have to be developed.
The level of total harmonic distortion seems to be constant over the years as shown in figure 1.6. In the most European countries a rising trend is measured [Eur01]. The advantage of the Dutch situation is the use of cables in the entire low- and medium voltage grid. Due to the low inductive impedance of the cables the harmonic voltage level stays at an acceptable level. Resonances however, could be more common due to the increasing capacity in the devices.

Nevertheless, on certain specific locations harmonic problems occur. Harmonic currents and/or harmonic voltages, amplified due to oscillation in the network, can increase the voltage to extreme values damaging equipment, overloading cables or capacitors or leading to malfunction of devices [Cob02]. Therefore, more knowledge
about the interaction between harmonic voltage of the supply and harmonic currents of devices is needed, to predict possible problems [Cob04].

### 1.5 Immunity and emission of devices

The expected quality of the supply voltage is described in standards as EN-50160 [Sta01] and the national grid code [Sta03]. The national grid code is mostly based on the European standard with some further limitations. Manufacturers of devices for the European market will use the EN-50160 as guide for the design, construction and use of their devices. There is a tendency to build devices as cheaply as possible, which will increase the chance of problems occurring when the supply voltage is distorted or is close to the limits of the required quality.

Computers are now essential to all businesses, whether as workstations, network servers or process controllers. They are vital to all data transactions and many communications functions. Problems with this equipment highlighted the problem of voltage dips [Pqi01]. Harmonic problems are leading to overloading of devices, motors, capacitors and overheated neutrals, as confirmed by a survey conducted by the European Copper Institute in 2001 [Pqi03].

Another power quality problem that occurs frequently is the flicker phenomenon. Analysis of the data of all customer complaints received by Continuon during the last three years shows the common causes to be low voltage and flicker [Con01]. Figure 1.7a gives an overview of the complaints, mainly from domestic customers, and figure 1.7b gives an overview of complaints from customers with a contracted power of more than 50 kVA.

![Figure 1.7: Overview of power quality problems following customer complaints](image)

The development of the flicker problem is very interesting. Of course, there is the above-mentioned increase of $P_l$ value in the grid. Otherwise, the use of type of lamps

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1 Continuon is a grid operator in the Netherlands
that are less sensitive to voltage variations is increasing too. Still, there are a lot of complaints about this phenomenon.

Some devices nowadays have a high distortion in the current they take from the grid. The majority of modern electronic units use switched mode power supplies (SMPS). These differ from older units in that the traditional step-down transformer and rectifier is replaced by direct controlled rectification of the supply to charge a reservoir capacitor, from which the direct current for the load is derived by a method appropriate to the output voltage and current required. The advantage – to the equipment manufacturer – is that the size, cost and weight is significantly reduced. The disadvantage – to the customers and the grid operator – is that the power supply unit draws pulses of current which contain large amounts of third and higher harmonics and significant amounts of high frequency components. Figure 1.8 shows a typical harmonic spectrum of a PC using a SMPS.

Compact fluorescent lamps (CFL) are now being sold as replacements for incandescent lamps. A miniature electronic ballast, housed in the connector casing, controls a folded 8 mm diameter fluorescent tube. CFLs rated at 11 watt are sold as replacements for a 60 watt filament bulb and have a considerable longer life expectancy. The harmonic current spectrum is shown in Figure 1.9. These lamps are being widely used to replace filament bulbs in domestic properties and especially in hotels where serious harmonic problems suddenly become common. Dutch government has started in 2006 a one million energy saving lamps program to encourage the use of this type of lamp.
Harmonic currents introduce harmonic voltages and they interact again with harmonic currents of other devices. So the interaction has to be analysed [Cob12, Cas01].

1.6 Dispersed generation

For many decades there has been an electricity system with generation from large centralized power plants. The main advantages of these conventional power generation plants are the price and the controllability of their output. The main disadvantages are the future availability of their primary energy sources (natural gas, coal, oil) and their environmental consequences. Therefore in the last decades there has been an increase in the development and use of renewable energy sources. Many research projects have been started to investigate the influence of dispersed generation on the design and performance of the grid (e.g., the DISPOWER project [www03], EU-Deep [www06], the microgrid and more microgrid project [www04]). An overview of different integrated projects can be found on the website [www05].

An impression of the future system with dispersed generation and storage systems, combined with such new techniques as fuel cells and micro turbines and conventional techniques such as CHP plants and hydro power, is shown in figure 1.10. The network will exist of good controllable generators as the CHP plant, multifuel plant and the hydro power plant. In the low and medium voltage grid small renewable generators are connected. The reversed energy direction and the unpredictable output of the most renewable generators (wind, solar) make the system more complex. These developments will have an influence on power quality phenomena.
The network has controllable generators such as the CHP plant, multifuel plant and the hydro power plant connected to the high voltage level. In the low and medium voltage grid small renewable generators are connected. The reversed energy direction and the unpredictable output of most renewable generators (wind, solar) make the design and operation of the system more complex. These developments will have also an influence on power quality phenomena. The connection of the new techniques is mostly with power electronics, introducing harmonic interaction. The voltage level in the grid will show a greater variation when additional measures are not taken. Furthermore, the consequences of a dip could be greater than it is now, when an adequate protection philosophy has not been applied to renewable energy sources. The use of dispersed generation could on the other hand improve the quality of the service, for instance in autonomously operating network parts, but additional control and protection strategies are needed to take full advantage of these possibilities [www07].
1.7 Research objectives

The main developments in the field of power quality and mentioned before were an important trigger in arriving at the research objectives. Condensing all information three main research objectives can be described as:

- **Classification of power quality phenomena to arrive at an analysis tool for grid operators, which makes it possible to handle an enormous amount of data and to give customers and the regulator clearer information about the quality of supply voltage.**
- **The influence of dispersed generation due to a large amount of renewable energy sources on power quality, especially on the voltage level and slow voltage variations. Also the possible contribution to the harmonic distortion is analysed.**
- **Power quality interaction between ‘supply’ voltage and ‘exchanged’ current at the point of common coupling (point of connection to the grid). Especially the relation between current capacity of a POC, the grid impedance and the current at the POC is analysed for harmonics and flicker.**

1.7.1 Classification of power quality phenomena

Power Quality phenomena in the grid need to be monitored, for several reasons. First of all it is a requirement of some national regulators and strongly recommended by the council of European Regulators [Erg01]. Another reason is the increasing amount of claims that customers send to the grid operators, claiming that there was damage within their installation or process due to inadequate power quality. Furthermore the grid operators want to know more about power quality in the grid for optimal grid operation. Analyzing the necessary data of the existing power quality devices is time-consuming and needs qualified people. The aim of this research is to develop a method that limits the data needed to analyse all power quality phenomena and that makes it possible to get a good picture of the power quality phenomena of the grid at a glance. Of course, detailed information can be gathered if necessary, for example in the case of disturbances and in case of specific circumstances. The described classification is an example, other methods are possible. Most customers are not familiar with power quality phenomena, so a translation to a general type of classification is needed. The choice has been made for an “ABCDEF-classification” as is already used for categorising cars and household equipment (see pictures in figure 1.11) [www01, www02].
Figure 1.11: Classification of cars and household equipment

Power quality measuring equipment is becoming more and more integrated into the system, located in general areas such as substations or in dedicated places such as sites with a large amount of dispersed generation or at the customer’s connection points if there are voltage complaints. Analysing all the data using an adequate classification method will help to understand the problem, to draw conclusions about elements such as annual trends and will support the communication of the quality of the supply voltage [Cob01, Cob07].

To realise the classification a lot of data of the national PQ-measuring program over the years 2000-2005 is analysed. Important results of this analysis were the actual level of power quality and the way the different power quality phenomena were distributed. Combining this information resulted in the chosen classification levels and the most appropriate standard distribution to use for compromising the data.

1.7.2. Influence of dispersed generation

Distributed energy sources like wind, solar and combined heat power systems will be implemented in the future grid [Kar01]. In the normal grid-connected situation, bidirectional power flows will occur. Local bursts of active and reactive power flows will change the voltage profile in the low and medium voltage grids. Furthermore, the widespread use of power electronic inverters with non-linear characteristics possibly increases power quality problems such as harmonic distortion [Bos01]. Although, with recent technology with fast switching components used to compose the input wave form, this problem is not that acute anymore. The power electronic devices could (theoretically) even be used in such a way that the power quality is enhanced locally, at a certain price: they are in principle identical to the systems used to set up active filters (for harmonic reduction) or static compensators (generating reactive power, necessary to control the voltage) [Mor01]. Unfortunately, currently most DG front-ends have to be set up too passively and inject only active power and leave the control of the
voltage parameters to the central system. It is likely that this will change in the future and DG units may also deliver “ancillary services”.

Part of the research is dedicated to studying the possible integration of dispersed generation into the low- and medium voltage grid without exceeding voltage limits. The possibility to regulate the voltage level with reactive power is analysed. Also the problem of harmonic interaction is analysed. Harmonic fingerprints are made of some PV-inverters which clearly presents the interaction of this device between harmonic voltages and currents. Also the influence of voltage dips on the dispersed generation is described.

For calculating the maximum implementation levels of dispersed generation into the low- and medium voltage grid measured profiles for both load and generation are used to build models. The harmonic problem is analysed using the same power system analyse tool, including models for the cables in the frequency domain. Measurements in a low voltage grid with a high amount of PV-systems (figure 1.12) were used to validate the simulations.

Figure 1.12: Holiday-Park with PV-systems

1.7.3. Interaction at customer’s connection point

The performance of the grid, with respect to most power quality phenomena, depends on the quality of the current of the loads or dispersed generators connected to the grid. Also the short circuit power of the grid is an important factor because the interaction between current and voltage at the point of connection will be strong as the short circuit power is low [lec01]. At the point of connection (POC), the grid operator has to deliver the contracted electric energy with adequate quality supply
voltage. This is only possible if there are some constraints regarding the current at the connection point. This issue has not yet been solved within codes or national or international standards. For flicker there are some restrictions in the national Dutch grid code [Sta03] and in the IEEE519 [Iee01] some guidelines are given for the harmonic currents on the POC. Still, a more integrated approach is needed. In this thesis a proposal for such guidelines will be given for each of the power quality phenomena.

Before these guidelines could be made the interaction between current and voltage had to be analysed. The influence of inrush and starting currents on the flicker level is analysed [Cob08]. Also, the interaction between the harmonic voltage and harmonic current of several devices is analysed. By making harmonic fingerprints a solid understanding of this interaction is realised [Bos01, Cob12, Cas02]. Already started work of Cigre-Cired JWG C4.103 on the assessment of emission limits for the connection of disturbing installations to LV power systems is used to complete the proposed guidelines for the POC [Cig02]. The combined approach for the flicker and harmonic guidelines by using similar grid impedances makes these guidelines useful in combination with grid design. Simulations with “Power Factory” using several typical grid structures are made to calculate the possible limits of the currents on the POC.

1.8 The IOP project

The research presented in this work has been performed within the framework of the 'Intelligent Power Systems' project. The project is part of the IOPEMVT program (Innovation Oriented research Program – Electro-Magnetic Power Technology), financially supported by SenterNovem, an agency of the Dutch Ministry of Economical Affairs. The 'Intelligent Power Systems' project is initiated by the Electrical Power Systems and Electrical Power Electronics Groups of the Delft University of Technology and the Electrical Power Systems and Control Systems Groups of the Eindhoven University of Technology. In total 10 Ph.D. students are involved and work closely together. The research focuses on the effects of the structural changes in generation and demand taking place, like for instance the large-scale introduction of distributed (renewable) generators [Rez01]. The project consists of four parts as illustrated in figure 1.12.

The first part (research part 1), inherently stable transmission system, investigates the influence of uncontrolled decentralized generation on stability and dynamic behaviour of the transmission network. As a consequence of the transition in the generation, less centralized plants will be connected to the transmission network as more generation takes place in the distribution networks, whereas the remainder is possibly generated further away in neighbouring systems. Solutions investigated include the control of centralized and decentralized power, the application of power electronic interfaces and monitoring of the system stability.
The second part (research part 2), manageable distribution networks, focuses on the distribution network, which becomes 'active'. Technologies and strategies have to be developed that can operate the distribution network in different modes and support the operation and robustness of the network. The project investigates how the power electronic interfaces of decentralized generators or between network parts can be used to support the grid. Also the stability of the distribution network and the effect of the stochastic behaviour of decentralized generators on the voltage level are investigated.

![Figure 1.12: Structure of the IOP project](image)

In the third part (research part 3), self-controlling autonomous networks, autonomous networks are considered. When the amount of power generated in a part of the distribution network is sufficient to supply a local demand, the network can be operated autonomously but as a matter of fact remains connected to the rest of the grid for security reasons. The project investigates the control functions needed to operate the autonomous networks in an optimal and secure way.

The interaction between the grid and the connected appliances has a large influence on the power quality. The fourth part (research part 4), optimal power quality, of the project analyses all aspects of power quality. The goal is to provide elements for the discussion between polluter and grid operator who has to take measures to comply with the standards and grid codes. Setting up a power quality test lab is an integral part of the project. The research described in this thesis is within research part 4.

Optimal power quality covers among others the following topics:

- Classification of all power quality phenomena to arrive at an analysis tool for grid operators, which makes it possible to handle an enormous amount of
data and to give customers and the regulator clearer information about the quality of supply voltage.

- Power quality phenomena in an autonomous working grid, influence of dispersed generation due to a large amount of renewable energy sources on power quality.
- Guidelines for the power quality interaction between supply voltage and current at the point of common coupling (point of connection to the customer's grid).
- Advanced measuring methods to analyse all power quality phenomena and to conclude what interaction has taken place between supply voltage and installation current.

1.9 Thesis outline

In chapter 1 power quality in general is described, the problems are stated and the research topics discussed.

Further understanding of the different power quality phenomena, is the topic of chapter 2 and the need to use the indices is described. Also the need to develop methods for compressing power quality data and to make this data fit for use is described. The classification explained in this chapter is an example of practical solution, which has been implemented in a system for substation automation.

In chapter 3, the voltage magnitude variation as power quality phenomena is analysed. The influence of dispersed generation in relation to this phenomenon is studied. Also the limits of implementing dispersed generation in existing low voltage grids are calculated. The limited possibilities of voltage level regulation with reactive power in the low voltage grid are described, including the influences on the losses in the grid.

Chapter 4 is the chapter that deals with dips. A method to predict the amounts of dips on a connection point called “the dip profile” is presented. This calculation method, which has already been implemented in a software package, is used to inform customers of the amount and depth of dips to be expected. Also a way to classify this dip profile as all other power quality phenomena is presented.

In chapter 5, the shape of the voltage is the main issue. The idea of a “fingerprint” of a device with respect to its harmonic behaviour is worked out. This fingerprint will give information about the harmonic currents in situations without any harmonic voltage distortion (lab situations) and the harmonic currents when the device is placed in the real grid where there will surely be some harmonic distortion in the voltage. A method of improving the harmonic calculations in the grid is also given in this chapter. Another important issue, the interaction at the point of connection (POC), and guidelines for the POC are dealt with also.
Chapter 6 deals with the flicker phenomenon. This power quality phenomenon is in practice the cause of around 50% of all complaints addressed to grid operators in the Netherlands. Some causes will be explained and an analysis of the increasing flicker level in the low voltage grid in the Netherlands will be given. The influence of the type of lamp on the flicker problem will be explained too. An important issue dealt with in this chapter will be a guideline for the point of connection of customers.

The grid with a great amount of dispersed generators, with the potential to work autonomously, is the subject of chapter 7. The influence on the power quality phenomena will be analysed. Disconnection of the DG or operating the grid including DG as a stand-alone grid will have serious consequences, which are described in this chapter.

The last chapter 8 will give the summary of all the results obtained from this research. The most important conclusions are given in this chapter. Due to the fact that every research solves questions and introduces new ones, this chapter will also give some ideas about further research.
Power quality monitoring and classification

Experts generally agree on the need for standardised power quality indices allowing to monitor and to report power quality on a common basis. Values for the quality indices represent a few numbers that are the result of characterising, reducing or extracting from a large volume of power quality measurement data [Bo03]. The systems for power quality data acquisition, storing and reporting are mostly separated stand alone applications, which have its drawbacks. However, distribution automation reveals new possibilities for continuous power quality monitoring. Advanced computer systems with open architecture make it possible to integrate power quality data with the normal network operation data [Mak01].

In this chapter an overview of power quality monitoring is given. The resulting power quality indices will be discussed and the compatibility levels as stated in the national grid code [Sta03] will be described. Then methods for normalising indices for power quality phenomena are introduced. An example of how power quality phenomena can be classified and translated into easy to understand and to analyse data is described. The end of this chapter gives details of some applications.

2.1 Power quality monitoring

Power quality monitoring can be defined as the process of gathering data about voltages and currents including time, transporting that data and converting it into useful information [Mc01]. The ideal power quality monitoring system should have the following characteristics:

- It gathers all of the data that is required.
- It moves the data to a certain location where it can be saved and processed.
- It converts the data into information that can be used to take action or to inform people involved.
- It combines the power quality data with other sources of data.

Power quality monitoring as stand-alone function on certain points in the network has its drawbacks because:
- It will not give a total overview of the voltage quality in the grid.
- An additional communication system is needed.

Monitoring these devices is difficult to integrate in normal operation.

Therefore, power quality monitoring will be integrated in substation automation systems. Two examples of integrated systems which are under development within Continuo are shown in figure 2.2 and figure 2.2. Figure 2.2 shows the integration of a power quality monitoring system in a substation, as already is implemented in several substations end 2006, beginning 2007 [Rie01].

![Distribution automation system, implemented in a HV/MV substation](image)

**Figure 2.1:** Distribution automation system, implemented in a HV/MV substation

The several components in the systems are:

- VIM (Voltage Interface Module); measuring the voltage.
- CIM (Current Interface Module); measuring the current.
- BIM (Breaker Interface Module); for status information about the breaker or giving commands to the breaker.

In every incoming and outgoing feeder the currents are measured with a high sampling frequency to gather information about the current waveform. This information can be used for several purposes such as:

- Power quality issues (for example harmonic distortion).
- Short circuit currents for calculating the location of the fault in combination with measured voltage.
- Remaining capacity of the feeder.

All the measured data can be stored on a local computer. Transmitting all data to a central operating room of the network operator is not efficient. Only in faulted situations it will be needed to get on line detailed information. For power quality phenomena, the data can be processed locally to determine power quality indices. These indices can be further analysed centrally. When needed, for instance in case of complaints, detailed information can be sorted out and examined centrally.

A second example of integrated distribution automation is the MV/LV transforming substation as shown in figure 2.2. With increasing DG there is a need to have more control on the low voltage network. Therefore more information about the voltage and the currents in the low voltage network must be gathered. This automation will be developed and realised in the coming years within a new IOP-EMVT project. [www06].

In the coming 5 to 10 years at all Dutch consumers premises an energy meter with additional functionality will be installed. The energy meter can be remotely managed and read. This could be based on powerline communication using the existing low voltage electricity network.

![Figure 2.2: Development of advanced MS/LS substation with additional functionalities](image)
In the MV/LV transforming substation possibilities for energy storage could be present. This approach enables the grid operator to control the low voltage level, to improve power quality (harmonics flicker) and to optimise the loading of the network. Again, concentrating on power quality phenomena, the amount of data available will be enormous, so it has to be converted locally and in normal situations only indices has to be communicated to a central location. Other examples of power quality monitoring, integrated with distribution automation are given in [Mak01].

One way to communicate with all substations is the application of TCP/IP networks. The development of advanced internet technologies enables grid operators to retrieve data or update data remotely. More information about such a web-based power monitoring system can be found in [Leo01].

It can be concluded that integration with central SCADA and local DMS systems is possible but converting data into useful information is still an issue.

In the following more information about power quality indices and methods for converting data into useful information will be given.

**2.2 Power quality indices**

For several reasons as described in [Bol03], there is a need for common power quality indices. With indices it is possible to report quality in a consistent and harmonised manner, either to customers, regulators or within the grid company. The values for these indices have to be compared to the limits described by the national regulator. Because there is still a lot of discussion about the acceptable levels and the corresponding time limits (95% or 99% or 100%), converting power quality data into indices has to be done in a flexible way, so changing the limits must be possible without a lot of consequences. A number of international standard documents define the measurement process, including EN 50160 [Sta01], IEC 31000-3-6 [Sta10], IEC 61000-4-7 [Sta11] and IEC 61000-4-30 [Sta12]. The last one is a standard that explains exactly how power quality instruments should work. More information about measuring power quality disturbances can be found in [Bol04].

In table 2.1 the existing power quality indices are given. Also is indicated where indices are still not available or which indices are subject of discussion in international committees. The table consists of indices for the quality of voltage (grid operator’s responsibility) and quality of (mostly) current which is the responsibility of the customer.
Table 2.1: Indices for power quality phenomena

<table>
<thead>
<tr>
<th>Power quality phenomena</th>
<th>Indices grid operator</th>
<th>Indices customer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude of voltage</td>
<td>$\Delta U_{\text{nom}}, \Delta U_c$</td>
<td>current capacity at the point of connection 2)</td>
</tr>
<tr>
<td>Harmonic voltage</td>
<td>$THD_{U_h}, U_h$</td>
<td>$THD_{I_h}, I_h$ 3)</td>
</tr>
<tr>
<td>Flicker severity</td>
<td>$P_{lt}, \Delta U$</td>
<td>$\Delta P_{st}, \Delta P_{lt}, \Delta U$ 4)</td>
</tr>
<tr>
<td>Voltage dips</td>
<td>-</td>
<td>- 5)</td>
</tr>
</tbody>
</table>

1) Discussion about the acceptable levels  
2) Only as indication, no time restrictions  
3) Harmonic currents are only regulated for devices and not yet at the POC  
4) Regulated in the Dutch grid code, in most countries no indices at the POC  
5) No regulation yet, discussion about acceptable number of dips is ongoing.

General remark: All power quality indices are defined for a certain percentile within a measuring period of one week. Measured are the 10-minutes average values. There is discussion in international committees concerning power quality about this measuring period of 10 minutes.

The current capacity of the point of connection is limited by the protection device at the POC. Certainly this is more an economic limit, because the grid operator includes a certain diversity factor for the grid design. There is only a weak relation with the voltage indices. Harmonic current limits are defined for devices, but at the point where there is a contract between customer and grid operator no harmonic current limits exist in European grid codes. For the grid operator, limits at the point of connection are needed. The IEEE 519 [Sta13] aims to state harmonics for a whole installation as is described in chapter 5. For flicker there is an additional requirement for flicker severity variation implemented in the grid code. In most European countries this is not the case. These additional requirements at the POC are topics analysed in chapter 5 and 6.

2.3 Voltage quality levels

The limits set by the national Regulator are used as the starting point for defining the quality of the voltage. As a minimum requirement, these limits have to be fulfilled at each POC (the point of connection of a customer). The European Standard EN50160 [Sta01] is always used in European countries as a basis for the quality of the supply voltage.
Table 2.2: Requirements for supply voltage, national Dutch grid code June 2005 [Sta03]

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>o 50 Hz +/-1% during 99.5% of each year</td>
</tr>
<tr>
<td></td>
<td>o 50 Hz +/-4%/6% during 100% of the time</td>
</tr>
<tr>
<td>Magnitude of voltage (Voltage level)</td>
<td>Low voltage:</td>
</tr>
<tr>
<td></td>
<td>o ( U_{\text{nom}} = 230\text{V} )</td>
</tr>
<tr>
<td></td>
<td>o ( U_{\text{nom}} +/-10% ) for 95% of all 10 min. average measured</td>
</tr>
<tr>
<td></td>
<td>values during 1 week</td>
</tr>
<tr>
<td></td>
<td>o ( U_{\text{nom}} +10/-15% ) for all 10 min. average values</td>
</tr>
<tr>
<td></td>
<td>Medium voltage ( U_n&lt;35\text{kV} )</td>
</tr>
<tr>
<td></td>
<td>o ( U_n=\text{nominal voltage as stated in contract with client} )</td>
</tr>
<tr>
<td></td>
<td>o ( U_n +/-10% ) for 95% of all 10 min. average measured values</td>
</tr>
<tr>
<td></td>
<td>during 1 week</td>
</tr>
<tr>
<td></td>
<td>o ( U_n +10/-15% ) for all 10 min. average values</td>
</tr>
<tr>
<td>Fast voltage variations</td>
<td>Low voltage and medium voltage ( U_n&lt; 35\text{kV} )</td>
</tr>
<tr>
<td>Flicker</td>
<td>o ( \leq 10% U_{\text{nom}} )</td>
</tr>
<tr>
<td></td>
<td>o ( \leq 3% U_{\text{nom}} ) in situations without loss of production,</td>
</tr>
<tr>
<td></td>
<td>disconnection of heavy loads or faulted connections</td>
</tr>
<tr>
<td></td>
<td>o ( P_L\leq1 ) during 99.5% of the time</td>
</tr>
<tr>
<td></td>
<td>o ( P_L\leq5 ) during 100% of the time</td>
</tr>
<tr>
<td>Unbalance</td>
<td>Low voltage and medium voltage ( U_n&lt; 35\text{kV} )</td>
</tr>
<tr>
<td></td>
<td>o The negative sequence voltage is smaller then 2% of the positive</td>
</tr>
<tr>
<td></td>
<td>sequence voltage during 99.5% of the time.</td>
</tr>
<tr>
<td></td>
<td>o The negative sequence voltage is smaller then 3% of the positive</td>
</tr>
<tr>
<td></td>
<td>sequence voltage during 100% of the time.</td>
</tr>
<tr>
<td>Harmonic distortion</td>
<td>Low voltage and medium voltage ( U_n&lt;35\text{kV} )</td>
</tr>
<tr>
<td></td>
<td>o THD\leq8% for all harmonics up to the 40\text{th} during 95% of</td>
</tr>
<tr>
<td></td>
<td>the time</td>
</tr>
<tr>
<td></td>
<td>o The relative voltage per harmonic is smaller than in the EN-50160</td>
</tr>
<tr>
<td></td>
<td>stated percentage for 95% of the 10 minutes measured values. For</td>
</tr>
<tr>
<td></td>
<td>harmonics that are not mentioned the smallest value referred to in</td>
</tr>
<tr>
<td></td>
<td>the standard counts.</td>
</tr>
<tr>
<td></td>
<td>o THD\leq12% for all harmonics up to the 40\text{th} during 99.9% of</td>
</tr>
<tr>
<td></td>
<td>the time</td>
</tr>
<tr>
<td></td>
<td>o The relative voltage per harmonic is smaller than the percentage</td>
</tr>
<tr>
<td></td>
<td>stated in EN-50160 multiplied by 1.5 for 99.9% of the ten-minute</td>
</tr>
<tr>
<td></td>
<td>values.</td>
</tr>
</tbody>
</table>

This is also the case for the national grid code. The quality of the voltage is characterised by the following aspects:
- Magnitude of voltage
- Voltage changes (Dips and flicker)
- Harmonic distortion
- Unbalance
- Frequency

Table 2.2 gives an overview of the power quality levels as stated in the national grid code on June 2005 [Sta03].

At the time of printing this thesis there were no requirements in the Dutch national grid code for the amount, depth and duration of voltage dips. This issue is described in chapter 4 where some suggestions for requirements are given. Because a dip is an event and not a continuous appearing phenomenon a different classification method is necessary. In chapter 4 this classification method for dips is described.

2.4 Normalising and classifying power quality

Making a classification we have to realise that most people that will use this classification are not familiar in detail with power quality and all the different limits of each phenomenon. This classification can be used for several purposes as:

- Customer’s information, important for the image of the grid operator but also for industrial customers.
- To report about the quality of the voltage to the management of the grid operator, the grid owner or the regulator
- To use in network operation and planning

Monitoring the quality of the voltage will lead to an enormous amount of data which has to be reduced to a format that can be analysed quickly and easily. An important element in the communication with the customer is that the results should be easy to interpret. The first step in reaching a suitable classification is to normalise all power quality aspects [Mey01]. The second step is to make the appropriate classification [Cob01, Cob07]. Choices made here by realising a classification are proven to be practical but can be discussed. Other choices can be made depending on purpose, planning levels, etc. Nevertheless, the handling of data into such visual classification is a promising development.

2.4.1 Normalising

For each continuous phenomenon we can calculate the normalised power quality level using the formula:
\[ r_{(v,q,p)} = 1 - \frac{m_{(v,q,p)}}{I_{(q)}} \]  \hspace{1cm} (2.1)

- \( r_{(v,q,p)} \) = the normalised power quality aspect \( q \), on location \( v \), for phase \( p \)
- \( m_{(v,q,p)} \) = the actual level of phenomenon \( q \), on location \( v \), for phase \( p \)
- \( I_{(q)} \) = the compatibility level of phenomenon \( q \)

When there is no disturbance the normalised value will be 1 \((m=0)\). If the disturbance level is equal to the accepted compatibility level, the normalised value will be zero. If the disturbance level exceeds the specified limit, the performance index \( r \) becomes negative.

The plane from “no disturbance” to a level of “twice the acceptable disturbance level” is divided into six areas ranging from very high quality (A) to extremely poor quality (F), as shown in figure 2.3. Although the number of areas is disputable, there are good arguments for choosing six. These arguments are:

- For each voltage disturbing phenomenon a compatibility level and a planning level can be recognised. So three areas could be defined by these levels (the levels of 0.33 and 0.66 could be fitted to these levels).
- More areas will define more levels of quality than necessary but also will lead to more switching results week by week to a different quality level.
- By analysing complaints it is of interest to have some differentiation in not acceptable quality, which makes it easier to make trends visible. But in the “not acceptable quality” part it is not helpful to have more areas than three for the same reason as mentioned before.

<table>
<thead>
<tr>
<th>Voltage level</th>
<th>Dips</th>
<th>Flicker</th>
<th>Harmonic distortion</th>
<th>Unbalance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.3: Classification of power quality phenomena**
The classification from very high quality to extremely poor quality is made on basis of a technical judgement of the voltage. Of course, for some customers poor quality can be acceptable quality too, certainly when they can pay less for their energy. These economic aspects are not introduced into this classification.

2.4.2 The Percentile Method

The most accurate method for classifying a certain power quality aspect is the so-called “Percentile Method” [Cob07]. For each continuous existing characteristic the Dutch Regulator uses a certain percentile and level as a limit for the measured average values. For example, the flicker level ($P_f$) has to be below 1 for 95% of all measured average ten-minute values and below 5 for all average values.

![Figure 2.4: Flicker level at a random chosen POC](image)

The measured flicker level for a point of connection of a customer (POC) chosen at random is shown in figure 2.4. By sorting the data the 95% percentile value can be established, which in the given example is 0.48 (see figure 2.5). Classification of the POC with respect to flicker can be done by normalising the flicker level, the result being: $r_{(P_f, P)} = 1 - \frac{0.48}{1} = 0.52$
This corresponds to a high quality classification (B) for this POC with respect to flicker. The disadvantage of this method is that the end result does not give a lot of information about the actual flicker level. Figure 2.6 shows two extreme distributions with the same 95% percentile result, nevertheless the distribution in a) presents a better performance with respect to flicker than situation b).

Grid operators also need good general information about the power quality level, so the 95% percentile value alone does not satisfy their needs. However, for checking the quality in relation to the standard (usually set by the regulator), this method is the most accurate.

### 2.4.3 The STAV Method

Classification according the “STAV (standard deviation, average value) Method” explores more information about the distribution of the aspect involved [Cob01]. Take for example the flicker level measured over the course of a week, as shown in
figure 2.4. Calculating the average value and the standard deviation of this distribution results in:

\[ P_{\text{lt,av}} = \frac{\sum_{i=1}^{n} P_{\text{lt},i}}{n} = 0.323 \quad \text{and} \quad \sigma = \sqrt{\frac{\sum_{i=1}^{n} (P_{\text{lt},i} - P_{\text{lt,av}})^2}{n-1}} = 0.082 \]

Figure 2.7 shows how the data, as shown in figure 1.3, is distributed. Figure 2.7 also includes the best fitted normal distribution.

Assuming that the flicker level is normally distributed, a classification method based on the same basic principles as used for the percentile method can be made. The most important requirements for the flicker level according to the national grid code are:

- 95\% of all ten-minute average values of \( P_{\text{lt}} \) within a period of 1 week have to be \( \leq 1 \).
- All ten-minute average values of \( P_{\text{lt}} \) within a period of 1 week have to be \( \leq 5 \).

The relation between the standard deviation and the average value of all ten-minute values can be calculated using the following formula (2.2).

\[ P_{r} \left\{ X \leq x \right\} = P \left\{ Y \leq \frac{x - P_{\text{lt,av}}}{\sigma} \right\} = P \left\{ Y \leq \frac{1 - P_{\text{lt,av}}}{\sigma} \right\} = 0.95 \quad (2.2) \]

- \( P_{r} \) = chance of occurrence
- \( X \) = normal distribution variable
- \( x \) = normal distribution value
- \( Y \) = standard normal distribution variable
- \( P_{\text{lt,av}} \) = average value of \( P_{\text{lt}} \) within given distribution
- \( \sigma \) = standard deviation of \( P_{\text{lt}} \) within given distribution

This is the case where \((1-P_{\text{lt,av}})/\sigma = 1.65\), based on the table for a standard normal distribution, as explained further in Appendix A.
According to formula (2.1) and the borders 0, 0.33, 0.66, 1, 1.33, 1.66 and 2 as explained in section 2.2.1, six planes can be made with the classification A through F, as shown in figure 2.8. Advantages of the STAV method are the quick overview of the quality of the considered aspect, a simplified result that is easy to communicate and less influence of some of the extreme measuring points on the weekly data. A disadvantage is that it does not answer the question of whether the measured value was within the limits required by the regulator in a certain week.

![Figure 2.8: Classification according STAV method (flicker)](image)

All other continuous power quality phenomena can be classified in the same way as for the flicker phenomenon. The figures for harmonics and unbalance are given in appendix A.

A particular point in relation to voltage level is that there are two limits. Take as an example the voltage measured during a week, as shown in figure 2.9.

![Figure 2.9: Voltage measured at random POC](image)

Calculating the average value and the standard deviation of this distribution results in:
\[ U_{av} = \frac{\sum V_i}{n} = 225.3 \, V \quad \text{and} \quad \sigma = \sqrt{\frac{\sum (V_i - U_{av})^2}{n-1}} = 2.43 \, V \]

Assuming that the voltage is normally distributed, a classification method based on the same basic principles as before can be used. Figure 2.10 shows how the data, as shown in figure 2.10, is distributed. Figure 2.10 also includes the best fitted normal distribution. The normally distributed fitting curve in figure 2.10 shows that the measured voltage is indeed close to a normal distribution. The limits given by the national Dutch regulator are taken to create the border between classification C and D. The requirements for the low voltage level are:

- The nominal voltage is 230 V.
- 95% of all measured average ten-minute values of the voltage within a period of 1 week have to be within ±10% of the nominal voltage.
- All average ten-minute values of the voltage within a period of 1 week have to be between –15% and +10% of the nominal voltage.

Figure 2.10: Comparing measured distribution with normal distribution

For the voltage level the two theoretical extreme distributions, which just fulfill the requirements of the national Dutch grid code, are shown in figure 2.11. This figure plots the ±10% limits of the voltage. The upper limit may not be exceeded. Here we suppose that 99.9% is acceptable. The limit on the left (lowest voltage) may be exceeded for 5% of all measured values.
Figure 2.11: Extreme distributions of low voltage level

For the upper limit the relation between the deviation and the average of all measured values is represented by:

\[ P(\frac{X - U_{av}}{\sigma} \leq x) = P\left( \frac{Y - U_{av}}{\sigma} \leq \frac{253 - U_{av}}{\sigma} \right) = 99.9\% \quad (2.3) \]

Looking at the statistical table of the normal distribution (see appendix A), this is the case where:

\[ \frac{253 - U_{av}}{\sigma} < 3.1. \]

For the lower limit the following formula has to be used:

\[ P(\frac{X - U_{av}}{\sigma} \leq x) = P\left( \frac{Y - U_{av}}{\sigma} \leq \frac{207 - U_{av}}{\sigma} \right) = 5\% \quad (2.4) \]

This is the case where \((207 - U_{av})/\sigma = -1.65\). The relation between the deviation and the average voltage for both extreme distributions are shown in figure 2.12.

---

2 For practical use, the 99.9% value is used instead of the 100% value
Figure 2.12: Border of normal classification, low voltage level

The lines drawn in figure 2.13 are the borders of the normal quality C. Again formula 1.1 and the borders from 0 to 2 as described in section 2.2.1 are used for normalising (in this case) the voltage level. The following borders can be defined for classification A, B, D, E and F.

Border A/B: \[ r = \frac{1}{3} = 1 - \frac{253 - U_{A/B}}{230} \times 100 \rightarrow U_{A/B} = 253 - \frac{2}{3} \times \frac{230}{10} = 237.66 \text{V} \]

Border B/C: \[ r = \frac{2}{3} = 1 - \frac{253 - U_{B/C}}{230} \times 100 \rightarrow U_{B/C} = 253 - \frac{1}{3} \times \frac{230}{10} = 245.33 \text{V} \]

A normalised border on the minimum voltage level side is calculated as follows:

Border B/C: \[ r = \frac{2}{3} = 1 - \frac{U_{B/C} - 207}{230} \times 100 \rightarrow U_{B/C} = 207 + \frac{1}{3} \times \frac{230}{10} = 214.66 \text{V} \]

Similarly, all other borders can be calculated, resulting in the classification areas as shown in figure 2.13.
In the next section, implementation of a power quality monitoring system in a substation of Continuon, including the classification method is described.

2.5 Monitoring Power Quality in substations and transforming substations

For the coming years Continuon has to refurbish more than 200 HV/MV substations. For an MV installation, the functionality will cover local and remote control, protection, disturbance recording, fault localisation, metering, power quality monitoring functions, primary equipment diagnostics and all other necessary secondary functionality. Signal converters will send/receive all necessary data to a central system where all required functionality is implemented. The communication interface between the signal converters and the centralised system as well as the signal converters themselves are specially designed on the basis of cost effectiveness, simplicity and long life [Rie01].

The system is able to measure harmonics up to the 50th and all other Power Quality aspects stated in EN 50160, such as voltage dips, sags, swells, flicker, etc.
The same kind of system has to be placed in transforming substations to get a picture of the quality of the supply voltage close to the connection point of customers. Gathering a lot of power quality data with this system is possible but analyzing all the data will take an enormous amount of time. For this reason the percentile or STAV method is used.

First of all there is the advantage of sending only three values of a weekly measured power quality phenomenon: the average, the standard deviation and the 95% percentile value, whatever is important for the regulator. Using this method makes it possible to analyze the data quickly. All weekly data from the substations and transforming substations measured is plotted on a screen, as shown in figure 2.15. This gives an overview of the quality of the supply voltage for each measured busbar in the different substations and for the different power quality phenomena.

![Figure 2.15: Classification of supply voltage in substations (example, not based on real data)](image)

Studying figure 2.15, we can conclude that there is one location with a voltage level problem and several locations with a flicker problem. To get more information about the grid situation a more detailed screen relating to voltage level can be selected. Figure 2.16 shows this screen, made using the STAV method. There is indeed one bullet across the border of plane C, placed in plane D. This means that the limit of the grid code (border between plane C and D) is exceeded.
Figure 2.16: Measured voltage in transforming substations (LV side), using STAV method

The flicker problem can be analysed using the screen shown in figure 2.17.

Figure 2.17: Flicker data for one selected point in the grid (one phase is exceeding the limit)

Only when more detailed information is needed can all the data of this measurement be downloaded and a graph of the measured values of $P_L$ made according to figure 2.4. In most cases this will not be necessary because the supply voltage will generally be well within the limits.

Presenting the data in the way described above makes it possible to implement data of several weeks, months or even years in the same plot. Trends in the different power quality phenomena can, with all selected data in one graph very easily be analysed.
2.6 Summary and conclusions

For several reasons as described in [Bol03], there is a need for common power quality indices. With indices it is possible to report quality in a consistent and harmonised manner, either to customers, regulators or within the grid company. However, due to the growing importance of power quality, monitoring the present power quality is needed and more monitoring programs are done in the last years. A new development is integrating power quality measurements into substation automation. However, this will lead to enormous amounts of data, even using indices. Therefore an additional classification will be helpful.

In this chapter a promising classification is made. The first step in reaching this classification is to normalise all power quality aspects [Mey01]. The second step is to make the appropriate classification [Cob01, Cob07]. The most accurate method for classifying a certain power quality aspect is the so-called “Percentile Method”. This method can be used for controlling the power quality on a single connection point of a customer. The disadvantage of this method is that the end-result does not give a lot of information about the actual power quality level. To overcome this disadvantage the “STAV Method” is introduced. Advantages of the “STAV Method” are the quick overview of the considered quality aspect, a simplified result that is easy to communicate and with less influence of some of the extreme measuring points on the weekly data. A disadvantage is that it does not answer the question of whether the measured voltage was within the limits required by the regulator in a certain week. Nevertheless, for the grid operator it is a very useful tool for controlling the performance of the grid and to inform customers and regulators about the general voltage quality in the network. The classification method described has shown to be very promising and is already used by Continuon and Westland Energy3 [Rie01, Lum01].

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3 Westland Energy is a grid operator in the Netherlands
Voltage level and dispersed generation

Voltage level is one of the most important aspects of supply voltage quality. Normally, meeting the requirements is not a big issue within the low and medium voltage grid. In combination with dispersed generation some new topics arise, which will be discussed in relation to voltage level regulation in low and medium voltage networks. The actual voltage level in existing grids and the actual limits according the Dutch grid code are important inputs for calculating the amount of dispersed generation which can be implemented without causing problems to the voltage level. Several solution are taken in consideration in different research projects such as load shedding, control of reactive power [Pre01] and control of distributed generators. These options are complex and need the involvement of customers. Also the communication between all devices is a complex issue. Therefore, in this chapter the (dis)advantages of regulating the voltage level with reactive power provided by the dispersed generation in the low and medium voltage grid is analysed. The upper limit of the voltage level is increased in 2004 [Ene04], so implementation of dispersed generation is possible to some extend without any problem and without a need of complex control. An indication of the amount of dispersed generation that can be integrated in the existing low and medium voltage grids is given.

3.1 Voltage magnitude variations, requirements

Before the year 1989 the nominal low voltage in the Netherlands was 220 V. Some other European countries had different values. For example England had a nominal voltage of 240 V. Due to the European standardisation of the low voltage this nominal voltage level is changed to 230 V for all European countries. For the Dutch situation it was agreed that the old nominal voltage level of 220 V would be changed to the new level over a 15-year period. The change in the nominal voltage in the period 1989 to 2004 is shown in figure 3.1 [Ene04].
So over the period of change up to 2004 the upper limit of the voltage level was 230 +6%, approximately 242 V. This was the same as the old upper limit of 220 V +10%, with the result that equipment should not suffer any problem with high voltages during this period. In 2004 the upper limit was changed to 230 V +10%, leading to a maximum acceptable voltage of 253 V. Actually still, the voltage level in the grid is mostly lower than 242 V and the maximum voltage level could increase with 11 V. Implementation of a high amount of dispersed generation is possible before the maximum voltage level of 253 V is reached.

The exact requirements for the low voltage level, seen as the compatibility level, are currently:

- The nominal voltage is 230 V.
- 95% of all ten-minute measured values of the average RMS voltage within a period of one week have to be within ±10% of the nominal voltage.
- All ten-minute measured values of the average RMS voltage within a period of one week have to be within −15% and +10% of the nominal voltage.

For the medium voltage there is a contracted voltage, the declared voltage, with the following bandwidth:

- 95% of all ten-minute measured values of the average RMS-voltage within a period of one week have to be within ±10% of the declared voltage.
- All ten-minute measured values of the average RMS-voltage within a period of one week have to be within −15% en +10% of the declared voltage.
So in medium voltage the nominal voltage is not fixed on a specific value, but is the contracted value, in other words the value that the grid operator and the consumer are agreed on.

Besides the compatibility level, a planning level is needed. Grids are designed for 30 to 40 years and most of them are operated for dozens more years. By designing a new grid these planning levels have to be used, taking in to account:

- Increase of the load during the lifetime of the grid
- Implementation of dispersed generation
- Voltage regulation possibilities in the grid
- Voltage regulation with load or dispersed generation

An example of a medium and low voltage grid used as basis for voltage level calculations is given in section 3.2.

3.2 Grid design

When designing a grid for many years of operation there has to be some clarity about the future developments, otherwise assumptions have to be made to be able to make the design. In this chapter only the voltage level will be addressed, but for example earthing requirements, the flicker implications and economic optimalisation are also important issues in designing the grid.

3.2.1 Voltage level calculations

Calculation of the actual voltage level in the low and medium voltage grid is mostly a simple straightforward calculation when load or generation is known, due to the fact that these grids are generally operated as radial networks as shown in figure 3.2.

![Figure 3.2: Part of a medium and low voltage grid](image-url)
The voltage level at point \( N_L \) in the low voltage network can be calculated taking into account:

- the voltage variation in the medium voltage grid
- the voltage variation across the transformer and the transformer ratio
- the voltage variation in the low voltage grid

The medium voltage \( U_M \) on the busbar of the substation is taken as constant.

The voltage variation in the medium voltage grid is:

\[
\Delta U_M = \sum_{i=1}^{N_L} \left[ \left( \sum_{j=1}^{N_L} \frac{P_j}{U_{L,j} \cdot \sqrt{3}} \right) \cdot R_{M,(i,j-1)} + \left( \sum_{j=1}^{N_L} \frac{Q_j}{U_{L,j} \cdot \sqrt{3}} \right) \cdot X_{M,(i,j-1)} \right]
\]  

(3.1)

The voltage variation across the transformer is:

\[
\Delta U_T = \left[ \sum_{i=1}^{N_L} \left( \frac{P_i}{U_{L,i} \cdot \sqrt{3}} \right) \right] \cdot R_T + \left[ \sum_{i=1}^{N_L} \left( \frac{Q_i}{U_{L,i} \cdot \sqrt{3}} \right) \right] \cdot X_T
\]

(3.2)

The voltage variation in the low voltage grid is:

\[
\Delta U_L = \sum_{i=1}^{N_L} \left[ \left( \sum_{j=1}^{N_L} \frac{P_j}{U_{L,j} \cdot \sqrt{3}} \right) \cdot R_{L,(i,j-1)} + \left( \sum_{j=1}^{N_L} \frac{Q_j}{U_{L,j} \cdot \sqrt{3}} \right) \cdot X_{L,(i,j-1)} \right]
\]

(3.3)

Where:

- \( U_{L,i} \) = line voltage at the low voltage side of the transforming substation
- \( U_M \) = line voltage at the busbar of the substation
- \( P \) = active power, at each connection point
- \( Q \) = reactive power, at each connection point
- \( R_M \) = resistance in the medium voltage grid
- \( X_M \) = inductance in the medium voltage grid
- \( R_L \) = resistance in the low voltage grid
- \( X_L \) = inductance in the low voltage grid
- \( T \) = transformation ratio of the transformer \((U_{MV}/U_{LV})\)
- \( R_T \) = resistance of the MV/LV transformer (transferred to LV-side)
- \( X_T \) = inductance of the MV/LV transformer (transferred to LV-side)
- \( U_{L,i} \) = line voltage at each connection point

By taking into account the transformer ratio the line voltage at point \( N_L \) is:
Realising an acceptable voltage level in a situation where only load occurs is less complex compared with the situation with generation. The voltage level can be regulated with the setpoint of the HV/MV transformer, the chosen cables in the MV and LV networks \((R\text{ and }X)\), and with the set point of the MV/LV transformer. Figure 3.3a shows this situation where the voltage deviation in the networks is partly compensated with the set point of the transformers. Achieving the right voltage level becomes more complicated when dispersed generation is integrated in the MV and LV network. Figure 3.3b shows a possible distribution of the voltage level along the cables of the different grids when dispersed generation is connected at the end of the LV grids.

\[
U_{N_L} = (U_M - \Delta U_N) \frac{1}{T} - \Delta U_T - \Delta U_L
\]

Figure 3.3: Voltage levels with and without dispersed generation

The influence of dispersed generation will be described in the following sections.

3.2.2 Dispersed generation in the grid

To analyse the influence of DG on the actual voltage level in the LV and MV grid, the influence on the LV grid will be studied first. Calculations will be made in the LV grid shown in figure 3.4. The low voltage network consists of four outgoing feeders with 240 customers connected to the low voltage network, using 150 mm\(^2\) Al low voltage cables. The nominal power of the transformer is in general 400 kVA. In the calculations for three feeders all connected customers, including power losses in the cables, are lumped to one load. In one feeder 10 feeding points are supposed (\(N\) is taken as 10) and at each point six customers are connected to the grid. This gives an accurate enough result of the voltage level along the cable and (most important) at the end of the feeder.
Dispersed generation in the low voltage grid can be a solar system or micro combined heat and power (μCHP). The generated electric power of a μCHP is approximately 1 kW and in winter time the simultaneous generation can be high. For solar systems there is always a high simultaneous generation and the generated power for each customer can be higher than 1 kW. So, it is interesting to analyse the maximum power of the PV systems which can be injected in the low voltage grid.

For an initial estimate the PV power is calculated which can be connected at one point along the low voltage cable leading to a voltage rise of 2%, 4% and 6% of the nominal voltage. In this (theoretical) situation no load is connected. The formulas used for these calculations are:

\[
\Delta U \approx I_{PV} \cdot R_g \cdot \cos \phi + I_{PV} \cdot X_g \cdot \sin \phi
\]

\[
P_{PV} = 3 \cdot U_p \cdot I_{PV}
\]

Where:

- \( \Delta U \) = 2%, 4% or 6% of the nominal voltage of 230 V
- \( I_{PV} \) = the current of the PV system
- \( \phi \) = angle between voltage and current (\( \cos \phi \) is taken as 1 for PV systems)
- \( U_p \) = phase to neutral voltage
- \( R_g \) = resistance of the grid
- \( X_g \) = inductance in the grid
- \( P_{PV} \) = three phase PV power which can be connected at one point of the cable

The results of these calculations are shown in figure 3.5 [Cob11].
Figure 3.5: Maximum PV power which can be connected at one point of LV cable

For example, 100 kW PV power can be connected on a 150 mm² Al low voltage cable with a length of 280 m when a voltage rise along the cable of 4% is acceptable.

PV systems are usually not located at one point but are installed on the roof of several customers and therefore distributed along the cable. The voltage rise along the cable with N connection points can be calculated as follows:

\[ \Delta U \approx \sum_{i=1}^{N} \left( I_{py} \cdot \cos \phi + I_{py} \cdot X_{g} \cdot \sin \phi \right) \]  \quad (3.7)

So the calculated PV power shown in figure 3.5 can be multiplied by a factor \( M \) giving the same voltage rise at the end of the cable as the given PV power connected at one point at the end of the cable:

\[ M = \frac{N^2}{\sum_{i=1}^{N} i} \]  \quad (3.8)

In figure 3.6 the factor \( M \) is given for 1 to 20 connection points along the cable.
Figure 3.6: M, multiplying factor for PV power when distributed along the cable

So if the maximum length of the cable is 280 m, and the PV systems are distributed along the cable at every 28 m (10 connection points), $M=1.8$ and the maximum PV power is 180 kW. This is anyway the maximum power because of the capacity of the low voltage cable (horizontal lines in figure 3.5).

To analyse the effect on the voltage level more precisely the load has to be taken into account. To gain information about the load profile the active and reactive power is measured at several substations and the result of one example is shown in figure 3.7 and 3.8, where the load profile of several weeks during the year is shown. The load pattern looks similar every day, with a maximum active load of 280 kW in this case and a rather small amount of reactive power, sometimes inductive and mostly capacitive at night.

Figure 3.7: Active power at a transforming MV/LV substation with around 240 customers
Figure 3.8: Reactive power at the same substation

The extreme values of the actual voltage level will occur in the following situations:

- Maximum DG combined with a minimum load
- Minimum DG combined with a maximum load

Figure 3.9 shows the active and reactive load pattern during one day. This figure also gives the injected PV power when a lot of PV systems are connected to the MV/LV substation. The voltage level in the low voltage grid will be analysed assuming that:

- The PV systems are equally distributed over the four outgoing feeders and equally distributed along the cables.
- The MV voltage stays constant, but there is a voltage drop along the MV/LV transformer.
- An assumed maximum PV power of 280 kW is combined with the minimum load of 70 kW.
- The maximum load of 280 kW is combined with zero DG, because in winter at the time given (proximally 7.30 pm) there will be no PV power.

The influence of reactive power is not taken into consideration, which is acceptable. The amount of reactive power is small compared with the active power. Furthermore, the value of $X_g$ is smaller than $R_g$ and $\sin \phi$ is small compared with $\cos \phi$. 

-50-
The results of calculating the voltage levels along the low voltage cables in the two given extreme situations are shown in figure 3.10. The maximum voltage drop along the cable is proximally 6 V, due to the total load of 280 kW. The voltage rise is less, because of the total injected power of 210 kW and is around 5 V. The straight lines are in the situation without voltage regulation and with a constant MV voltage. By regulating the MV voltage using an automatic tap changer the voltage deviation can be limited to about 6 V, as shown by the dotted lines.

In the situation that in one feeder only DG is placed and in the other feeder only load, regulating the MV voltage is not always possible. Nevertheless, the voltage deviation in the low voltage grid is acceptable and compensation on a lower level in the low voltage grid is not needed.
Looking at the results it can be concluded that it is possible to connect DG to the low voltage grid at least with the same power as the maximum load. In this example the implementation of DG-power equal to 70% of the nominal power of the transformer did not give any voltage level problem. This will be the case in most Dutch low voltage grids. Only in old grids where the impedance is extremely high additional calculations should be made.

To analyse the influence of the variations of voltage level in the MV grid a common grid structure as shown in figure 3.11 is used. The MV grid consists of 15 outgoing feeders and each outgoing feeder has 12 transforming MV/LV substations. The length of the MV cable between each substation is 1 km. The type of cable is 240mm² Al.

Figure 3.11: Commonly used Dutch MV grid structure

The amount of load and distributed generation is assumed to be the same as in the low voltage calculations. The result of the voltage level calculations for the low voltage grid (transforming substation 12) is shown in figure 3.12. The straight lines are again representing the situation without voltage regulation and with a constant MV voltage at the HV/MV station.

Figure 3.12: Voltage level along LV cable, calculated with a real MV grid
Due to the voltage drop in the MV grid (in the maximum load situation) or the voltage rise (in case of maximum DG) the voltage variation at the low voltage busbar in the transforming substation can be approximately 26 V. The voltage level in the low voltage grid is still within the given limits. Again, regulating the medium voltage at the primary side of the transformer station, the voltage variation within the low voltage grid could be limited to 6 V as shown by the dotted lines.

Voltage regulation is mostly done at the HV/MV transformer. In grids with a lot of DG the allowed voltage limits in the low voltage grid can be reached when no additional voltage regulation is used. Suggestions are done to control the voltage using a controller within the interface of each DG or to regulate the reactive power [Pre01]. In section 3.3 it will be concluded that regulating the voltage with reactive power is not a solution for the low voltage grid. For the MV grid it could be a possibility but has also limited effects. In section 3.4 new voltage regulation concepts with more advantages will be given.

### 3.3 Voltage level variation with reactive power

Dispersed generation on a LV cable will lead to higher voltages on each POC. To investigate if it is interesting to use reactive power as tool for voltage control, the situation as shown in figure 3.13 will be studied. In this figure we see a LV cable with N=20 connection points. At each point there is assumed to be a minimum load and a considerable amount of DG power. The characteristics of the various components are:

- Transformer: 400 kVA, 10.000/400V, $u_k=4\%$
- LV-cable: 95 mm² Al, length between each point 20 m
- Load: 150 W, power factor=0.9
- Generator: 6 kW, variable power factor

![Figure 3.13: low voltage situation with dispersed generation](image-url)
The cable is represented as a resistant and reactive impedance as shown in figure 3.13. In each part of the low voltage cable the voltage drop can be calculated using formula (3.3). The voltage variation across the transformer can be calculated using formula (3.2).

At first we calculate the situation that only active power is delivered by the dispersed generator. The reactive power is set to zero. Figure 3.14 shows the voltage at each POC. Using power factor 1, the active power is 2000 W at each phase. Furthermore, the voltages are shown with active power rates of 1600 W and 1200 W at each phase.

![Figure 3.14: Voltage at each POC, only active power generated (3 values)](image)

The higher voltage at the end of the LV cable is due to the active power generated by the dispersed generators. The power of the loads is too small to have a significant influence. If the high voltage at the end of the cable is a problem, we must reduce the active power. A reduction in voltage might be achieved by consuming reactive power. The situation of the generators using a constant apparent power has been calculated here. Reducing active power means then an increase of inductive reactive power. The results of these calculations are shown in figure 3.15.

The highest part of the voltage drop is due to the inductance of the transformer. This leads to a lower voltage at the beginning of the cable. The voltage drop along the cable, due to the reactive power, is only a few volts because of the small inductive impedance of the low voltage cable.
In contrast to the small positive effect on the voltage level in the grid, there is a negative effect on the power losses. Consuming reactive power by generators leads to higher currents in the grid and therefore to higher power losses. Power losses in each situation shown in figures 3.14 and 3.15 are given in table 3.1.

**Table 3.1: Power losses in the low voltage cable**

<table>
<thead>
<tr>
<th></th>
<th>Only active power</th>
<th>Constant apparent power (2000 VA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 W generation</td>
<td>920 W</td>
<td>920 W</td>
</tr>
<tr>
<td>1600 W generation</td>
<td>566 W</td>
<td>999 W</td>
</tr>
<tr>
<td>1200 W generation</td>
<td>297 W</td>
<td>1047 W</td>
</tr>
</tbody>
</table>

The same situation could occur in a MV grid. The characteristics of a MV grid however are slightly different from a LV grid. Figure 3.16 shows a typical MV grid. After point N there is a grid-opening, so the situation is comparable in that sense with a LV grid. The size of the cable (240 Al is used in the calculations) is greater than the LV cable. This already gives a better R/X ratio, which is needed for regulating voltage with reactive power. Another different cable characteristic is the capacitance as shown in figure 3.16. For low voltage situations the effect of the capacitance is negligible.
Figure 3.16: typical Dutch MV grid

For the calculations the following characteristics are used:

- Transformer: 150/10 kV, $u_k=6\%$, $P_n=66$ MVA
- Coil with an inductance of 0.3 ohm (at substation)
- MV cable: 240 mm² Al, length between each point 1000 m
- Load: 15 kW, power factor=0.9
- Generator: 200 kW, variable power factor

Again there is created a situation with a minimum of load and a considerable amount of DG power. Using these data, results in the voltage at each POC as shown in figure 3.17. The maximum phase voltage is around 6050 V, a rise of 250 V across the MV cable. Without the coil at the beginning of the MV cable the voltage rise would have been higher. Decreasing the active power, keeping the reactive power zero, gives a proportional decrease in the voltage rise as shown in figure 3.17 (dotted lines).

Figure 3.17: Voltage at each MV POC, only active power generated (dotted lines) and constant apparent power (straight lines)
If the high voltage at the end of the cable is a problem, we must reduce the active power. This already reduces the voltage. Further reduction can be achieved by more inductive reactive power. Again, the situation of the generators using a constant apparent power has been calculated here. Reducing active power means then an increase of reactive power to keep the total apparent power of the dispersed generators at 200 kVA. The results of these calculations are also shown in figure 3.17 (solid lines). Table 3.2 shows for completeness the power losses in the situation of constant power.

Table 3.2: Power losses in the medium voltage cable

<table>
<thead>
<tr>
<th></th>
<th>Only active power</th>
<th>Constant apparent power (200 kVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 kW generation</td>
<td>40.9 kW</td>
<td>40.9 kW</td>
</tr>
<tr>
<td>160 kW generation</td>
<td>25.1 kW</td>
<td>44.4 kW</td>
</tr>
<tr>
<td>120 kW generation</td>
<td>13.2 kW</td>
<td>46.5 kW</td>
</tr>
</tbody>
</table>

Comparing the LV situation with the MV situation, we can conclude:

- In the LV situation the R/X ratio is normally too high to reach an efficient voltage regulation using reactive power.
- In MV grids regulation of voltage with reactive power could be useful but will lead in most cases to an increase of power losses.
- An R/X ratio less than 2 is advisable for an effective voltage regulation with reactive power.

We can conclude that it is not efficient to limit the voltage variations using reactive power. Nevertheless, implementation of a very high amount of dispersed generation is only possible with more advanced voltage regulation methods. In section 3.4 some concepts will be described.

3.4 Voltage regulation concepts

Regulating the final voltage at the POC of customers can best be done on the MV voltage level. Of course, some voltage variations can be made by regulating the active or reactive load and the active and reactive output of dispersed generators in the low voltage grid itself, but it will never be very efficient as was demonstrated in section 3.3. Furthermore, it would need a lot of regulators, which influences these powers with the permission of the customers involved. The best option for a low voltage grid is a good grid design which keeps the voltage variations by full use of the capacity of the low voltage grid within the given limits. In this way regulators can be centralized and restricted to the places where transformers are placed.
3.4.1 Existing voltage regulation methods

One of the most commonly used methods of controlling the voltage level is regulating the tap changer of a HV/MV transformer as shown in figure 3.18.

![Diagram of Voltage Regulation](image)

Figure 3.18: Voltage regulation, keeping voltage at MV busbar constant

The tap changer of the HV/MV transformer is controlled by an automatic voltage control (AVC) relay which compares the actual voltage on the busbar with the desired voltage level given by $V_{\text{ref}}$. The relay will ensure that the voltage on the MV busbar ($V_m$) is within a defined voltage dead band $V_d$ of the AVC relay. The dead band of the relay prevents continuous switching of the tap changer. If $V_m > V_{\text{ref}} + V_d/2$, the AVC relay instructs the tap changer to reduce $V_m$ and if $V_m < V_{\text{ref}} - V_d/2$ the AVC relay instructs the tap changer to increase $V_m$. Introducing DG in the MV or LV grid will not influence the results or the advantages of this method.

Another method is regulating the voltage at the MV busbar depending on the load in the MV network. The voltage set point is dependent on the transformer loading. This is called compounding [Pro02]. The set point at high load will be several percentage points higher than the set point at low load. An often used value is half of the difference between maximum and minimum voltage at maximum load. In this case LV voltages are centred round an average value. This halves the voltage variation (difference between maximum and minimum voltage) at the end of the network. In the case of DG in the MV grid it can cause a voltage problem. If load alone is connected in one feeder, and in another feeder mainly DG, at the HV/MV substation it will be recognised as a low load situation and the voltage will be decreased. In the feeder with only load this can give a voltage problem.
Some voltage control in the low voltage grid can be done, using the tap changer of the MV/LV transformer. This is normally only done manually and is only possible when the transformer is switched off.

### 3.4.2 New voltage regulation methods

For regulating the voltage in grids with DG several new concepts have been developed [Pro03]. Voltage regulation can be done at three levels, namely:

- On the HV/MV transformer, but with adapted control (central control)
- On the MV/LV transformer, by automatic control instead of manual switching of the tap changer (decentralised control)
- With DG and load control (local control)

#### 3.4.2.1 Central control on HV/MV transformers

Additional measurements are needed to gather the necessary data to adjust the tap changer to its ideal setting. A possible solution for the compounding problem is measuring the power in the outgoing feeders, as shown in figure 3.19. Now the difference between the low load situation and DG mixed with high load can be recognised and the tap changer can be optimized [Pro02],[Pro03].

A more advanced method is to measure the voltage in the transforming substation at the end of each feeder as shown in figure 3.19. To obtain an optimal voltage for all LV customers the tap changer of the HV/MV transformer may be controlled in such a way that there is a minimum deviation from a certain reference voltage.

In formula: $$MinDev = \sum_i (V_i - V_{ref})^2$$

(3.7)

This reference voltage can be constant over time but may also vary based on load or generation conditions in the network. When energy meters with more functionality⁴ are installed on every customer site even information can be gathered about voltage levels in the LV feeders. However, given the voltage drop or rise in most LV feeders, it is not necessary. It makes the method unnecessarily complex.

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⁴ The so-called “smart energy meter” is a new type of energy meter with additional functionalities as disconnection on distance, limiting current, voltage level measurement, automatic reading.
3.4.2.2 Decentralised control on MV/LV transformers

Most MV/LV transformers in use have tap changers which may be set only when the transformer is out of service. They are adjusted only in response to structural changes in the grid. A few years ago a MV/LV transformer with an electronic regulator as shown in figure 3.20 was introduced [Gro01].

The PWM switching topology chosen makes a high level of stability of the secondary voltage level possible, independent of the 10 kV voltage variation and independent of load current. The switching concept can be explained in the following way:
If switch 1 is continuously switched on, the highest transformer winding ratio is chosen, resulting in the lowest transformer secondary voltage. If switch 2 is continuously switched on, the secondary voltage level will be increased by 2.5%. The step from closing switch 1 to closing switch 2 is a relatively large voltage step of 2.5% upwards. The tap windings are chosen for this design as 4 steps of 2.5% each. By applying PWM control of IGBTs, it is not necessary to select the fixed secondary voltage level corresponding to switch 1 or switch 2, but with the PMW technique the secondary voltage can be controlled gradually in between these two levels. Moreover, operating in this stabilised regulation mode, any secondary voltage level in the range between the outer tapping switches 1 and 4 can be set.

By using this concept the voltage at the low voltage busbar of the transforming substation can be kept constant. As seen in section 3.2 the voltage rise or drop in the low voltage grid itself is small so not much additional voltage regulation is needed. No additional measurements and controls are necessary in the low voltage grid.

### 3.4.2.3 Local control at the customers

The most complex way to control the voltage level is to control important loads or generators in the MV or LV grid. Several solutions to control local generators are developed within for example the microgrid project [www04]. An example of preventing disconnection of DG due to a high voltage level is given in [Bra01]. In the case of LV applications (uCHP or PV) it seems not logical to regulate the active power. For uCHP, most of the active power is produced when the heat is needed. PV systems will deliver active power when there is enough sunlight and reducing this active power would mean decreasing the efficiency of the system. So for LV applications this is not the best solution. Also for MV applications by controlling loads and generators extra measurements, controllers and coordination are needed, which makes it is not a very interesting possibility.

### 3.5 Summary and conclusions

The change in limit of the upper acceptable voltage level from +6% to +10% of the nominal voltage level gives the possibility to implement a considerable amount of DG into the low voltage grid. Grids developed in the last ten years where the fault voltage was a main topic for designing the grid, impedances had to be limited. In these “strong” grids with this additional 4% of possible voltage rise, implementation of DG to a maximum of 70% of the nominal power of the transformer is possible. Due to the simultaneous production of power, the use of PV systems can give some problems if the systems are not distributed over the different outgoing feeders. The low voltage grid is often designed with a so called after diversity maximum load for each domestic customer of 1 to 1.1 kVA. If PV systems are connected with a nominal
power of several kW's at each customer’s installation, problems with the actual voltage level and capacity of the LV cable can occur.

Voltage regulation in the low voltage grid using reactive power is not effective. Due to the high $R/X$ ratio the voltage variations are mainly influenced by the active power and the resistance of the low voltage cable. In the MV grid it is a more effective method but still not advisable.

On this moment voltage regulation takes place only at the HV/MV transformer. Introducing DG on a larger scale will influence existing voltage regulation methods, i.e. compounding will be influenced in a negative way.

Other methods have to be introduced to support the implementation of DG. Two main methods are:

- Intelligent regulation of the voltage at the MV busbar in the HV/MV substation. Information from the outgoing feeders or (even better) information about the voltage on the primary side of MV/LV transformer stations can be used to calculate the set point of the tap changer
- Keeping the voltage on the low voltage side of the MV/LV transformer constant by regulating the voltage on the primary side of this transformer. This method is the most effective one, but it desires a greater investment in the grid.
Voltage dip profiles and classification

Dips are of all power quality aspects, causing the most costs at the customer's side [Bo01]. Depending on the depth and time of the dip, it can cause interruption of a process, malfunction of devices or damage to either of them. To identify the dip problem, we have to locate the origin, establish the impact on the customer and calculate the costs involved. The solutions to a dip problem can be found in devices, the installation or even the grid. Manufacturers are responsible for ensuring that their devices function properly and have a degree of immunity against voltage dips. Grid operators do not yet have to limit the amount of voltage dips but can take some measures to reduce the dip depth and duration. Nevertheless, some degree of voltage dip will always exist, so customers have to take their own responsibility for a certain amount of dips. In future, the grid operator should inform his customers about a predictable dip profile. In this thesis, research has been done on topics such as the origin of dips, classifying voltage dips and predicting the dip profile for customers. The calculation methods used are based on known methods [Bo01], [Iee02]. New is the composition of a total dip profile for a low voltage customer. The Dutch situation has been taken as an example.

4.1 Origin of dips

The main causes of a dip are:

- Short circuits in the grid (low, medium or high-voltage network)
- Switching of heavy loads (mostly due to reconnection after a disconnection)
- Inrush currents of high-power transformers (mostly placed in substations)

The switching of heavy loads and inrush currents will only give a dip in specific circumstances, and will be ignored in this research. Dips due to short circuits in the grid will be estimated for the low, the medium and the high-voltage grid. First of all we have to define what is meant by a “voltage dip”.

-63-
**4.1.1 The definition of a dip**

The definition of a voltage dip is: a voltage between 1% and 90% of the nominal voltage during a period of 0.5 cycle to 1 minute. The “supply voltage dip” area in figure 4.1 illustrates this dip definition, as described in EN 50160.

Within this light grey area a lot of dips of different origin and characteristics can occur. There is a big difference between a dip of up to 88% of the nominal voltage during 1 cycle and a dip of up to 5% of the nominal voltage during 50 seconds. Within the definition used in EN50160 [Sta01], the depth and the time of the dip are seen as the dip characteristics. Figure 4.2 illustrates the definition of dip depth and dip duration, in the situation of a one or a three phase connection.

![Figure 4.1: Area of a supply voltage dip [EN-50160]](image1)

![Figure 4.2: Definition of a voltage dip, one and three phase connection](image2)

The depth is by definition the difference between the lowest rms voltage and the nominal or declared voltage for the specified voltage level. The duration is the time between the first moment that the supply voltage is lower than 90 % of the nominal (or declared) voltage and the moment that the rms value (1-cycle rms value updated every ½–cycle according [Sta12]) of each phase is above the 90% value of the nominal or declared voltage.
The dip table as shown in table 4.1 will be used for calculating and classifying all dips. The advantage of this table is that most of the existing immunity curves can be included. As an example the ITIC curve and the SARFI 70 are drawn into the table.

**Table 4.1: Sorting table for different dip types**

<table>
<thead>
<tr>
<th>ΔΦ/λΦ</th>
<th>0.01-0.02</th>
<th>0.02-0.1</th>
<th>0.1-0.5</th>
<th>0.5-1</th>
<th>1-2</th>
<th>2.5</th>
<th>5-10</th>
<th>10-20</th>
<th>20-50</th>
</tr>
</thead>
<tbody>
<tr>
<td>80-90</td>
<td>ITIC-curve</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70-80</td>
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<td>60-70</td>
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<td>50-60</td>
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<td>40-50</td>
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<td></td>
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<td>30-40</td>
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<tr>
<td>20-30</td>
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<td>10-20</td>
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<tr>
<td>1-10</td>
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</tbody>
</table>

The ITIC curve was derived by a working group of CBEMA, which changed its name to the Information Technology Industry Council. The intention was to develop a curve that more accurately would reflect the sensitivity of computers and other devices containing digital technology like copiers, fax machines, and point-of-sales terminals. So although specifically applicable to computer-type equipment, the ITIC curve is generally applicable to other equipment containing solid-state devices.

SARFI is an acronym for System Average RMS Variation Frequency Index. It is a power quality index that provides a count or rate of (in this case) voltage sags. The size of the system is scalable: it can be defined for a single monitoring location, a single customer service, a feeder, a substation, groups of substations, or for an entire power delivery system. The SARFI curve corresponds to a rate of voltage sags below an equipment compatibility curve. For example SARFI<sub>ITIC</sub> considers voltage sags and interruptions that are below the ITIC curve. SARFI<sub>70</sub> considers voltage sags and interruptions that are below 70% of the nominal or contracted voltage.

**4.1.2 The low voltage network**

From results of calculation as given in appendix B can be concluded that:

- Only 10% of the short circuits in low voltage cables will lead to dips at the MV bar of the transforming substation.
- Around 90% of short circuits in low voltage cables will lead to dips at the LV busbar of the transforming substation
A general idea about dips that originate in the low voltage network can be obtained by analysing the failure data from the Dutch national database [Wol01]. Figure 4.3 shows how the different causes of interruption are divided; thereby giving an indication how often a dip affects customers connected to the same transformer.

Due to faults in the low voltage network, the Dutch average interruption frequency is about 0.029/year. Almost 75% of all interruptions are due to short circuits but only 80% of all short circuits will lead to a decrease in the voltage level below 90% of the nominal voltage. It is estimated therefore that 60% of all interruptions lead to a dip for customers on another outgoing feeder of the same transformer. We can conclude that dips that originate in the low voltage network occur with a frequency of 0.0174/year multiplied with the amount of outgoing low voltage feeders. The average amount of outgoing feeders is five; hence studying this phenomenon in the low voltage network is not really an issue.

**4.1.3 The medium voltage network**

The medium voltage grid in the Netherlands is mostly a meshed grid, but operated radial. Dips will occur due to short circuits in the medium voltage grid. The configuration of the grid and the length of the medium voltage cables are important factors which will influence the amount and depth of the occurring dips. Figure 4.4 shows two different configurations of medium voltage feeders.

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**Figure 4.3: Causes of interruption in LV network**

**Figure 4.4: Two different MV feeders**

-66-
Only one protection device is installed in the beginning of the first feeder. There is no secondary protection device along the cable. In the second feeder this secondary protection device is installed after the transforming substation 5 and also a coil is mounted at the beginning of the feeder.

The consequents for the occurring dips of these two different configurations are:

- Short circuits occurring behind the secondary protection device will lead to deep dips at the transforming substations placed before this secondary protection device.
- The amount of these deep dips will be very limited because the only occur due to a short circuit in this particular feeder.
- Due to the necessary selectivity of the two protection devices in series the duration of the dips will be longer.
- The coil will limit the short circuit current with as result that dips will be not so deep and the amount of dips will be reduced.

In appendix B calculations of the amount and depth of dips occurring in the two typical MV grids are given. Results of these calculations are given in table 4.2 and 4.3. Similar calculations are described in [Rom01] with comparable results.

Table 4.2: Number of dips due to short circuits in MV grid without coil and without second protection device

<table>
<thead>
<tr>
<th>(dU)</th>
<th>(t_d)</th>
<th>0.01-0.02</th>
<th>0.02-0.1</th>
<th>0.1-0.5</th>
<th>0.5-1</th>
<th>1-2</th>
<th>2-5</th>
<th>5-10</th>
<th>10-20</th>
<th>20-60s</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-90</td>
<td>3.8</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>70-80</td>
<td>0.95</td>
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<tr>
<td>60-70</td>
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<td></td>
<td>0.95</td>
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<td>50-60</td>
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</tr>
</tbody>
</table>
Faults in the MV grid can be divided in three groups of faults with the given occurrence [Pro01]:

- 25%: three phases to earth faults
- 25%: two phases to earth faults
- 50%: one phase to earth faults

It is important to study how these faults (and the corresponding dip) transfer to the LV side, because this is the place where most devices are connected to. In Dutch MV grids mostly Dy transformers are used. Therefore:

- Three phases to earth faults will result in a three phase dip at the low voltage level.
- Two phases to earth faults will lead to one phase dip at the low voltage level.
- One phase to earth faults will not transfer to a dip on low voltage level.

The transfer of dips from medium voltage to low voltage is described in appendix B. More information can be found in [Bol01].

### 4.1.4 The high voltage network

In the year 2005 a national measuring program for dips in the HV grid, was started in the Netherlands. The national regulator requested for this to get more insight information about the number and type of dips in the HV grid. The information gathered was meant to be used for developing a standard for acceptable dips in the grid. In this research it is not the intention to analyse the HV grid, nevertheless the results of this measuring programme is included to get a total analyse of dips at the point of connection, with their origin and possible causes. The total number of dips, measured during 2005 is given in table 4.4.
Table 4.4: Number of dips in HV grid (including extreme weather conditions)

<table>
<thead>
<tr>
<th>ΔU</th>
<th>0.01-0.02</th>
<th>0.02-0.1</th>
<th>0.1-0.5</th>
<th>0.5-1</th>
<th>1-2</th>
<th>2-5</th>
<th>5-10</th>
<th>10-20</th>
<th>20-60a</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-90</td>
<td>6520</td>
<td>5920</td>
<td>4520</td>
<td>3200</td>
<td>2700</td>
<td>2000</td>
<td>1200</td>
<td>800</td>
<td>600</td>
</tr>
<tr>
<td>70-70</td>
<td>920</td>
<td>6520</td>
<td>5920</td>
<td>4520</td>
<td>3200</td>
<td>2700</td>
<td>2000</td>
<td>1200</td>
<td>800</td>
</tr>
<tr>
<td>50-60</td>
<td>120</td>
<td>3200</td>
<td>1200</td>
<td>120</td>
<td>920</td>
<td>2000</td>
<td>1200</td>
<td>800</td>
<td>600</td>
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<tr>
<td>40-50</td>
<td>120</td>
<td>920</td>
<td>2000</td>
<td>1200</td>
<td>800</td>
<td>600</td>
<td>1200</td>
<td>800</td>
<td>600</td>
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<tr>
<td>30-40</td>
<td>120</td>
<td>1200</td>
<td>2000</td>
<td>1200</td>
<td>800</td>
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<td>1200</td>
<td>800</td>
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<tr>
<td>20-30</td>
<td>120</td>
<td>2000</td>
<td>1200</td>
<td>800</td>
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<tr>
<td>10-20</td>
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<td>1200</td>
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<tr>
<td>1-10</td>
<td>120</td>
<td>2000</td>
<td>1200</td>
<td>800</td>
<td>600</td>
<td>1200</td>
<td>800</td>
<td>600</td>
<td>600</td>
</tr>
</tbody>
</table>

All measured dips in the table are divided by 20, because this was the number of measurement devices, randomly placed in the HV grid. So, by dividing the measured dips by the number of placed measurements, the average number of dips on each location can be calculated.

End November 2005 there were two days with a lot of ice, snow and strong winds. Within these two days there were a lot of problems, due to galloping lines. Needless to say, a lot of dips can be expected in such extreme weather conditions. Normally, these events take place once every ten years and disturb the analysis of the average quality of the grid. The data excluding these extreme weather conditions is shown in table 4.5.

Table 4.5: Number of dips in HV grid (excluding extreme weather conditions)

<table>
<thead>
<tr>
<th>ΔU</th>
<th>0.01-0.02</th>
<th>0.02-0.1</th>
<th>0.1-0.5</th>
<th>0.5-1</th>
<th>1-2</th>
<th>2-5</th>
<th>5-10</th>
<th>10-20</th>
<th>20-60a</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-90</td>
<td>6520</td>
<td>5920</td>
<td>4520</td>
<td>3200</td>
<td>2700</td>
<td>2000</td>
<td>1200</td>
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<td>70-70</td>
<td>920</td>
<td>6520</td>
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<td>4520</td>
<td>3200</td>
<td>2700</td>
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<td>50-60</td>
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<td>3200</td>
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<td>920</td>
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<td>40-50</td>
<td>120</td>
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<td>2000</td>
<td>1200</td>
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<tr>
<td>30-40</td>
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<td>1200</td>
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<td>20-30</td>
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<td>10-20</td>
<td>120</td>
<td>1200</td>
<td>2000</td>
<td>1200</td>
<td>800</td>
<td>600</td>
<td>1200</td>
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<tr>
<td>1-10</td>
<td>120</td>
<td>2000</td>
<td>1200</td>
<td>800</td>
<td>600</td>
<td>1200</td>
<td>800</td>
<td>600</td>
<td>600</td>
</tr>
</tbody>
</table>

The data given in the tables represents measured dips. Some of the measured dips are one phase dips in the HV grid. Others are two or three phase dips. So we have to find out how to transfer these dips to the MV grid and further on to the LV side of the MV/LV transformer. Table 4.6 shows the result as only three phase dips are counted.

-69-
Three phase dips are counted as such as for all phases the rms voltage has been below 90\% of the contracted voltage during the same period.

Table 4.6: Number of three-phase dips (excluding extreme weather conditions)

<table>
<thead>
<tr>
<th>(\Delta U )</th>
<th>( \frac{U}{U_0} )</th>
<th>0.01-0.02</th>
<th>0.02-0.1</th>
<th>0.1-0.5</th>
<th>0.5-1</th>
<th>1-2</th>
<th>2-5</th>
<th>5-10</th>
<th>10-20</th>
<th>20-60s</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-90</td>
<td>1900</td>
<td>220</td>
<td></td>
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<tr>
<td>70-80</td>
<td>800</td>
<td>120</td>
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<tr>
<td>60-70</td>
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<td>40-50</td>
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<td>700</td>
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<td>30-40</td>
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<td>700</td>
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<td>10-20</td>
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</tbody>
</table>

In section 4.2, which focuses on the dip profile, we will use these tables to make a general dip profile.

**4.2 The dip profile**

Before customers can take adequate measures they must have some knowledge about the number, depth and duration of the dips. Therefore an assumption of the “dip profile” is made giving an indication about the calculated dips on the POC. We have to be aware of the fact that the dip profile developed here is a very general one, giving an idea about the number and type of the dips occurring in the LV grid. Given the natural variation in the dips that occur, it is not wise to make extended and detailed calculations. An estimate of possible dips on a yearly basis is enough. For the medium voltage grid, calculations like those in appendix B can be made for a specific substation, and this is done in [Ham01]. For a general dip profile that will be a good estimate for a customer (or device) connected to the low voltage side of a transformer, table 4.2 and 4.3 (MV grid) and 4.5 and 4.6 (HV grid) can be used.

By taking these tables together we have to be aware that the dips in these tables occur in the MV and HV grid. We will have to make the translation to the LV grid. Furthermore, they include all kinds of dip, in one, two and three phases. For the HV grid the number of three phase dips has already been determined and these kinds of dips will transfer to the LV side without significant changes. For the MV grid the following assumptions are made:
Almost all networks in the Netherlands are of a meshed type and consist of secondary protection devices, which mean that dips occurring due to short circuits in the secondary part are counted.

Approximately 1/3 of the network has outgoing feeders with coils so when making the general dip profile, 2/3 of table 4.2 and 1/3 of table 4.3 (values with duration 0.1-0.5 will be placed in time zone 0.5-1) will be taken. Due to the fact that proximally 50% of all faults are one phase faults only 50% of the values are counted.

The three-phase dips will be counted separately, which is ¼ of all dips occurring in the MV grid, because these three-phase dips will result in dips at the customer's installation and mitigation is mostly expensive.

By adding the values in table 4.5 and 4.6 (3 phase dips, HV grid) and the values of table 4.2 and 4.3 according to the given assumptions, we get the values given in table 4.7. The first value in each box is the total number of expected dips and the second value is the number of three-phase dips. All dips above the ITIC curve will normally not give a problem. So these dips are not included in the table.

The table is not as detailed as before because of the small number of dips. When analysing the affect of a dip on an installation, the boxes are still detailed enough. The reasons why these boxes are chosen are explained in section 4.5.

Table 4.7: Total dip profile for dips at LV level

<table>
<thead>
<tr>
<th>Duration</th>
<th>Dip Duration</th>
<th>0.01-0.02</th>
<th>0.02-0.1</th>
<th>0.1-0.5</th>
<th>0.5-1</th>
<th>1-2</th>
<th>2-5</th>
<th>5-10</th>
<th>10-20</th>
<th>20-60s</th>
</tr>
</thead>
<tbody>
<tr>
<td>80-90</td>
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<td>70-80</td>
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<td>10-20</td>
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</tr>
</tbody>
</table>

So the total number of dips (one, two or three phases) is around 4.65 dips a year. If we look only at the three-phase dips, the total number is 2 dips a year. The origin of most dips is due to faults (faults in the MV grid, faults in HV components, human
The occurrence of these faults can be described as a Poisson process under certain assumptions. The Poisson distribution is a discrete probability distribution. It expresses the probability of a number of events occurring in a fixed period of time, if these events occur with a known average rate and are independent of the time since the last event. The number of discrete occurrences N is counted for that they take place during the given time interval, in this case the amount of dips/year. The probability that there are exactly k occurrences (dips/year) is:

\[ P(N = k) = \frac{e^{-\lambda} \lambda^k}{k!} \quad (4.1) \]

Where:
- \( e \) = the base of the natural logarithm (\( e = 2.71828 \))
- \( k \) = being a non-negative integer (\( k = 0, 1, 2, \ldots \)) and in this specific case the amount of dips/year
- \( \lambda \) = a positive real number equal to the expected number of occurrences that occur during the given time interval, in this case the average amount of dips/year

So the probability that a certain event (with a dip as result) will occur can be calculated with formula (4.1), with \( \lambda \) being the expected (average) number of dips a year. Figure 4.5 shows the Poisson distribution with an average number of five dips a year.

\[ P(N = k) = \frac{e^{-\lambda} \lambda^k}{k!} \]

Figure 4.5: Poisson distribution, \( \lambda \) = average number of dips/year = 5

Faults are events with a distribution according a Poisson process because two important conditions are fulfilled. Orderliness, which implies that arrivals don't occur simultaneously and memorylessness what means that the number of events occurring in any bounded interval of time after time \( t \) is independent of the number of events occurring before time \( t \).
Good assessment of voltage dips and the corresponding distribution can also be reached using a Monte Carlo simulation approach as described in [Olg01].

When analysing the dip profile we can conclude that an average number of dips can be calculated, the depth and duration can be predicted. The calculations are made with several assumptions which may be different in practice. Also, given the variation over several time periods in a year, a classification using a sliding window of for example 5 years is advisable.

Comparing these values with the reported dips in underground cable networks of other countries (see table 4.8 [Iec02]) could lead to the conclusion that in the Netherlands the amount of dips are relatively small and the dip problem will not be a big issue. The table however shows the amount of dips which is only exceeded at 5% of all measured location. The amount of dips in 95% of all substations is lower than the number of dips in the table. The average value will still be higher than the Dutch average but the differences are small. Nevertheless, in the last few years grid operators in the Netherlands have been receiving more and more customer complaints about voltage dips and their effect on the customer’s installation. These are mostly industrial customers with sensitive processes such as in semiconductor, paper and pulp, and pharmaceutical industries.

Table 4.8: UNIPEDE survey on frequency of occurrence of dips [Iec02]

<table>
<thead>
<tr>
<th>ΔU (V/√3)</th>
<th>0.01-0.1</th>
<th>0.1-0.5</th>
<th>0.5-1</th>
<th>1-3</th>
<th>3-20</th>
<th>20-80s</th>
</tr>
</thead>
<tbody>
<tr>
<td>70-80</td>
<td>23</td>
<td>19</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>45-70</td>
<td>5</td>
<td>19</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1-40</td>
<td>1</td>
<td>8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

4.3 Cost of dips

The economic justification for preventing production interruptions with industrial customers due to voltage disturbances must take the following elements into consideration:

- What is the dip profile the customer will encounter?
- How vulnerable is the process to various types of voltage disturbances?
- What is the net cost of production outages due to these disturbances?

Survey is done over a period of three years, in nine countries. The survey was carried out at 126 sites. Measurements were made at the LV busbar of distribution transformers. Table 4.29 contains the value which is exceeded at only 5% of the locations.
- How effective is a particular solution in avoiding these outages?
- How does the cost of the solution compare to the savings that can be realised?

There are several elements of cost associated with a process interruption that should be recognised and quantified in the economic evaluation.

- **Cost of Lost Production:** in the simplest case; this is the incremental margin on product that is not manufactured and therefore cannot be sold.
- **Cost of Damaged Product:** if the interruption damages a partially completed product, the cost of repairing that product must be recognised. In some cases, the product cannot be repaired, so the value of the raw materials (including the energy consumed up to the point where the disruption occurred) must be accounted for, together with the cost of the incremental value added to the product. In the commercial business, a major source of concern is lost computer data.
- **Cost of Maintenance:** the cost of reacting to a process disruption experience. This includes everything involved in restoring production, including diagnosing and correcting the problem, cleanup and repair, disposing of damaged product, and environmental costs. In some industries (e.g., plastics and electronics), an interruption of several hours may result in the need to invest many days and thousands of euros in cleaning up the process system before it can be returned to service.
- **Hidden Cost:** this factor may be the most difficult to quantify but it can easily be the most significant. If the impact of the voltage dip is a control error, it is possible that the impact on product may not be apparent until the product is in the hands of the consumer. Product recall and/or public relations costs can be significant.

In table 4.9 an indication is given of the cost of a voltage dip, with interruption of the process as result.

Using these indications and analysing the different sectors in the Netherlands and the power they require, in combination with the expected dips leading to process problems (three-phase dips, remaining voltage <50%), shows that costs for the Dutch market are around 26 million euros. Also dips with remaining voltages higher than 50% or one-phase dips can lead to process problems, but mitigation can be realised within the customer installation without excessive costs [Did03].

-74-
Table 4.9: Cost of interruption of processes (€/kW demand), source EPRI [Her01]

<table>
<thead>
<tr>
<th>Category</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Industrial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automobile manufacturing</td>
<td>5</td>
<td>7.5</td>
</tr>
<tr>
<td>Rubber and plastics</td>
<td>3</td>
<td>4.5</td>
</tr>
<tr>
<td>Textile</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Paper</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Printing (newspapers)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Petrochemical</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Metal fabrication</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Glass</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Mining</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Food processing</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Pharmaceutical</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>Electronics</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Semiconductor manufacturing</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td><strong>Commercial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communications, information processing</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Hospital, banks, civil services</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Restaurant, bars, hotels</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Commercial shops</td>
<td>0.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Mitigation of voltage dips is therefore an important issue. However, a general solution is not available. Every case needs an individual approach, looking at the specific process, the mitigation method needed and the economics of the dip problem [Dri02].

4.4 Mitigation of dips

Dips can be mitigated at several places in the installation or in the grid. Figure 4.6 shows the possible locations with an indication of costs involved [Did01]. Modifications in the process equipment itself (in controls and motors) tend to be the cheapest to implement. Modifying the grid is an interesting option because several customers can profit from this solution, but this is not always possible and is likely to be very expensive.

In general most practicable are protective measures installed between the sensitive process and the grid. Some of the possible solutions are:
- A flywheel and motor-generator (M/G) combination to protect critical processes against all voltage dips where the duration is shorter than the hold-up time of the flywheel. When a dip occurs, the motor-generator set feeds the load, the energy being supplied by the gradually slowing flywheel.

- A dynamic voltage restorer (DVR) which makes the missing voltage through a transformer, installed in series with the load. The load remains connected to the grid and the DVR calculates the missing part of the voltage waveform and corrects it. Depending on the concept, the energy to support the load during a dip originates either from the network or from an additional energy storage unit (usually a capacitor bank).

- A static compensator (statcom) which acts as a current injector in parallel (shunt) with the load. A statcom mitigates voltage dips by injecting reactive power into the system. The dip mitigating capability can be enhanced by adding energy storage such as superconducting magnetic energy storage (SMES).

- A shunt connected synchronous machine. This solution has similarities with the statcom, but does not contain power electronics.

![Figure 4.6: Places to mitigate dips and costs involved](image)

In theory, installing an uninterruptible power supply (UPS) is the easiest way to protect sensitive processes against all kinds of dips. However, due to its considerable purchase and maintenance costs, UPS equipment is installed only in places where the damage resulting from power supply problems is very high, such as in hospitals, computer facilities and financial institutions. In other cases, including most industrial processes, the installation of protective equipment must be subject to a cost-benefit analysis, which often shows that installing a UPS is too expensive [Did02].

In order to analyse whether the expected reduction in outage cost outweighs the cost of the protective equipment, the Net Present Value method can be used:
\[ f \cdot p_{prev} \cdot C_{dip} \geq C_{inv} \cdot \left[ \frac{(1+i)^n \cdot (1 + p_{mant}) - p_{mant}}{(1+i)^n - 1} \right] \] (4.2)

Where:
- \( C_{inv} \) = initial investment per kVA
- \( f \) = annual number of outages due to dips
- \( p_{prev} \) = percentage of outages being prevented
- \( C_{dip} \) = outage cost per interruption per kVA
- \( P_{mant} \) = maintenance costs per kVA per year as a percentage of \( C_{inv} \)
- \( i \) = discount factor
- \( n \) = project time (a)

Table 4.10: Typical voltage dip mitigation technologies and costs

<table>
<thead>
<tr>
<th>Alternative category</th>
<th>Typical cost (€)</th>
<th>Total initial cost (€)</th>
<th>Operating and maintenance cost (% of initial cost per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls protection (1 – 5 kVA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CVT Constant Voltage Transformer</td>
<td>1000/kVA</td>
<td>1000-5000</td>
<td>10</td>
</tr>
<tr>
<td>UPS Uninterruptible Power Supply</td>
<td>500/kVA</td>
<td>500-2500</td>
<td>25</td>
</tr>
<tr>
<td>Dynamic dip corrector</td>
<td>250/kVA</td>
<td>250-1250</td>
<td>5</td>
</tr>
<tr>
<td>Machine or groups of machines protection (10 – 300 kVA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UPS</td>
<td>500/kVA</td>
<td>5000-150.000</td>
<td>15</td>
</tr>
<tr>
<td>Flywheel</td>
<td>500/kVA</td>
<td>5000-150.000</td>
<td>7</td>
</tr>
<tr>
<td>Dynamic dip corrector</td>
<td>200/kVA</td>
<td>2000-60.000</td>
<td>5</td>
</tr>
<tr>
<td>Facility protection (2 – 10 MVA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic voltage regulator (50% voltage boost)</td>
<td>300/kVA</td>
<td>600,000-3,000,000</td>
<td>5</td>
</tr>
<tr>
<td>Static switch (10 MVA)</td>
<td>600,000</td>
<td>600,000</td>
<td>5</td>
</tr>
<tr>
<td>Fast-transfer switch (10 MVA)</td>
<td>150,000</td>
<td>150,000</td>
<td>5</td>
</tr>
</tbody>
</table>

By introducing 'optimistic' values for a mitigation system (e.g. \( C_{inv} = 100 \) €/kVA, \( p_{mant} = 0 \), \( p_{prev} = 100\%)\), this formula can be used to determine whether the reduction in
voltage dip costs will outweigh the cost of the most common mitigation devices. Typical voltage dip mitigation technologies and costs involved are shown in table 4.10. [Mcg01]

4.5 Classification of dips

By developing a classification for dips there are some general applications where this classification can be used:

- Giving information about the background (sources) of the dips.
- Giving some guidance about the way to solve possible dip problems.
- Giving information about the quality of the grid.
- Showing responsibilities (manufacturer, grid operator, customer).

A distinction can be made between the following sources of the dip problem:

- Faults in the HV grid.
- Faults in the MV grid (primary section).
- Faults in the MV grid (secondary section, own feeder).
- Low voltage problems.

Faults in the HV grid are mostly of short duration, so the duration of the dip is rather short too. Faults in the MV grid are disconnected in times varying from 0.3 seconds to a few seconds. The depth of the dip is mostly not very big, but sometimes the depth can be large if it is a fault in the same feeder after a secondary protection device.

Low voltage problems leading temporarily to a voltage below 90% of the nominal voltage can last a longer time but these dips are never deep. In fact it should not be counted as a real dip. It is more a problem with voltage level than a dip problem. So looking to the source of the dip, different areas can be recognised as shown in table 4.11.

Another way of looking to the problem is through the “how to solve the problem” debate. Most severe dip problems are the three-phase dips, with a remaining voltage less than 50% [Did03]. Customers can protect their installation against these kinds of dips, only with high costs. This can be a reason to divide the table into dips with remaining voltages below and above 50% of the nominal voltage. Seen from the manufacturer’s point of view the ITIC curve is an important curve. All dips that occur with a remaining voltage above this curve should not give any problem in the installation. Furthermore, we can conclude that dips with a remaining voltage below 70%, in combination with duration of longer than five seconds, seldom occur.

-78-
Table 4.11: Sources of dips

All these considerations make it advisable to divide the table in six parts, as shown in table 4.12. The green part lies above the ITIC curve and is the responsibility of the manufacturer. All devices have to work properly within this area. Furthermore the following parts can be recognised:

- S1: Short duration 1, mostly having its origin in the HV grid, but with a remaining voltage above 50% of the nominal voltage. Easy to solve in customer’s own installation.
- S2: Short duration 2, mostly having its origin in the HV grid, but with a remaining voltage below 50% of the nominal voltage. Difficult to solve in customer’s own installation.
- M1: Short duration 1, mostly having its origin in the MV grid, but with a remaining voltage above 50% of the nominal voltage. Easy to solve in customer’s own installation.
- M2: Short duration 2, mostly having its origin in the MV grid without coils or with secondary protection, but with a remaining voltage below 50% of the nominal voltage. Difficult to solve in customer’s own installation.
- L1: Long duration 1, occurs due to low voltage problems, mostly with high remaining voltage which makes it easy for the customer to solve in customer’s own installation.
- L2: Long duration 2, will lead to severe problems but will in practice only occur in very extreme situations.
This is a similar classification of dips as is described in the South African standard NRS 048 [Nrs01]. The areas chosen in this standard are given in table 4.13.

Although it is also a dip depth and time presentation, it is a little bit more complex and not completely according to the EN50160 dip definition. Furthermore it defines some small dips areas, what increases the problem of unstable values. Also the important border of 50% is not used.

The way to develop an “ABCDE” classification in the same sense as done in this research for other power quality phenomena is shown in figure 4.7 [Cob07].
Figure 4.7: Converting measured dips to “ABCDE” classification

First we have to define $L_{dip}$, being the limit for dips, as for example a $P_b$ value of 1 was the limit for the flicker phenomena. In each defined dip zone two parameters has to be given. These parameters are:

- The amount of dips, which normally should not be exceeded. This value could be determined by taken the 95% value of measured dips in a substation. In this example it is taken as 8 for the dip zone in the upper left corner of the table.
- The weighting factor. A certain weighting factor must be given to each defined dip zone. A deep dip with long duration will have a much higher impact on the installation than a shallow dip with short duration. These weighting factors should have a relation with the costs of mitigation of the corresponding dip. Research as described in [Wan01] or [Dri02] could be helpful to determine these weighting factors. In figure 4.22 this relation is not yet made, but the values of 1 (zone S1), 2 (zone M1) 4 (zone L1 and S2), 8 (zone M2) and 16 (zone L2) are given as example.

The maximum limit value for dips $L_{dip}$ can be calculated using the given limits for the number of dips and the weighting of each dip zone (see figure 4.7). When on a POC or a substation the amount of dips are measured as is displayed in the right table, the dip value $m_{dip}$ can be calculated. In this case it is 31, resulting in classification B, high quality but near to acceptable quality. As explained in section 4.2, the measured value
to be used should be an average value over a period of five years. A gliding window of five years could be used, giving a more stable and reliable classification of the grid.

More research has to be made after the optimal level for voltage dips objectives. The total costs for network and customer has to be considered, for determine the weighting factors. Measurements have to be performed and published to estimate the existing performance level and to determine the maximum amount of dips for each zone. This can be done for several type of grids (cables, lines, urban grids, rural grids). These measurements also see the “hidden dips” which are not included in the calculating or prediction process. With “hidden dips” is mend the dips due to faults in the grid, lasting a very short time and do not lead to interruptions.

4.6 Summary and conclusions

Because the MV grid normally exists of cables buried in the ground and the length is relatively short, the number of dips in the Netherlands is small in comparison with most other countries. Nevertheless, depending on depth and time of occurrence, dips can cause interruption of a process, malfunction of devices or damage to either of them. For a customer with a sensitive process or installation it is important to be aware of the dip problem and to know to some extent the number (including depth and duration) of the dips, the so-called dip profile. With this knowledge he can decide whether countermeasures are cost-effective.

There are several causes for dips. The most important are faults in the MV or HV grid. Three-phase faults will have the greatest impact on the installation or processes of customers if they are sensitive to voltage dips. Mitigation of dips will be very difficult or expensive if a lot of active and/or reactive energy is required to keep the voltage on an acceptable level. If the remaining voltage falls below 50% of the nominal voltage, a critical border is reached.

The reasons for classifying dips are:

- To make it easy to inform customers about the expected dip profile, without details which are irrelevant or even unjustified.
- To make it easy to inform the national regulator about the quality of the grid, in relation to this power quality phenomenon.
- To make it easy to gather information about dips in the grid and to draw some conclusions about the quality of the grid, taking into consideration trends over a period of several years.

Converting the dip table into a system indices or the presented “ABCDEF” classification makes it very suitable as a management tool to control the overall quality.
of the grid and to communicate about this power quality phenomenon in the same way as for other phenomena.

It is also possible to make the general classification more tailor-made for a specific customer with a sensitive process or installation. A good insight is then needed into the cost arising from a dip and the possible cost of mitigating a dip.
Harmonic distortion

At the moment problems with harmonic distortion are often local. The main reason for high levels of distortion is oscillation in the electrical circuit of particular harmonic voltages and/or currents. In most European countries the level of harmonic distortion of the supply voltage has increased over the last decade [Eur01]. Although in the Netherlands the overall harmonic distortion did not increase, in certain specific circumstances there is an increase in distortion. For instance, in the case of a concentrated implementation of solar energy systems a significant increase of harmonic distortion is measured [Cob11]. Furthermore, high values of harmonic currents and voltages have been measured in cases with resonance on specific frequencies. The reason for this research on harmonic distortion is to get a better understanding of harmonic currents of devices and their interaction with other devices and voltages. Therefore, the “harmonic fingerprint” is developed which defines the harmonic behaviour of the device. This harmonic fingerprint can be very useful for type tests of devices. Finally, it is of importance to analyse what is an acceptable limit of harmonic currents at the connection point of a customer. These limits are depending on the connection (current) capacity at the POC and the grid impedance. Typical grid impedances are defined in relation to the flicker problem and used for the calculation of maximum acceptable harmonic currents, in order to get an integrated grid design approach.

5.1 Standards for harmonic distortion

Standards for harmonic distortion are made for the supply voltage and for limiting harmonic currents of devices. There are two problems concerning the standards for the harmonic current: firstly there is no standard for the point of connection (POC) of a customer and secondly the interaction of harmonic voltages on currents has not been dealt with, and vice versa. These problems are elaborated in sections 5.2 and 5.5.

5.1.1 The voltage

The distortion of the voltage in the Netherlands has to be within the limits given in the Dutch grid code [Sta03]. This code states that for low voltage and medium voltage networks with $U_{nom}<35$ kV:
- THD is ≤8% for all harmonics up to the 40th. For 95% of the time.
- The relative voltage per harmonic is less than the percentage stated in the EN-50160 for 95% of the 10-minute measured values. For harmonics that are not mentioned the smallest mentioned value out the standard counts.
- THD is ≤12% for all harmonics up to the 40th for 99.9% of the time.
- The relative voltage per harmonic is less than the percentage stated in the EN-50160 multiplied by 1.5 for 99.9% of the 10-minute measured values.

So the grid code refers to the EN-50160 [Sta01], in which the maximum limits of the harmonic voltages are described as shown in table 5.1. Besides the given maximum limits of the individual harmonics EN-50160 also refers to the total harmonic distortion (THD) with a maximum of 8% for 95% of the time. This THD can be calculated using the formula:

\[
THD = \sqrt{\frac{U_2^2 + U_3^2 + \ldots + U_N^2}{U_1^2}} \cdot 100\%
\]

5.1)

According to EN 50160, \( N \) is the number of harmonics included and shall be taken as 40.

Table 5.1: Limits of the harmonic voltages according to EN-50160

<table>
<thead>
<tr>
<th>Odd harmonics</th>
<th>Even harmonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not multiples of 3</td>
<td>Multiples of 3</td>
</tr>
<tr>
<td>( b )</td>
<td>Relative voltage</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>3.5</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>19</td>
<td>1.5</td>
</tr>
<tr>
<td>23</td>
<td>1.5</td>
</tr>
<tr>
<td>25</td>
<td>1.5</td>
</tr>
</tbody>
</table>

In principle almost every device should function properly with the given limits. In practice we see that some devices do not function well in this distorted environment. The limits may be reached because of the interaction between harmonic voltages and maximum harmonic currents. So, it is important to analyse this interaction.
5.1.2 The harmonic currents

Regulating harmonic currents of devices is carried out according to several IEC-61000 standards. Table 5.2 shows an example for an undefined device with a nominal current of 16 A (class A, which is used for some household appliances, dimmers for incandescent light bulbs, audio equipment and solar inverters) according to IEC61000-3-2 [Sta05].

From the grid operator’s point of view this standard does not fulfil practical needs. First of all the standard itself defines these maximum harmonic currents in an ideal situation where the device is connected to an ideal sinusoidal voltage, which in practice is never the case. Secondly, the grid operator will not be interested in the harmonic current of each device but more in the total harmonic current at the connection point of a customer (defined as POC in figure 5.1). The responsibility between grid operator (voltage) and customer (current) can best be regulated at this point.

Table 5.2 Maximum harmonic current 16A devices, class D; IEC 61000-3-2 [Sta05]

<table>
<thead>
<tr>
<th>Harmonic order $h$</th>
<th>Maximum permissible harmonic current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odd harmonics</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>1.14</td>
</tr>
<tr>
<td>7</td>
<td>0.77</td>
</tr>
<tr>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>11</td>
<td>0.33</td>
</tr>
<tr>
<td>13</td>
<td>0.21</td>
</tr>
<tr>
<td>$15 \leq h \leq 39$</td>
<td>0.15$\cdot$(15$/h$)</td>
</tr>
<tr>
<td>Even harmonics</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.08</td>
</tr>
<tr>
<td>4</td>
<td>0.43</td>
</tr>
<tr>
<td>6</td>
<td>0.30</td>
</tr>
<tr>
<td>$8 \leq h \leq 40$</td>
<td>0.23$\cdot$(8$/h$)</td>
</tr>
</tbody>
</table>
Figure 5.1: Devices with harmonic currents connected behind the POC in the installation

5.2 Interaction between voltage and currents

An important issue that has to be tackled is the interaction between the harmonic voltages and the harmonic currents. Devices are, according to the appropriate standards, tested with an undistorted voltage. Possible interaction with a harmonic voltage distortion is not included in the standard, and this may lead to undefined harmonic currents. To get more insight into this interaction the measurement system as described in 5.2.1 and used for PV inverters [Bos01] is used for all kind of loads. With this measuring system the total interaction between harmonic voltages and harmonic currents of the device (in this thesis called the “harmonic fingerprint”) can be made.

5.2.1 Principle of defining interaction

A model to identify the harmonic currents with and without harmonic background voltage is shown in figure 5.2. [Hes01].

Figure 5.2: Model with load connected to the network

The symbols used in the model are:
\[ U_g = \text{grid background harmonic voltage} \]
\[ U = \text{voltage at the point of connection} \]
\[ R_g = \text{grid resistance, including the influence of the skin effect} \]
\[ L_g = \text{grid inductance} \]
\[ I_0 = \text{harmonic current emission of the load without background distortion} \]
\[ C = \text{capacitance of the load} \]
\[ G = \text{total conductance of the load} \]
\[ P = \text{active power at connection point (for calculating } G \text{)} \]
\[ Q = \text{reactive power at connection point (for calculating } C \text{)} \]
\[ h = \text{number of harmonic order} \]

The measurement is done following the procedure as displayed in figure 5.3. In first instance, the load is connected to an undistorted voltage, so producing only the fundamental current and the harmonic current \( I_0 \) shown in figure 5.2. This harmonic current emission of the load can be measured. Secondly, a distortion is added to the supply voltage, a 3rd harmonic voltage varying from 0.5% to 5% and a phase shift from 0 to 360°. The response of the harmonic current is measured for each situation. This procedure is carried out for each harmonic voltage as shown in figure 5.3.

The voltage, current, active and reactive powers are measured. The conductance and capacitance related to the injected harmonic number can be calculated with:

\[
G_{(h)} = \frac{P_{(h)}}{U_{(h)}^2} \tag{5.1}
\]

\[
C_{(h)} = \frac{-Q_{(h)}}{h \cdot \omega \cdot U_{(h)}^2} \tag{5.2}
\]

In order to obtain a positive value of the capacitance, a negative sign has been added to the reactive power \( Q_{(h)} \) (reactive power is negative at capacitive loads). If the measurement gives a negative \( C_{(h)} \), the result must be seen as an inductance. Instead of the absolute value of \( G_{(h)} \) and \( C_{(h)} \) it is more practical to work with a normalised value.
Figure 5.3: Procedure to measure harmonic current and harmonic interaction

Therefore $G_{(h)}$ will be divided by $G_{ref}$ defined as the value of a conductor that would dissipate the nominal power when the load is connected to the nominal grid voltage at fundamental frequency. This gives:

$$G_{ref} = \frac{|P_{nom}|}{U_{nom}}$$  \hspace{1cm} (5.3)

Using (5.1) and (5.3), the normalised load conductance for the $h^{th}$ harmonic can be calculated with:

$$\frac{G_{(h)}}{G_{ref}} = \frac{P_{(h)} \cdot U_{nom}}{U_{(h)} \cdot |P_{nom}|}$$  \hspace{1cm} (5.4)

Similar a normalised value of the capacitance can be used. Therefore $C_{(h)}$ will be divided by $C_{ref}$ defined as the value of the capacitor that would carry the same current as the load at nominal power. This gives:
\[ C_{\text{ref}} = \frac{|P_{\text{nom}}|}{\omega \cdot U_{\text{nom}}} \]  

(5.5)

Using (5.2) and (5.5), the normalised inverter capacitance for the \( b \)th harmonic can be calculated with:

\[
\frac{C_{(h)}}{C_{\text{ref}}} = \frac{-Q_{(h)} \cdot U_{\text{nom}}^2}{h \cdot U_{(h)}^2 \cdot |P_{\text{nom}}|} 
\]  

(5.6)

\( C_{\text{ref}} \) and \( G_{\text{ref}} \) depend on the nominal grid voltage and the nominal grid frequency. In case of a 50Hz/230V grid, the following formulas can be used to calculate the reference quantities \( C_{\text{ref}} \) and \( G_{\text{ref}} \) of the loads:

\[
C_{\text{ref}} = \frac{|P_{\text{nom}}|}{\omega \cdot U_{\text{nom}}^2} = \frac{|P_{\text{nom}}|}{2 \cdot \pi \cdot 50 \cdot 230^2} = 60 \cdot 10^{-9} \cdot |P_{\text{nom}}| 
\]  

(5.7)

and

\[
G_{\text{ref}} = \frac{|P_{\text{nom}}|}{U_{\text{nom}}^2} = 18.9 \cdot 10^{-6} \cdot |P_{\text{nom}}| 
\]  

(5.8)

### 5.2.2 Resistor and capacitor as example

To explain the method described in the previous section and to show the response to harmonic voltages of passive components, the results of measuring a resistor and a capacitor will be given. Figure 5.4 shows the results of a resistor, corresponding with 1 kW load at 230 V. The left-hand picture is the harmonic voltage connected to the resistor. All bullets are harmonic voltages which were added to the fundamental voltage with a given amplitude and phase. The harmonic current response on this harmonic voltage is given in the picture on the right. The thicker bullets in the two pictures relate to each other. So the harmonic current is linear with the harmonic voltage and in phase, as expected.

The value of \( G_{(h)}/G_{\text{ref}} \) can be calculated using these voltages and currents and is equal to 1 for each harmonic and each amplitude and phase. So the resistor will keep the same impedance or conductance, independent of the harmonic voltage. As all harmonic currents and voltages are in phase the harmonic reactive power is zero, which means that \( C_{(h)} = 0 \) for each harmonic.

For the capacitor we get similar pictures as for the resistor, except that a phase shift of 90 degrees occurs. The results of the measurements on a capacitor are given in figure 5.5. The 90° phase shift is displayed by the thicker bullets in the two pictures, which relate to each other.
Figure 5.4: Harmonic voltage and current interaction resistor

Figure 5.5: Harmonic voltage and current interaction capacitor

The value of $G_{(h)}$ can be calculated with these voltages and currents and will be 0 for each harmonic and each amplitude and phase, due to the 90-degree phase shift. Calculating the $C_{(h)}/C_{ref}$ shows a value equal to 1 for each harmonic.

Important features of the resistor and the capacitor are:

- There is no harmonic current when the harmonic voltage is zero. So there is no harmonic current source $I_0$.
- There is a linear behaviour between voltage and current.
- There is no interaction between the harmonics ($5^{th}$ harmonic voltage only gives a $5^{th}$ harmonic current and no currents of other frequencies).
Harmonic calculations in grids with only passive components are not very complex. These calculations become complex when components are applied with harmonic interaction and harmonic interference. In the following sections the features of several devices with electronic components will be described, with special attention to the linearity and interaction between harmonics.

5.2.3 Linearity

It is interesting to know if devices act in the frequency domain as a linear load or source. If this is the case, the value of $G$ and $C$ in the model of figure 5.2 will be constant for a given frequency which simplifies network calculations. The principle of linearity is shown in figure 5.6.

![Figure 5.6: Linear behaviour](image)

In the figure $I_0$ is the harmonic current produced by the device when there is no harmonic distortion in the supply voltage. When a harmonic voltage $U_{g1}$ occurs in the supply voltage with a certain frequency, a current will flow through the conductance $G$ and the capacitor $C$, given as $I_{Y1}$. Notice that $Y = G + j\omega C$. $G$ and $C$ can be calculated from $Y$ using following formulas:

$$ G = \text{real}(Y) $$

$$ C = \frac{\text{imag}(Y)}{\omega \cdot h} \quad (5.9) $$

The total harmonic current will be $I_1$. If the value of the harmonic voltage doubles to $U_{g2}$, the current through $G$ and $C$ will double, leading to $I_{Y2}$ and a total harmonic current of $I_2$.

A second aspect of linear behaviour is illustrated in figure 5.7. Again $I_0$ is the current produced by the device when there is no harmonic distortion in the supply voltage.
When a harmonic voltage $U_{1f}$ occurs in the supply voltage with a certain frequency, a current will flow through the conductance $G$ and the capacitor $C$, given as $I_{y1}$. The total harmonic current will be $I_1$. If the phase angle of the harmonic voltage changes, the phase angle of the current through $G$ and $C$ will change accordingly, leading to $I_{y2}$ and a total harmonic current of $I_2$.

The model accuracy for predicting a certain harmonic current depends on the error introduced by assuming linearity. To analyse if it is possible to make network calculations with a constant value of $Y$ (or $G$ and $C$) the method of linear regression can be used. Linear regression is a method for finding the linear relationship between data sets. It finds coefficients $a$ and $b$ in the expression:

$$ I = a \cdot U + b $$

such that the square error that is introduced is minimal. $I_0$ is equal to the offset term $b$ and $Y$ is equal to gradient $a$ ($a = dI/dU$). Note that both data sets are complex and that $I_0$ and $Y$ are complex as well. The advantage of this method is that $I_0$ and $Y$ are determined from all data points and describe the linear relation in the best possible way.

Figure 5.8 shows an example of a data set and the fitted line. Note that it is not necessary to calculate $Y$ and $I_0$ for each phase separately.
Figure 5.8: Example of data set (dots) and fitted lines for the 11th harmonic current

The model accuracy describes how well the model can predict the harmonic current for a given harmonic voltage distortion. Two parameters, $R^2$ and $\text{RMSE}$, are used to quantify it. $R^2$ is the ratio of the $\text{SSR}$ (sum of squares of the regression) and $\text{SST}$ (sum of squares around the average), in the formulas:

$$R^2 = \frac{\text{SSR}}{\text{SST}}$$
$$\text{SSR} = \sum_{i=1}^{n} (y_i - \bar{y})^2$$
$$\text{SST} = \sum_{i=1}^{n} (y_i - \bar{y})^2$$

(5.11)

with:
- $y_i$ = predicted value of the dependant data set
- $y_i$ = corresponding real value of the dependant data set and
- $\bar{y}$ = average of the dependent data set.

There are several interpretations of $R^2$, but in essence it tells something about how well the fit describes the dynamics in the data set. For real data sets, $R^2$ lies in the interval of $[0,1]$ where a value closer to one indicates a better fit. For complex data sets however, it is not straightforward to calculate $R^2$. Therefore $R^2$ is calculated separately for the real and imaginary parts of the data set. This can however result in values above one. This is because the real and imaginary parts of the data are coupled. The fit that is good for the real part can be bad for the imaginary part and vice versa. $R^2$ does not provide a confidence interval for any of the model parameters, but it provides an indication of how well the data points can be fitted into a straight line.

$\text{RMSE}$ is the mean square root of the error between the measured harmonic current and the harmonic current estimated by the model. In formula (5.11) an indication is
given how precise the model estimates the harmonic current. For example, the estimation is accurate up to about 5% of the fundamental as \( RMSE \) is 0.05.

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i - \hat{y}_i)^2}
\]  
(5.12)

### 5.2.4 Cross interference

A further aspect of linearity is zero cross interference. Zero cross interference means that an \( n \)th harmonic voltage will give only a reaction on the \( n \)th harmonic current, and not at other frequencies. To quantify the influence of a harmonic voltage on other harmonic currents, the standard deviation of all harmonic currents per set of measurements is calculated. If there is no influence, the standard deviation is zero.

Figure 5.9 shows an example of a plot where deviations for all harmonics in the current are plotted when a 5th harmonic voltage is applied. The crosstalk ratio is defined as the ratio between the highest and the second highest deviation. A high ratio indicates less cross interference.

![Figure 5.9: Example of plotting the cross interference](image)

### 5.2.5 PV inverter

An interesting group of devices are the inverters used to couple dispersed generators to the grid. For the design of these inverters different rules are used, showing different reactions on a distorted supply voltage. Measurement results of one type of inverter will be given. More detailed information can be found in section 5.4.
The measured current, without any distortion of the supply voltage, is shown in figure 5.10. The 3rd harmonic current is about 10% of the nominal fundamental current. The 5th harmonic current is 2% of the fundamental nominal current and so on. These currents are below the limits given in IEC61000-3-3.

Figure 5.10: Harmonic current without harmonic distortion of supply voltage

Figure 5.11 shows an example of 3rd harmonic voltages and currents measured at the terminals of one of the tested inverters. The harmonic voltages have been adjusted to 121 set points with amplitude [0,0.5,…5%] and phase [0, 30,…330]. The voltage measurements form the expected star shape. The current plot in figure b also shows a star shape. This indicates that there is a linear relation between harmonic current and voltage. The points indicated by an asterisk are set points where the phase of the harmonic voltage put into the source was equal to zero. In this way, it can be calculated which current and voltage points belong together. For convenience, the phase angles are added in figure 5.11. Compared with the voltage plot, the centre of the current plot is shifted away from the origin and rotated. Speaking in terms of the proposed model, the shift away from the origin is equivalent to $I_0$. The rotation is equivalent to the phase shift between the harmonic voltage and the current induced in the admittance. The phase shift is between 90 and 180 degrees, indicating that the real part of $Y$ is negative and the imaginary part positive. Consequently, $G$ is negative and $C$ positive. Current and voltage phasors for a measurement where the harmonic voltage was 4% of the fundamental with phase 270 degrees are drawn in the plots shown in figure 5.11.

The cross-interference between different harmonics is also measured. The plot in figure 5.12 shows the influence of the 3rd harmonic voltage on harmonic currents. The plot shows that this 3rd harmonic voltage does not influence other harmonic currents significantly.
This nice linear behaviour makes it possible to calculate a constant value of $G$ and $C$ for each harmonic number. These values of $C$ and $G$ are given in figure 5.13 and 5.14. An important conclusion, given these results, is the negative value of $G$ for frequencies below the 23rd harmonic. This negative value of $G$ can lead in practice to malfunctioning of the inverter, due to a high distortion at the entrance to the device. See 5.3 and [Ecn01].
5.2.6 Energy-saving light bulb

The power industries worldwide suggest the use of energy-saving light bulbs. The most common type of such light bulbs is the self-ballasted compact fluorescent light bulb with electronic gear. However, that type of light bulb is a highly non-linear load, producing an extremely distorted current with a total harmonic distortion (THD) usually exceeding 100%, as shown in figure 5.15.
However, this picture does not show the influence of an already distorted supply voltage. What is happening when a distorted voltage is connected to the light bulb is shown in figure 5.16a for a 3rd harmonic distortion and figure 5.16b for a 25th harmonic distortion.

The connected harmonic voltage is the same as in previous sections. The 3rd harmonic current with no distortion in the supply voltage has a value of $I_3 = -0.06 - j0.16$ A. The basic 25th current $I_{25}$ is almost zero. Introducing a harmonic voltage distortion on the 25th harmonic frequency shows a linear behaviour of the light bulb’s current. The reason behind this behaviour will be given in section 5.2.8.
5.2.7 Personal computer

Another frequently used device is the personal computer. Almost every household uses one or more of these devices. Also the simultaneous use of personal computers is increasing. Consequently it is interesting to measure the harmonic fingerprint. The 3rd and 25th harmonic reaction on a distorted voltage is presented in figures 5.17a and b.

![Figure 5.17 a/b: Harmonic current of personal computer for 3rd and 25th harmonic distortion](image)

The pictures have some similar characteristics to those of the energy-saving light bulb. A rectifier is placed at the entrance to both devices, which is mainly responsible for the reaction as will be explained in section 5.2.8.

5.2.8 Behaviour of a rectifier

The typical behaviour of the energy-saving light bulb and the personal computer can best be explained by looking into the details of voltages and currents of a rectifier. A rectifier is placed at the entrance of these devices and a lot of other devices. The basic diagram of the rectifier is shown in figure 5.18.

![Figure 5.18: Rectifier at the entrance to a device](image)
Figure 5.19 shows the shape of the current in case of an undistorted voltage and no load connected to the rectifier. At the moments when the AC voltage becomes higher than the DC voltage there will be an AC current which charges the capacitor.

![Figure 5.19: Typical AC and DC voltages and AC current of a rectifier](image)

Of course the AC current is not sinusoidal and the harmonic content of this current is shown in figure 5.20. If a 5th harmonic voltage is added to the fundamental voltage the shape of the current will change. Due to a higher \( \frac{du}{dt} \) the current into the capacitor will be higher and the capacitor will be charged and discharged a little bit more. These phenomena can be seen in figure 5.21. This also changes the harmonic content of the current as can be seen in figure 5.22. Not only has the content of the 5th harmonic current changed, but also the harmonic current of other harmonics. So some cross interferences have appeared.

![Figure 5.20: Harmonic content of the AC current in case of an undistorted voltage](image)
In addition, the phase shift of the harmonic voltage influences the shape of the AC current. Figure 5.23 shows as an example the shape of the current and the voltages with a 90-degree phase shift of the 5th harmonic voltage. See figure 5.24 for the harmonic content of the AC current. The differences are small which can be explained by the small differences in amplitude comparing the amplitudes in figure 5.25 for 90 degrees phase shift and the situation without phase shift.
Knowing the amplitude of the harmonic currents is not enough to get a good picture of the total current on a POC to which more devices are connected. The phase shift of the harmonic currents is important too. Figure 5.25 shows how the phase shifts of the 5th harmonic current changes, by changing the 5th harmonic voltage. The degrees plotted in the figure are the phase shifts of the corresponding voltage.

Figure 5.23: AC current and voltages in case of 5th harmonic distortion, 90-degree phase shift

Figure 5.24: Harmonic content AC current by 5th harmonic voltage distortion, 90-degree phase shift
For both the energy-saving light bulb and the personal computer we have seen that the influence of the 25th harmonic voltage on the 25th harmonic current is much stronger. For this higher frequency there is a star shape, what indicates a linear behaviour. The reason for this strong relation is shown in figure 5.26, where a 25th harmonic voltage is added to the fundamental. In the shape of the current, there is a strong 25th harmonic component, due to the corresponding moments that the capacitor is charged.

The harmonic content of the AC current is shown in figure 5.27. The strong 25th harmonic component is clearly visible, but also a lot of cross-interferences with other harmonics around the 25th harmonic frequency.
Another element which influences the AC current and the harmonic content is the presence of inductivities at the entrance to the rectifier. Some devices are equipped with filters, thereby changing the phase shift of the harmonic currents. The most important conclusion is that it will not be possible to use a constant $G$ and $C$ for such devices. For some devices it will be a good solution. For others it is acceptable as a first approach, but for others it will result in big errors. For this reason in section 5.4, which deals with calculating harmonic voltages and currents, the harmonic fingerprint will be used instead of constant values of $G$ and $C$.

5.3 Resonance problems

Most harmonic problems in the grid are due to local resonance problems. In general there are two kinds of resonance, parallel and series resonance. The principle of these possibilities is shown in figures 5.28 and 5.29.

In this situation there is series resonance of the supply reactance $L_g$ and the capacitance in the network $C$ in combination with the capacitance of the load. In this
case the background supply voltage is the externally generated distortion. The
impedance of the circuit at the resonance frequency is low, resulting in high
current distortion.

\[ f_0 = \frac{1}{2\pi \sqrt{L \cdot C}} \]  

Figure 5.29: Parallel resonance

In the case of parallel resonance, again the capacitors connected to the network and
the supply inductance play an important role. The impedance of the network, seen
from the current source will be high at resonance frequency, resulting in high voltage
distortion. The current sources are the harmonic currents injected by the connected
load or connected dispersed generation.

The series and parallel resonance frequency can simply be calculated with the
following equation:

\[ U = \frac{U_{g(h)} + I_{(h)}(R_{g(h)} + j\omega L_{g(h)})}{1 + (R_{g(h)} + j\omega L_{g(h)}) \cdot (G_{(h)} + j\omega C_{(h)})} \]  

This system will become unstable when the denominator of the function (5.14) gets
close to zero. This occurs when

\[ 1 + R_{g(h)} G_{(h)} + j\omega (C_{(h)} R_{g(h)} + L_{g(h)} G_{(h)}) - \omega^2 L_{g(h)} C_{(h)} = 0 \]

So, both equations have to be fulfilled:
\begin{align}
1 + R_{g(h)}G_{(h)} - \omega^2 L_{g(h)}C_{(h)} &= 0 \\
C_{(h)}R_{g(h)} + L_{g(h)}G_{(h)} &= 0
\end{align}

Introducing in these equations the general equations 
\[ Z_0 = \sqrt{\frac{L}{C}} \quad \text{and} \quad \omega_0 = \frac{1}{\sqrt{L_0 C}} \]

and solving the equations (5.16 and 5.17) results in instability occurring as:

\[ G = -\frac{R}{Z_0^2} \]

and

\[ \omega = \omega_0 \sqrt{1 - \left( \frac{R}{Z_0} \right)^2} \]

Real instability can only take place for negative values of \( G \). However, for low values of the denominator significant amplification of harmonics may occur.

5.4 Calculation of harmonic currents and voltages

For harmonic load flow calculations a lot of information is needed: not only the “harmonic fingerprints” of the devices or installation connected to the grid, but also the characteristics of the different grid components. An important grid component in the MV and LV grid is the cable.

5.4.1 Grid components

Cables are widely used in the Netherlands for medium voltage (MV) and low voltage (LV) networks. The cables used are of various types. For harmonic calculations the impedances of the cables has to be known at the harmonic frequencies. Figure 5.30 shows two typical cables, used for medium a), and low voltage b) networks.

The medium voltage cable consists of round aluminium massive conductors. The conductor screen is fabricated of weak conducting synthetic material. The insulation is XLPE and the insulation screen is again a weak conducting synthetic material. The earth screen consists of copper-braided round copper wires. The low voltage cable consists of aluminium massive conductors with a sector formation and its insulation is of PVC. The resistance and reactance of the cables are shown in the following figures. Appendix C describes the measuring method.
Resistance

The resistance of the medium and the low voltage cable is shown in figure 5.31 as function of the harmonic order. The resistance increases almost linear in respect to the frequency of the applied voltage, which can be ascribed to the skin and proximity effect. Due to the higher cross-section of the MV cable the skin effect is more prominent compared with the low voltage cable. The resistance increases by a factor of 3 to 6 between 50 Hz and harmonic order 50.

Reactance and inductance

Figure 5.32 shows the measured reactance for the medium and low voltage cable. The calculated inductance is plotted in figure 5.33. It shows that there is a little decrease of the inductance by higher frequencies.
It is important for harmonic calculations to use available information about the cable impedances in the frequency domain or otherwise do some theoretical or practical work to acquire them.

**5.4.2 Harmonic load flow calculations**

The occurrence of harmonics is analysed using general analysis techniques. An individual assessment can be made for each significant frequency. The analysis can be made for the symmetric components using the standard models and the zero sequence components which require special representation. As can be seen in figure 5.2, the three main parts in the model are the source of the harmonic background.
voltage, the network and the loads (or generators) connected to the network. All these components are frequency dependent.

**5.4.2.1 Harmonic sources**

For the harmonic background voltage the average harmonic distortion in the grid on a higher voltage level can be taken as a start. Another possibility is to use measured data of harmonic voltages from a specific location. The small influence of the currents flowing at the lower voltage level on the harmonic voltage sources makes this first step acceptable. For the emitting sources (e.g. loads producing harmonic currents) one can initially ignore the influence of the voltage background distortion on the harmonics producing loads. Then the representation of the emissions reduces to a parallel set of current sources, each for a different frequency as shown in figure 5.34.

![Figure 5.34: Harmonic emission modelled as current sources](image)

When loads behave in a linear manner they can be modelled further with a $G$ and $C$, as explained in section 5.2. However, most of all devices do not have such linear behaviour and more information about the harmonic interaction with a harmonic background distortion is necessary. This can be put in a matrix for each harmonic current source defining what the harmonic current is, in relation to the harmonic voltage connected, as shown in figure 5.35 for the 5th harmonic. In the matrix the result of the measuring procedure as shown in figure 5.3 can be used. For more accurate results even the interference between several frequencies can be implemented by extending the matrix. For each harmonic voltage the matrix will give the harmonic currents for all frequencies.

![Figure 5.35: Matrix for each current source](image)
In the calculating process, which is an iterative process, the most applicable current for each frequency can be used, until satisfactory convergence is achieved.

5.4.2.2 Network
To determine the impedance characteristics of the network to which the emitting load is connected, the supply system must be represented as a network of impedance elements up to the grid connection. Lines and cables are represented as equivalent networks. The reactance and capacitance values are a function of frequency. However, even the resistance increases due to skin effects, as has been explained in section 5.4.1. Transformers can be represented by their short-circuit equivalents. Generators and their reactance’s need to be represented as ideal sources, assuming that they do not generate harmonic voltages as such. The harmonic background voltage can be modelled as voltage source at a higher voltage level to be sure that it can be influenced in the voltage level for which the calculations are made.

5.4.2.3 Steady state analysis
In steady state analysis the boundary conditions are the voltages at the POCs. The harmonic current injections are introduced as current sources in the simulations of the distribution grid, which allows computation of the voltages throughout the grid. This process is repeated until satisfactory convergence is achieved. In most cases it is necessary to evaluate the network's impedance from a certain connection point, in order to predict possible resonances for harmonic frequencies. A good estimation of the capacitance of the load (for each frequency) is necessary to achieve satisfactory results.

Software algorithms have been developed to compute the phenomena. They produce graphs in which the complex impedance is plotted with an indication of the harmonics of interest or trend lines showing the evaluation of the modulus of the impedance versus the frequency [Uie01].

5.5 Currents at the connection point
As stated before, it is important to have requirements for the harmonic distortion not only for devices but also for the connection point. This is certainly the case for the industrial customers. In case only devices with a nominal current smaller than 16A are used, standards for these devices have to limit the harmonic current enough to connect them to the installation (and the network) without any problem. For more current-demanding devices some acceptance tests have to be developed. Figure 5.36 shows a flowchart which could be used when connecting devices to the grid. The various steps in the flowchart will be described.
The first step is the easiest one. A device with a nominal current less than 16 A and made in compliance with IEC 61000-3-2 [Sta02], should not give a problem. Only in the case that extreme amounts of these devices are connected to the grid, problems could occur. The grid operator should investigate this. If the nominal current exceeds 16 A or the device does not comply with IEC 61000-3-2, the question is whether the nominal current exceeds 75 A. If not, the appropriate question is whether the device complies with IEC 61000-3-12 [Sta05]. If the device complies with this standard and the short circuit ratio $R_{sc}$ is above 33, connecting is possible. For the calculation of $R_{sc}$ see equation (5.23). In all other cases harmonic currents and voltages have to be calculated. The grid operator will look in these cases to the POC, where criteria should be checked for the maximum allowed harmonic distortion of the current. If the result of the calculations is positive (harmonic currents and voltages are within given limits), connecting is acceptable, otherwise other solutions have to be found.

5.5.1 Harmonic current of devices according to IEC 61000-3-12

This standard [Sta05] gives limits for harmonic currents produced by equipment connected to low voltage systems with input currents $>16$ A and $\leq 75$ A per phase. The following data has to be available:

- $112$
- the rated line current
- the specified reference fundamental current
- the short-circuit ratio used for calculation or test
- the required minimum short-circuit ratio
- a statement about the table applied (i.e. about the type of equipment)

The rated line current is the measured rms line current $I_{equ}$ in nominal operation. The reference fundamental current can be measured or calculated with formula (5.20).

$$I_t = \frac{I_{equ}}{\sqrt{1 + THD_i^2}}$$

(5.20)

The short circuit ratio $R_{sc}$ used for testing has to be given because in the standard the acceptable level of harmonic currents depends on this short-circuit ratio. As an example, table 5.3 gives the current emission limits for balanced three-phase equipment. The formulas for calculating the total harmonic distortion $THD_i$ and the partial weighted harmonic distortion $PWHD_i$ are:

$$THD_i = \sqrt[2]{\sum_{h=5}^{40} \left( \frac{I_h}{I_1} \right)^2}$$

(5.21)

$$PWHD_i = \sqrt[2]{\sum_{h=5}^{40} \left( \frac{I_h}{I_1} \right)^2}$$

(5.22)

**Table 5.3: Current emission limits for balanced three-phase equipment (Table 3, IEC 61000-3-12)**

<table>
<thead>
<tr>
<th>Minimum $R_{sc}$</th>
<th>Admissible individual harmonic current $I_h/I_1$ (%)</th>
<th>Admissible harmonic current distortion factors (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_5$</td>
<td>$I_7$</td>
</tr>
<tr>
<td>33</td>
<td>10.7</td>
<td>7.2</td>
</tr>
<tr>
<td>66</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>120</td>
<td>19</td>
<td>12</td>
</tr>
<tr>
<td>250</td>
<td>31</td>
<td>20</td>
</tr>
<tr>
<td>$\geq350$</td>
<td>40</td>
<td>25</td>
</tr>
</tbody>
</table>

The relative values of even harmonics up to order 12 shall not exceed $16/h\%$. Even harmonics above order 12 are taken into account in $THD_i$ and $PWHD_i$ in the same way as odd order harmonics.
The partial weighted harmonic distortion is used in order to ensure that the effects of the higher order harmonic currents on the results for the \( \text{THD} \) are reduced sufficiently and individual limits need not be specified. A manufacturer has to give the required minimum short-circuit ratio for connecting the device to the grid. This minimum short-circuit ratio can be defined on the POC. The type of equipment can be divided in three classes:

\[ \begin{align*} 
A &= \text{balanced three-phase equipment} \\
B &= \text{balanced three-phase equipment under specified conditions as mentioned in the standard} \\
C &= \text{non-balanced equipment (including 3\(^{\text{rd}}, 9\text{th} \ldots \text{harmonic current})} 
\end{align*} \]

The limits for the harmonic current are given in three different tables. The limit for the 5\(^{\text{th}}\) harmonic current is shown in figure 5.37. The limit for the \( \text{THD} \) is shown in figure 5.38.

![Figure 5.37: Limits for the 5\(^{\text{th}}\) harmonic current according IEC-61000-3-12](image1)

![Figure 5.38: Limits for the THD, according 61000-3-12](image2)
The minimal short circuit ratio used in this standard is important. The short circuit ratio can be calculated with the following formula:

\[ R_{sc} = \frac{U_L}{\sqrt{3} \cdot Z \cdot I_{eq}} \]  

(5.23)

This formula can be used for single phase equipment and balanced three phase equipment. \( Z \) is the line impedance of the system at the power frequency. The grid impedance (or short circuit power) on the point of connection (POC) is needed for applying this standard.

For some typical currents, the short circuit ratio is calculated in relation to the system impedance \( Z \). The results of the calculations are shown in figure 5.39.

\[ \text{Figure 5.39: Short circuit ratio in relation with system impedance} \]

**5.5.2 Current criteria for the POC**

By using standards we assume that harmonic currents will be limited. For all devices up to 75 A complying with IEC 61000-3-12 and connected to the grid with sufficient short circuit power this will normally be the case. Nevertheless, in specific cases some calculations have to be made. This will certainly be the case with high-power applications. Additional requirements for the harmonic currents at the POC are necessary to evaluate the possible connection of the devices. In this case a harmonic
fingerprint of the device would be very helpful to analyse if connection is possible without causing problems.

5.5.2.1 Transfer coefficients for harmonics in the low voltage grid

The transfer coefficient of harmonic voltages between point A (source of distortion) and point B (point of evaluation) is defined as the ratio of harmonic voltage values at the same instant at these two points:

\[ T_{U_{h,AB}} = \frac{U_{h,B}}{U_{h,A}} \]  \hspace{1cm} (5.24)

Propagation on the low voltage level depends on the location of the observation point, the short-circuit power of the source and the location of the disturbance. Consider the low voltage grid as shown in figure 5.40. Assume that the disturbing load is connected at location C giving a variation of \( U_h \) defined as \( \Delta U_{h,C} \).

![Figure 5.40: Low voltage grid and its impedances](image)

For the other locations the contribution to the harmonic voltage distortion, due to the source location C can be calculated with:

\[ \Delta U_{h,A} = T_{U_{h,CA}} \cdot \Delta U_{h,C} = \frac{Z_{A,h} \cdot \Delta U_{h,C}}{Z_{A,h} + Z_{AB,h} + Z_{BC,h}} \] \hspace{1cm} (5.25)

\[ \Delta U_{h,B} = T_{U_{h,CB}} \cdot \Delta U_{h,C} = \frac{Z_{A,h} + Z_{AB,h} \cdot \Delta U_{h,C}}{Z_{A,h} + Z_{AB,h} + Z_{BC,h}} \] \hspace{1cm} (5.26)

\[ \Delta U_{h,D} = \Delta U_{h,E} = T_{U_{h,CD}} \cdot \Delta U_{h,C} = \frac{Z_{A,h} \cdot \Delta U_{h,C}}{Z_{A,h} + Z_{AB,h} + Z_{BC,h}} \] \hspace{1cm} (5.27)
Customers at D or E see the \( U_h \) present at the busbar A, with its origin in the other feeder, in the worst case without reduction. Table 5.4 gives practical values of the impedances and modulus of the transfer coefficients assuming a MV/LV transformer of 400 kVA, a very strong MV grid and a 150 mm\(^2\) Al low voltage cable with a length of 500 m. Customers B and D are connected at 250 m and C and E at the end of the feeders.

**Table 5.4: Impedances and transfer coefficients**

<table>
<thead>
<tr>
<th>Impedances</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z_A = 5 + j15 \text{ m}\Omega )</td>
<td>(</td>
</tr>
<tr>
<td>( Z_{AB} = 50 + j45 \text{ m}\Omega )</td>
<td>(</td>
</tr>
<tr>
<td>( Z_{BC} = Z_{AD} = Z_{DE} = Z_{AB} )</td>
<td>(</td>
</tr>
</tbody>
</table>

The transfer coefficient for points A and B is given in figure 5.48, with a harmonic polluting source placed along the cable between point A and point C. This is given for a 400 kVA transformer combined with a medium voltage grid having a short-circuit power of 50 MVA. Also the results of the calculation with a 630 kVA transformer combined with a MV grid having a 100 MVA short-circuit power are shown in figure 5.41.

![Figure 5.41: Calculated transfer coefficients in low voltage network](image)

The transfer coefficient can vary between 0.1 and 1 depending on the different variables.
5.5.2.2 Propagation through transformers

Additional to harmonic propagation within the low voltage grid, harmonic voltages will be transferred from the high voltage grid to the medium voltage grid and further to the low voltage grid, and visa versa as shown in figure 5.42.

![Diagram of harmonic voltage transfer through transformers](image)

Figure 5.42: Transfer of harmonic voltages between different voltage levels

To calculate the harmonic contributions from the customers on a certain voltage level the following formulas can be used [Sta10]:

\[
\begin{align*}
\Delta U_{h,HV} &= \alpha \sqrt{U_{h,HV}^\alpha - (T_{h,MV\rightarrow HV} \cdot U_{h,MV})^\alpha} \\
\Delta U_{h,MV} &= \alpha \sqrt{U_{h,MV}^\alpha - (T_{h,LV\rightarrow MV} \cdot U_{h,LV})^\alpha - (T_{h,LS\rightarrow MV} \cdot U_{h,LV})^\alpha} \\
\Delta U_{h,LV} &= \alpha \sqrt{U_{h,LV}^\alpha - (T_{h,MV\rightarrow LV} \cdot U_{h,MV})^\alpha}
\end{align*}
\] (5.28)

The value of the coefficient \( \alpha \) depends on the harmonic order of the voltage. The following set can be used in the absence of further information [Lie01]:

-118-
Consider the medium voltage grid as shown in figure 5.43. Assume the disturbing load is connected at location 10 on the low voltage side of the transformer, giving a variation of $U_h$ defined as $\Delta U_{h,10}$.

For locations A and B the contribution to the $U_h$ can be calculated with:

$$
\Delta U_{h,A} = T_{U_{h,10,A}} \cdot \Delta U_{h,10} = \frac{Z_{A,h}}{Z_{A,h} + Z_{AB,h} + Z_{BC,h} + Z_{tr10,h}} \cdot \Delta U_{h,10} \quad (5.29)
$$

$$
\Delta U_{h,B} = T_{U_{h,10,B}} \cdot \Delta U_{h,10} = \frac{Z_{A,h} + Z_{AB,h}}{Z_{A,h} + Z_{AB,h} + Z_{BC,h} + Z_{tr10,h}} \cdot \Delta U_{h,10} \quad (5.30)
$$

The transfer coefficient from the busbar of the substation back into the MV grid is in the worst case again 1, assuming that no resonance exists.

Figure 5.44 gives practical values of the transfer coefficients from the LV side of the transformer assuming a MV/LV transformer of 400 kVA or 630 kVA in relation with a certain short circuit power at the MV-side of the transformer.
Figure 5.44: Transfer coefficients from LV to MV grids

Since the transfer of harmonic voltages from a lower to a higher voltage level is very low, certainly in grids with a short-circuit power above 100 MVA, the formulas for the higher harmonics can certainly be reduced to:

\[
\begin{align*}
\Delta U_{h,HV} &= U_{h,HV}^{\alpha} \\
\Delta U_{h,MM} &= U_{h,MM}^{\alpha} - (T_{h,HV \rightarrow MV} \cdot U_{h,HV})^{\alpha} \\
\Delta U_{h,LM} &= U_{h,LM}^{\alpha} - (T_{h,MM \rightarrow LV} \cdot U_{h,MM})^{\alpha}
\end{align*}
\]

(5.31)

5.5.2.3. Acceptable harmonic currents at the POC

IEEE 519 aims to state harmonics for a whole installation. The current distortion limits are given as a function of the short-circuit current at the POC as shown in table 5.5.

Table 5.5: Limits harmonic current distortion according to IEEE 519

<table>
<thead>
<tr>
<th>(I_{sc}/I_{l})</th>
<th>&lt;11</th>
<th>11&lt;(b)&lt;17</th>
<th>17&lt;(b)&lt;23</th>
<th>23&lt;(b)&lt;35</th>
<th>(b\geq35)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>4</td>
<td>2</td>
<td>1.5</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>20..50</td>
<td>7</td>
<td>3.5</td>
<td>2.5</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>50..100</td>
<td>10</td>
<td>4.5</td>
<td>4</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>100..1000</td>
<td>12</td>
<td>5.5</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>(\geq 1000)</td>
<td>15</td>
<td>7</td>
<td>6</td>
<td>2.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Another approach to find limits for the harmonic current distortion is to determine the global contribution to voltage distortion caused by the LV system under consideration. This method will be explained for the 5\textsuperscript{th} harmonic voltage.

Figure 5.45 shows the 5\textsuperscript{th} harmonic level in a certain HV, MV and LV grid measured in 2005 [Ene02].

![Figure 5.45: Measured 5\textsuperscript{th} harmonic voltage](image)

Considering that on the MV level 4.5\% is acceptable (all data is beneath this value) and that the planning level in the LV grid should be somewhere beneath the compatibility level, acceptable planning levels for the 5\textsuperscript{th} harmonic voltage are:

| Planning level for 95\% percentile of 5\textsuperscript{th} harmonic voltage |
|-----------------------------|-------------------|-------------------|
| HV                          | MV                | LV                |
| 3.5                         | 4.5               | 5.5               |

The harmonic voltage emission which is accepted and that can be allocated to the total of loads supplied by the considered LV system is represented by:

\[
\frac{\Delta U_{U5,LV}}{U_i} = \sqrt{I_{U5,LV}^a T_{U5,MV\rightarrow LV}^a \cdot L_{U5,MV}^a} = \sqrt{5.5^{1.4} - 1 - (4.5)^{1.4}} = 2\% \quad (5.32)
\]

In chapter 6 about flicker a calculation is made of the maximum grid impedance related to the nominal current of the protection device on the POC to reach sensible
flicker criteria on the POC. The different types of connection (domestic customers, small business, etc.) and the related maximum grid impedances are given in table 5.6.

Table 5.6: Grid impedances related to maximum current on POC

<table>
<thead>
<tr>
<th>Connection type</th>
<th>Amperage (I_{pr})</th>
<th>Maximum Z_{g} (\text{m} \Omega)</th>
<th>I_{sc}/I_{pr}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 phase+neutral</td>
<td>40 A (35 A)</td>
<td>326 (373)</td>
<td>30</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>25 A</td>
<td>523</td>
<td>30</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>40 A (35 A)</td>
<td>326 (373)</td>
<td>30</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>50 A</td>
<td>261</td>
<td>30</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>63 A</td>
<td>207</td>
<td>30</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>80 A</td>
<td>163</td>
<td>30</td>
</tr>
</tbody>
</table>

The low voltage grid shown in figure 5.46 is used to calculate the acceptable harmonic currents on the POC. All typical types of connection are supposed to be there on the same feeder and at the position with maximum grid impedance.

Figure 5.46: A low voltage feeder with all typical low voltage loads

Normally there about five outgoing LV feeders protected by 250 A fuses. The nominal current of the transformer is 630 A. The simultaneous use is low, typically 0.1 for domestic customers in the low voltage grid. Most disturbing loads will be connected to 3 phase installations, where mostly a limited number of these installations are connected to the low voltage network. This has to be taken into account to determine the number of installations that have to be taken into account by calculating the \( \Delta U_{h5} \) on the POC.

Due to the low simultaneous it will be sufficient to calculate the \( \Delta U_{h5} \) on the POC, in the case where two points of connection on the same feeder have disturbing loads.

The limit for the \( \Delta U_{h5} \) at the POC is:

\[
\frac{\Delta U_{h5}}{U_i} = \sqrt[\frac{5}{4}]{\frac{3}{2}} = 1.22\% \tag{5.33}
\]

The maximum amount of harmonic current injected in the several points of the grid can be estimated by using the formula:

\(-122-\)
The impedance of the grid for the 5th frequency is calculated by using the information about the increase of the resistance as described in section 5.4.1 and the normal linearity of the reactance with frequency. The results of the calculations are given in table 5.7.

Table 5.7: Calculated maximum 5th harmonic current

<table>
<thead>
<tr>
<th>Amperage ($I_{pr}$)</th>
<th>$Z_{g,5}$ (mΩ)</th>
<th>$I_5$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 A</td>
<td>1110</td>
<td>2.5</td>
</tr>
<tr>
<td>40 A (35 A)</td>
<td>730</td>
<td>3.8</td>
</tr>
<tr>
<td>50 A</td>
<td>590</td>
<td>4.7</td>
</tr>
<tr>
<td>63 A</td>
<td>470</td>
<td>6.0</td>
</tr>
<tr>
<td>80 A</td>
<td>380</td>
<td>7.4</td>
</tr>
</tbody>
</table>

The conclusion of these calculations is that limiting the 5th harmonic current on the POC to 10% of the fundamental current is a suitable solution. These kinds of calculations can be made for all harmonics and the total demand distortion to achieve some percentage for each separate harmonic.

5.5.3 Possible solutions

A general overview of possible solutions will be given. Three general ways to mitigate harmonic problems are:

- Limit the emission by polluting loads.
- Immunise the victim of the pollution.
- Alter the coupling between the polluting loads and the victim.

5.5.3.1 Limit the emission by polluting loads.

Setting limits on the polluting loads is the main task for the appropriate standards. Nevertheless, for specific loads or high-power loads these limits depend on the short-circuit power of the grid. When reduction of harmonic currents is necessary this can be done by changing the type of load, for instance another design of rectifier circuit or adding internal filtering components. Specific active rectifiers which can be used are, for example, Power Factor Correction (PFC) and Active FrontEnd (AFE).
5.5.3.2 Immunise the victim of the pollution

Curative techniques can be applied directly at the loads or at the point of connection. They have to block or isolate the harmonics. The general name for such active devices is “power conditioner”. The most common applications are passive or active filters. This can be a passive filter just tuned to the frequency close of the harmonic that has to be tackled. Another possibility is a filter bank, where several filter legs are combined to mitigate several harmonics. With an active filter circuit it is possible to modulate a current that contains anti-harmonics, harmonic components with the same amplitude but with an opposite phase.

5.5.3.3 Alter the coupling between the polluting load and the victim

Reconfiguration of the installation can be applied when the problem occurs in only one installation. Separation of sensitive loads and less sensitive loads can solve the problem. This separation can be made by connecting the polluting load to a transformer other than the sensitive load. If the total installation is connected to the same transformer, the problem can be solved or at least improved by connecting the sensitive load directly to the main distribution board. If the problem occurs in more than one installation, increasing the short circuit power of the grid will reduce the harmonic voltages.

5.6 Summary and conclusions

Harmonic problems are not yet a big issue in the low and medium voltage grids in the Netherlands. Problems are mostly local and occur due to resonances. The average level of the total harmonic distortion (THD) measured in these grids is shown in figures 5.47 and 5.48. The 95% average values of THD are around 2.5%, which is far below the limit of 8%. The deviation from the average in the medium voltage network is less than the deviation in the low voltage network, which can be explained by the fact that most distorting devices are connected to the low voltage grid and transferred to the medium voltage grid with a substantial reduction. The other way around, distortion originating in the medium voltage grid is transferred to the low voltage grid without or with only a small reduction.
Nevertheless, the average values of THD are relatively small, but in neighbouring countries a rising level of harmonic voltages has been identified, which makes it necessary to stay alert to this phenomenon [Eur01]. Moreover, the fact that harmonic problems are to a great extent heating problems leading to overheating and shorter
life-time of components, makes a good analysis of possible harmonic distortion necessary.

For a reasonable prediction of harmonic voltages and currents the following information has to be available:

- Existing harmonic background voltage.
- Impedances of the grid in the frequency domain.
- Harmonic fingerprint of connected devices or installations.

Making a harmonic fingerprint for each device is time consuming but it can be very helpful when designing a device. Devices should be robust for harmonic distortion of the supply voltage and should give only a limited reaction on this distortion preventing a further distortion. For testing purposes (needed for a standard), making a total fingerprint is perhaps useful. Tests which have to be done on each device could be limited to test the device, using a “test distortion” which is comparable with the average distortion of the supply voltage in the network.

Calculations in the grid can be carried out by modelling a device as a harmonic current source. Depending on the characteristics of the device, modelling it as a $G$ and $C$ for each harmonic frequency is possible. For devices which behave in a not-linear way, a total harmonic fingerprint is the most accurate way to model it.

The introduction of additional power electronics will result in an increase of the harmonic distortion, as can be noticed by using inverters for connecting dispersed generation to the network. This can be avoided by creating proper standards, so that manufacturers of these inverters are able, without commercial constraints, to develop higher quality inverters which limit the harmonic currents.

For the grid operator it is necessary to have criteria for the maximal distorted current on the POC. Developing these requirements is possible, based on acceptable planning levels and calculated global contribution to voltage distortion caused by the low voltage system. This global contribution can be transferred to the limits for harmonic current distortion on the POC, taking into account the low simultaneously use of devices.

It is important to look to possible resonances in the grid by checking the amount of inductances and capacitors in the network. In spite of the introduction of more electronic devices, in general harmonic problems occur mostly under these circumstances.
Flicker

Flicker is a difficult problem to quantify and to solve. The untimely combination of the following factors is required for flicker to be a problem: some deviation in voltage supplying lighting circuits and a person being present to view the possible changes in light intensity due to the voltage variation. The voltage deviations involved are much less than the thresholds of susceptibility for electrical equipment, so major problems with equipment are seldom experienced. The human factor significantly complicates the issue, which is partly solved by developing the “flicker meter” and so establishing terms for flicker as $P_{st}$ and $P_{lt}$.

In this thesis these factors will be explained and some remarks will be given on the flicker meter. However, it is not the main issue of the research. Calculating flicker levels in the grid and connecting disturbing devices to the grid are the most important issues. New is the development of requirements at the POC related to certain grid impedances. The same grid impedances are used for calculating the maximum harmonic currents at the POC to realise consistent grid design rules.

These “reference” grid impedances, however are developed for the most demanding phenomenon, flicker.

6.1 Standards for flicker

There are several standards dealing with the flicker phenomenon. The most important ones are the flicker standards for devices (IEC 61000-3-3 [Sta06] and IEC 61000-3-11 [Sta07]). Furthermore, in the national Dutch grid code requirements for flicker at the POC are implemented. Flicker is related with voltage variations and the frequency of occurrence. The voltage variations are caused by variations in the current. The interaction between voltage and current is again an important issue.

6.1.1 The voltage

The following requirements related to flicker have been written down in the Dutch national grid code for low and medium voltage ($U_c < 35$ kV) networks:

- Voltage variations $\leq 10\% \ U_{nom}$.
• Voltage variations \( \leq 3\% \ U_{\text{nom}} \) in situations without loss of production, disconnection of heavy loads or faulted connections.
• \( P_s \leq 1 \) during 99.5\% of the time.
• \( P_s \leq 5 \) during 100\% of the time.

Typical is the maximum voltage variation of 3\% in the situation without exceptional changes of load or generation in the network. This requirement is more demanding than the limits on the value of \( P_s \) and is not very practical or necessary for the low and medium voltage network. This will be described in section 6.4. The meaning of \( P_s \) (and \( P_d \)) will be described in section 6.2.

6.1.2 The flicker contribution at the POC

In the EN 50160 and the most national grid codes there are no additional requirements for the installations on this aspect of flicker. But in the Dutch grid code, the following requirement is implemented: “The contribution of the customer to the flicker level at the POC is limited by a maximum contribution on \( P_s \) and \( P_d \) by demanding: \( \Delta P_s < 1 \) and \( \Delta P_d < 0.8 \); according to IEC 61000-3-3 a reference impedance of the network of 283 m\( \Omega \) may be used”.

This requirement gives some guidance to the responsibility of the grid operator, who has to make a suitable connection to the grid and to establish a certain minimum short circuit power (or maximum impedance, not necessary the reference impedance). The responsibility of the customer is to limit the inrush currents and other fast load variations, by putting limits on his contribution to the flicker level. More detailed information about the consequences of these standards is given in section 6.4.

6.2 The meaning of \( P_{lt} \) and \( P_{st} \)

Flicker is a difficult problem to quantify. Standard IEC 61000-4-15 [Sta08] summarizes the research that supports the IEC 61000-3-3 [Sta06] flicker standard and establishes a measurement method. Especially a flicker meter which:

• Records voltage fluctuations.
• Converts voltage changes to an estimate of light intensity variation from an incandescent bulb.
• Weights this estimated light intensity variation according to the repetition to account for human perception.
• Determines an instantaneous flicker perceptibility reading (\( P_{\text{inst}} \)).
• Derives a short-term flicker indication (\( P_s \)) over a ten-minute period.
• Derives a long-term flicker indication (\( P_d \)) over a two-hour period.
The functional diagram of the IEC flicker meter is shown in figure 6.1, showing the various areas, designated by blocks that are required to implement a flicker meter according to IEC 61000-4-15.

Block 1 establishes the reference level against which the voltage fluctuations are measured. IEC 61000-2-8 [Sta09] discusses the effects of using fixed or sliding voltage references. A sliding rms voltage reference is continuously calculated over a specified interval to represent the value of voltage at the point in the network just before a change occurs. Using this type of reference, it is simple to establish the tolerance band outside of which a voltage deviation has occurred. A fixed reference is awkward to use because the supply voltage may be exhibiting long-term as well as short-term variations, whereas only the short-term variations give rise to light flicker.

In block 2, the modulation caused by flicker is separated from the 50 Hz (or 60 Hz frequency) of the AC supply. The squaring multiplier simulates the variation in light output from an incandescent bulb in response to voltage fluctuation.

Figure 6.1: Functional diagram of the IEC flicker meter [IEC61000-4-15]

Block 3 accounts for human perceptibility. The first sub block, a Butterworth filter, limits the measured frequencies to those the eye can observe. It eliminates the DC and the double main frequency ripple components of the demodulator output. The second subblock shapes the frequency response envelope to correspond to the eye’s sensitivity to flicker, peaking at 8.8 Hz. The transfer function \( F_u \) for block 3, using a 230 V lamp in a 50 Hz system is of the following type:

\[
F_u(s) = \frac{1.74802a_s s}{s^2 + 4 \cdot \pi \cdot 4.05981s + (2 \cdot \pi \cdot 9.15494)^2} \cdot \frac{1 + s/(2 \cdot \pi \cdot 2.77979)}{(1 + s/(2 \cdot \pi \cdot 1.22535))(1 + s/(2 \cdot \pi \cdot 21.9))}
\]  

(6.1)
The final section of block 3 in figure 6.1 selects an appropriate measurement range. Because there could be a very wide range of perceptibility values, selection is necessary.

Block 4 combines a squaring multiplier and a first-order sliding filter to simulate the brain’s ability to identify change.

Finally, block 5 performs the statistical analysis required to assess the probability that the measured flicker would be irritating or actually hazardous.

The measure of severity based on an observation period of ten minutes is designated as $P_s$ and is derived from the statistics obtained from the level classifier in block 5. The formula used for calculating this $P_s$ is:

$$P_s = \sqrt{0.0314 P_{0.1} + 0.0525 P_{1} + 0.0657 P_{3} + 0.28 P_{10} + 0.08 P_{50}}$$

(6.2)

$P_{0.1}$, $P_{1}$, $P_{3}$, $P_{10}$ and $P_{50}$ are the flicker levels exceeded for 0.1, 1, 3, 10 and 50% of the time during the observation period. The suffix $s$ in the formula indicates that the smoothed value should be used. The 0.3 s memory time constant in the flicker meter ensures that $P_{0.1}$ cannot change abruptly and no smoothing is needed for this percentile. The smoothing value for the other percentiles can be calculated using the following equations:

$$P_{1s} = (P_{0.7} + P_{1} + P_{1.3}) / 3$$

$$P_{3s} = (P_{2.2} + P_{3} + P_{4}) / 3$$

$$P_{10s} = (P_{6} + P_{8} + P_{10} + P_{13} + P_{15}) / 5$$

$$P_{50s} = (P_{30} + P_{50} + P_{90}) / 3$$

(6.3)

The ten-minute period on which the $P_s$-value (short-term flicker) is based is suitable for assessing the disturbances caused by individual sources with a short duty-cycle. So the short-term value can be used for setting constraints on devices or even complete installations. As parameter for the quality of the grid, where the combined effect of several disturbing loads operating randomly has to be taken into account, it is necessary to provide a criterion for the long-term assessment of the flicker severity. For this purpose, the long-term flicker severity $P_l$ has been defined.

$P_l$ is derived from the short-term severity values over an appropriate period, in general taken as 2 hours, using the following formula:
\[ P_a = \frac{\sum_{i=1}^{12} P_{st(i)}}{12} \]  

(6.4)

\( P_{st(i)} \) are consecutive readings of the short-term severity value.

For most types of voltage changes, the \( P_a \) value can also be found by using empirical equations (6.5) and (6.6) [Mom01]. Each relative voltage change waveform can be expressed by a flicker impression time, \( t_f \) in seconds:

\[ t_f = 2.3 (F \cdot d_{max})^{1/2} \]  

(6.5)

\( d_{max} \) = the maximum relative voltage change expressed as a percentage of the nominal voltage

\( F \) = shape factor, associated with the shape of the voltage change waveform

For different values of \( F \), see [sta9]. In this thesis \( F \) will be taken as 1, representing the worst case of most voltage change waveforms.

The basis for the \( P_a \) evaluation is the sum of the flicker impression times of all evaluation periods within a total interval of the length \( T_p \) in seconds:

\[ P_{st} = \left( \frac{\sum t_f}{T_p} \right)^{1/2} \]  

(6.6)

Figure 6.2: Flicker curve \( P_a=1 \) [IEC 61000-3-3]
The observation period for $P_{st}$ is taken as ten minutes. In the case of rectangular voltage changes of the same amplitude ‘$d$’ separated by equal time intervals, the curve of figure 6.2 can be used to deduce the amplitude corresponding to $P_{st}=1$ for a particular rate of repetition. This curve is often used by grid operators to define the maximum allowed voltage variation by a customer who is using equipment switched on and off with a certain rate of repetition.

### 6.3 The flicker level in the network

Figure 6.3 shows the average level of $P_{lt}$ in low voltage networks in the Netherlands, measured during the years 1996-2005, except 1997. This are the results of the national Dutch PQ measuring program as mentioned in chapter 1. Clearly it shows an increasing flicker level during this period.

![Figure 6.3: Average $P_{lt}$ in low voltage networks](image)

A possible reason for this increasing flicker level is that the characteristics of the devices used in new installations are not analysed before they were connected to the grid. A second cause is the increasing power of devices used in installations, certainly in most domestic appliances. This increase of flicker level has resulted in an increase of customer’s complaints as stated by Dutch grid operators.

![Figure 6.4: Overview of power quality problems following customer complaints](image)

(a) Domestic customers  
(b) Small industrial customers
Figure 6.4 gives an overview of origins of complaints of customers connected to the Dutch low voltage networks. Figure 6.4a gives an overview of the complaints, mainly from domestic customers, and figure 6.4b gives an overview of complaints from customers with a contracted power of more than 50 kVA. The cause of these flicker complaints is mostly due to high inrush currents by using for example elevators or welding machines. Fast voltage variations, leading to variations in the light, occur due to variations in the current multiplied by the impedance of the grid. The Dutch grid code refers to an impedance of 283 mΩ. This impedance can be used to analyse the reason for a high flicker level. This can be high current variations or high impedance of the grid. Of course, in practice it is not that simple because it can be quite difficult to analyse these problems due to background flicker level. Some device manufacturers give guidance in their manual as to what power can be used, depending on the impedance of the grid at the location where the device will be used. Table 6.1 gives an example of such guideline. The question is: will the customer use this guideline? Most customers are not aware of the grid impedance. Furthermore the flicker problem can be acceptable to one customer for his purposes, but it can annoy his neighbour.

Table 6.1: Guideline for using a wood chipper

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Grid impedance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600/1700</td>
<td>0.35</td>
</tr>
<tr>
<td>1800/1900/2000</td>
<td>0.25</td>
</tr>
<tr>
<td>2100/2200/2300/2400</td>
<td>0.24</td>
</tr>
</tbody>
</table>

As stated in 6.1.1, currents at the customer’s point of connection may not lead to voltage variations of more than 3%. Voltage changes for a single phase connection can be calculated using formula (6.7).

\[
\Delta U = \left| U_g - U_l \right| \approx I(R_A + R_N) \cos \varphi + I(X_A + X_N) \sin \varphi \quad (6.7)
\]

In IEC 61000-3-3 [Sta06] it is stated that the reference impedances of the grid are:

- \( R_A = 0.24 \, \Omega \) (phase resistance)
- \( R_N = 0.16 \, \Omega \) (neutral resistance)
- \( X_A = 0.15 \, \Omega \) (50 Hz phase inductance)
- \( X_N = 0.1 \, \Omega \) (50 Hz neutral inductance)
This explains the grid impedance, $Z_{ref} = 283 \text{ m}\Omega$, as mentioned in the Dutch grid code. In fact it is the reference impedance of the phase. By using the reference impedances and formula (6.7), we can calculate the current of the device which will give a voltage change of 3%, in relation with the power factor of the device. The results of these calculations are shown in figure 6.6.

As shown in figure 6.6 a current of 16 A and a reasonable power factor gives, related to the reference impedance a voltage change of more than 3%. This is for a device connected to one phase and neutral. Inrush-currents of a motor are mostly with a power factor of 0.4-0.5. Currents for a heating element of a copying machine are with power factor 1. However, looking at the inrush currents of a lot of domestic appliances the conclusion could be that the requirement of a voltage change lower than 3%, is very difficult to achieve. It would be better to delete it from the grid code and change it into a more practical and achievable requirement. Suggestions will be given in section 6.6.
For three phase equipment the voltage variation on the line voltage can be calculated using formula (6.8).

\[ \Delta U \approx \left| I(R_\text{e}) \cos \varphi + I(X_\text{e}) \sin \varphi \right| \sqrt{3} \]  (6.8)

With the same inrush currents, three phase equipment will cause less voltage variation since there is no current flowing through the neutral. However, the nominal power of three phase equipment is mostly higher, so higher inrush currents will occur.

### 6.4 Origin of flicker problems

The main sources of rapid voltage fluctuations in the low voltage grid are:

- elevators
- photocopying machines
- motors in heat pumps or air conditioning equipment
- welding machines
- heavy loads that are connected to the low voltage grid

In the medium voltage grid the following sources are mainly responsible for rapid voltage variations [Uic02]:

- large industrial motors with variable loads
- arc furnaces and welding machines
- saw mills or rolling mills
- switching capacitors

Almost all complaints about flicker occur in the low voltage grid. The devices connected to the low voltage grid are in the scope of IEC 61000-3-3 standard [Sta06]
if they absorb a rated current less than 16 A per phase, or the IEC 61000-3-11 [Sta07]
if their rated current is between 16 A and 75 A per phase.

The most commonly used motor is the induction motor. The principle of the
induction motor is based on the principle of a rotating magnetic field, produced by
three magnetically displaced windings conducting three-phase electric currents. The
rotating field induces a current in the rotor windings of the induction motor. The
interaction between the rotor and the stator currents produces an electromagnetic
torque to drive the rotor of the motor. When starting, the current drawn from the AC
grid is much higher than the nominal value. This inrush current creates a voltage
variation with a depth that depends on the characteristics of the electrical network.
This voltage variation can, depending on the repetition rate, be the source for flicker
problems.

Another type of disturbance is the current of a copying machine where the heating
elements are switched on and off in order to regulate the temperature of the devices.
The voltage variation is mostly small but if the cycle period is about 0.1 of a second,
which corresponds to the maximum sensitivity of the human eye, it can still cause
flicker. The shape factor is mostly close to 1.

Although more devices could be a source of flicker, they are not described within this
thesis. For more detailed information about origins of flicker, see [Ute02].

6.5 Calculation of flicker levels

There are many origins of flicker as described in the previous sector. They can be in
the HV, MV and low voltage network resulting in a certain flicker level in that grid.
Propagation of flicker will be described in the following sections.

6.5.1 Propagation within the same voltage level

Transfer coefficient of flicker between point A (source of flicker) and point B (point
to evaluate) is defined as the ratio of $P_s$ values at the same instant at these two points:

$$T_{Pst,AB} = \frac{P_{st,B}}{P_{st,A}}$$  \hspace{1cm} (6.9)

Propagation on the low voltage level depends on the location of the observation
point, the short circuit power of the source and the location of the disturbing load
[Mom01].

Consider the low voltage grid as shown in figure 6.7. Assuming the disturbing load is
connected to location C, the variation of $P_s$ is defined as $\Delta P_{st,C}$. 

-136-
For the other location the contribution to the $P_{st}$ can be calculated with:

$$\Delta P_{st,A} = T_{Pst,C4,A} \cdot \Delta P_{st,C} = \frac{Z_A}{Z_A + Z_{AB} + Z_{BC}} \cdot \Delta P_{st,C}$$  \hspace{1cm} (6.10)$$

$$\Delta P_{st,B} = T_{Pst,CB} \cdot \Delta P_{st,C} = \frac{Z_A + Z_{AB}}{Z_A + Z_{AB} + Z_{BC}} \cdot \Delta P_{st,C}$$  \hspace{1cm} (6.11)$$

$$\Delta P_{st,D} = \Delta P_{st,E} = T_{Pst,C4} \cdot \Delta P_{st,C} = \frac{Z_A}{Z_A + Z_{AB} + Z_{BC}} \cdot \Delta P_{st,C}$$  \hspace{1cm} (6.12)$$

Customers at D or E see the $P_{st}$ present at the busbar A, with the origin in the other feeder without reduction.

Table 6.2 gives practical values of the impedances and the transfer coefficients assuming a MV/LV transformer of 400 kVA, a very strong MV grid and a 150 mm$^2$ Al low voltage cable with a length of 500 m. Customers B and D are connected at 250 m and C and E at the end of the feeders.

Figure 6.8 shows the modulus of the transfer coefficient for point A and B with a flicker source placed along the cable between point A and point C. It is the same figure as given in chapter 5 (figure 5.41).
### Table 6.2: Impedances and transfer coefficients

<table>
<thead>
<tr>
<th>Impedances</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_A = 5 + j1.5$ mΩ</td>
<td>$</td>
</tr>
<tr>
<td>$Z_{AB} = 50 + j45$ mΩ</td>
<td>$</td>
</tr>
<tr>
<td>$Z_{BC} = Z_{AD} = Z_{DE} = Z_{AB}$</td>
<td>$</td>
</tr>
</tbody>
</table>

#### Figure 6.8: Calculated transfer coefficients in low voltage network

The transfer coefficient can vary between 0.1 and 1 depending on the different variables.

### 6.5.2 Propagation through transformers

In addition to flicker propagation within the low voltage grid, voltage variations will be transferred from the high voltage grid to the medium voltage grid and further to the low voltage grid and visa versa, as shown in figure 6.9.
To calculate the flicker contributions from the customers on a certain voltage level the following formulas can be used:

\[
\Delta P_{st,HV} = \alpha \left( P_{st,HV} - (T_{PV,HV\rightarrow HV} \cdot P_{st, MV})^\alpha \right)
\]

\[
\Delta P_{st,MV} = \alpha \left( P_{st,MV} - (T_{PV,MV\rightarrow MV} \cdot P_{st,LV})^\alpha - (T_{PV,LV\rightarrow HV} \cdot P_{st, HV})^\alpha \right)
\]

\[
\Delta P_{st,LV} = \alpha \left( P_{st,LV} - (T_{PV,MV\rightarrow LV} \cdot P_{st, MV})^\alpha \right)
\]

(6.13)

The value of the coefficient \( \alpha \) depends on the characteristics of the disturbing loads and can be classified into the following four categories [Uie02]:

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The value of ( P_t ), resulting from the arithmetic sum of all ( P_t ) produced by each disturbing load when there is a high probability of simultaneous voltage variations</td>
</tr>
<tr>
<td>2</td>
<td>This value is used when there is simultaneous random disturbance</td>
</tr>
<tr>
<td>3</td>
<td>This is the value used mostly when the risk of simultaneous voltage variations is minimal</td>
</tr>
<tr>
<td>4</td>
<td>Used uniquely for the addition of voltage fluctuations produced by arc furnaces, operated in such a manner to avoid simultaneous operations</td>
</tr>
</tbody>
</table>
Consider the medium voltage grid as shown in figure 6.10. Assume the disturbing load is connected on location 10, at the low voltage side of the transformer, giving a variation of $P_d$ defined as $\Delta P_{st,10}$.

For the other locations the contribution to the $P_d$ can be calculated with:

$$
\Delta P_{st,A} = T_{Pst,10A} \cdot \Delta P_{st,10} = \frac{Z_A}{Z_A + Z_{AB} + Z_{BC} + Z_{10}} \cdot \Delta P_{st,10} \quad (6.14)
$$

$$
\Delta P_{st,B} = T_{Pst,10B} \cdot \Delta P_{st,10} = \frac{Z_B}{Z_A + Z_{AB} + Z_{BC} + Z_{10}} \cdot \Delta P_{st,10} \quad (6.15)
$$

$$
\Delta P_{st,D} = \Delta P_{st,E} = \Delta P_{st,A} \quad (6.16)
$$

The customer connected to the low voltage side of transformer 5 sees the $P_d$ present at the busbar B, as the origin is somewhere else in the MV network.

The transfer coefficients form LV to MV grid depends on the impedances of the transformer and the short circuit power of the MV grid at the MV side of the transformer. Figure 6.11 gives practical values of the transfer coefficients assuming a MV/LV transformer of 400 kVA or 630 kVA, in relation to the short circuit power at the MV side of the transformer.
Figure 6.11: Practical values of transfer coefficients from LV to MV

Since the transfer of voltage variation from a lower to a higher voltage level is very low, certainly in grids with a short circuit power above 100 MVA, the formulas (6.13) can be reduced to:

\[
\begin{align*}
\Delta P_{st, HV} &= \sqrt{P_{st, HV}^2} \\
\Delta P_{st, MV} &= \sqrt{P_{st, MV}^2 - (T_{Pst,HV\rightarrow MV} \cdot P_{st, HV})^2} \\
\Delta P_{st, LV} &= \sqrt{P_{st, LV}^2 - (T_{Pst,MV\rightarrow LV} \cdot P_{st, MV})^2}
\end{align*}
\]

(6.17)

As stated in [Uie02] the transfer coefficients for high to lower voltage levels are proximally:

\[
T_{HV\rightarrow MV} = 0.9 \\
T_{MV\rightarrow LV} = 1
\]

6.6 Requirements at the connection point

Requirements at the connection point have to be clear, easy to explain to the customer and easy to translate to grid design rules. Several standards are dealing with the limitation of voltage changes due to the equipment [Sta06, Sta07]. Nevertheless, there is still a need for requirements at the POC. By connecting a possible disturbing device to the network a general procedure, using in first instance the existing standards, can be followed. A proposal of additional requirements at the POC will be described for cases that devices are used which do not comply with the standards.
6.6.1 The general connection procedure

A procedure for evaluating devices connected to the low voltage grid without causing problems is shown in figure 6.12. If the nominal current of the device is equal to or less than 16 A and it is made according to IEC 61000-3-3 [Sta06], it should be evaluated by the customer but in general it can be connected. It is not possible and not desirable for the grid operator to have any influence on connecting devices of this limited power.

If the nominal current is between 16 A and 75 A, devices are probably made according IEC 61000-3-11 [Sta07]. Within the IEC 61000-3-11 there are two possibilities. The first option is to state that the equipment is intended for use only in premises having a contracted current \(I_c\) of 100 A or more per phase, supplied from a distribution network having a nominal voltage of 400/230 V. The equipment should be clearly marked in this way and the user should determine in consultation with the grid operator that the service capacity at the POC is sufficient for the equipment. This equipment has to be tested according IEC 61000-3-11 using the impedances as mentioned in this standard (see figure 6.13).
Figure 6.13: Testing the equipment for flicker limits [IEC61000-3-11]

Where:
- \( R_A = 0.15 \ \Omega \), \( X_A = j 0.15 \ \Omega \)
- \( R_N = 0.1 \ \Omega \), \( X_N = j 0.1 \ \Omega \)

The voltage variation limits measured are:
- The value of the short-term flicker indicator, \( P_{st} \) shall not be greater than 1.0.
- The value of the long-term flicker indicator, \( P_{lt} \) shall not be greater than 0.65.
- The relative voltage change, \( d(t) \) shall not exceed 3.3% for more than 500 ms.
- The relative steady-state voltage change, \( d_c \) shall not exceed 3.3%.
- The maximum relative voltage change, \( d_{\text{max}} \) shall not exceed 4, 6 or 7% depending on the equipment under test, see [Sta07].

In the Dutch situation, customers with a contracted current of 100 A or more will be at least connected to the low voltage side of a transformer. A weak grid with a short circuit power of 30 MVA on the medium voltage side and a 250 kVA transformer will have lower impedance than the values described in the standard. So connecting this equipment will not give any disturbance to other customers.

The other possibility within IEC 61000-3-11 is to determine the maximum permissible system impedance \( Z_{\text{max}} \) at the interface of the user’s supply point. To determine this maximum impedance, a test should be made with the test circuit in figure 6.13. The reference impedance may be replaced by a test impedance. The values of \( d_{\text{c,ref}}, d_{\text{max,ref}}, P_{\text{st,ref}}, \) and \( P_{\text{lt,ref}} \) have to be measured. If \( Z_{\text{test}} \) is not equal to \( Z_{\text{ref}} \), the measured values will have to be recalculated using the following formulas:
\[ d_c = d_{c, \text{test}} \frac{Z_{\text{ref}}}{Z_{\text{test}}} \]  
(6.18)

\[ d_{\text{max}} = d_{\text{max, test}} \frac{Z_{\text{ref}}}{Z_{\text{test}}} \]  
(6.19)

\[ P_{st} = P_{st, \text{test}} \frac{Z_{\text{ref}}}{Z_{\text{test}}} \]  
(6.20)

\[ P_{lt} = P_{lt, \text{test}} \frac{Z_{\text{ref}}}{Z_{\text{test}}} \]  
(6.21)

As stated in 6.1.2 the requirements at the POC are: “The contribution of the customer to the flicker level at the POC is limited by a maximum contribution on \( P_s \) and \( P_l \) by demanding: \( \Delta P_s \leq 1 \) and \( \Delta P_l \leq 0.8 \); according to IEC 61000-3-3 a reference impedance of the grid of 283 m\( \Omega \) may be used”. The equipment can only be connected to the network when the grid impedance \( Z_g \) is lower than the minimum of the four calculated values using formulas 6.22 to 6.25:

\[ Z_{g2} = Z_{\text{ref}} \frac{3.3\%}{d_c} \]  
(6.22)

\[ Z_{g1} = Z_{\text{ref}} \frac{d_{\text{max}}}{d_{\text{max}}} \text{ (according IEC 61000-3-11)} \]  
(6.23)

\[ Z_{g3} = Z_{\text{ref}} \left( \frac{1}{P_{st}} \right)^{\frac{1}{2}} \]  
(6.24)

\[ Z_{g4} = Z_{\text{ref}} \left( \frac{0.65}{P_{lt}} \right)^{\frac{1}{2}} \]  
(6.25)

Connecting these devices to the minimum calculated impedance means that the voltage variations and the value of \( P_s \) and \( P_l \) will not exceed the given limits.

**6.6.2 Additional requirements at the POC**

If the device is not made according IEC 61000-3-3 or IEC 61000-3-11, the customer has to determine in consultation with the grid operator whether the requirements at the POC are still fulfilled by connecting this device.
According to the Dutch grid code the voltage variation at the POC has to be limited to 3%. But it can be calculated that even a vacuum cleaner as shown in figure 6.14 with an measured inrush current of 35 A could not be connected. So first of all more practical limits have to be found.

On the low voltage grid, most of the customers have a connection defined with the nominal current of the protection device at the interface with the grid operator as shown in table 6.3.

![Vacuum cleaner](image)

**Figure 6.14: Vacuum cleaner with measured inrush current of 35 A**

**Table 6.3: Possible type of connection to the low voltage network:**

<table>
<thead>
<tr>
<th>Connection type</th>
<th>Amperage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 phase+neutral</td>
<td>40 A (35 A)</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>25 A</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>40 A (35 A)</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>50 A</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>63 A</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>80 A</td>
</tr>
</tbody>
</table>

It is understandable if a customer is asked to limit the inrush current of his devices to the same value as the amperage of his connection. The maximum value of $\Delta P_{st}$ has to be equal to 1, according to the IEC 61000-3-3. For each type of connection the maximum value of the grid impedance can be calculated using formulas (6.5) and (6.6). By taking $t_f$ in minutes (6.5) can be written as:

$$t_f = \frac{2.3}{60} (F \cdot d_{max})^{0.2}$$  \hspace{1cm} (6.26)

By defining $r$ as repetition rate per minute $P_{st}$ can be calculated with:

$$P_{st} = \sqrt{\frac{10 \cdot r \cdot t_f}{10}}$$  \hspace{1cm} (6.27)
\[
\frac{2.3}{60} \left( F \cdot d_{\text{max}} \right)^{1/2}
\]
(6.28)
\[
= \frac{2.3}{60} \cdot r \cdot \left( F \cdot \frac{\Delta U_{\text{max}}}{U_{\text{nom}}} \cdot 100\% \right)
\]
(6.29)

Where: 
\[
d_{\text{max}} = \frac{\Delta U_{\text{max}}}{U_{\text{nom}}} \cdot 100\%
\]

The maximum voltage variation will never be higher than:
\[
\Delta U_{\text{max}} = I \cdot Z_g
\]
(6.30)

Looking to figure 6.5 this will be the case as the voltage of the grid \( U_g \) is in line with the voltage at the beginning of the installation \( U_i \). By recalculating formula (6.29) and substituting formula (6.30) into it we get formula (6.31).
\[
\Delta P_{\text{st}} = 36.1 \cdot \frac{I \cdot Z_g}{U_{\text{nom}}} \cdot \frac{1}{\sqrt{r}}
\]
(6.31)

For each type of connection the maximum grid impedance can be calculated to allow an inrush current equal to the nominal current of the protection device at the POC. The values of \( \Delta P_{\text{st}} \) and \( r \) can be taken as 1 respectively 0.1 (once per ten minutes). For low voltage the nominal voltage is 230 V. The calculated values of the grid impedances are shown in Table 6.4.

<table>
<thead>
<tr>
<th>Connection type</th>
<th>Amperage</th>
<th>Maximum ( Z_g ) (m( \Omega ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 phase+neutral</td>
<td>40 A (35 A)</td>
<td>326</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>25 A</td>
<td>523</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>40 A (35 A)</td>
<td>326 (373)</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>50 A</td>
<td>261</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>63 A</td>
<td>207</td>
</tr>
<tr>
<td>3 phases+neutral</td>
<td>80 A</td>
<td>163</td>
</tr>
</tbody>
</table>

The maximum \( \Delta P_{\text{st}} \) for a customer can be evaluated by calculating the global contribution to the flicker level caused by the LV system under consideration, \( \Delta P_{\text{st},\text{LV}} \). Therefore, some planning levels for the MV and HV systems are needed. To establish these planning levels we can study the measured levels of \( P_b \) in some Dutch networks during the year 2005 [Ene02]. Results of these measurements are shown in figure 6.15.
The chosen planning level for the LV network is chosen as 1 which is equal to the compatibility level. This is the highest possible level but realistic given the results of the PQ measurements. The planning levels for the MV en HV network are chosen as 0.5 and 0.65 which seems realistic looking to figure 6.15. Another reason to choose these levels is the necessary space in the LV network where most of the polluting load is connected.

The global contribution to the flicker level that can be allocated to the total of loads supplied by the considered LV system is:

$$\Delta P_{F, LV} = \sqrt{I^{\alpha}_{P, LV} - T_{P, MV \rightarrow LV}^{\alpha} \cdot L^{\alpha}_{P, MV}} \cdot \frac{1}{\sqrt{1 - 1 \cdot (0.65)^3}} = 0.91$$

Figure 6.16 shows a typical Dutch low voltage network with domestic customers, and sometimes combined with small industrial customers or shops. In the figure the grid impedances are placed in relation to the nominal current of the protection device at the POC. The five outgoing LV feeders are protected by 250 A fuses. The nominal current of the transformer is 630 A. The simultaneous use is low, typically 0.1 for domestic customers in the low voltage grid. Polluting load is often 3 phase equipment and the 3 phase connections are mostly limited. Due to the low simultaneous use we will, similar what is done by calculating the limits for the harmonic currents, calculate
the $\Delta P_b$ at the POC, taking into account the maximum disturbance of two customers at the same time.

The meaning of a $\Delta P_b$ equal to 0.72 can be estimated using formula (6.4). Using a $P_e=1$ the repetition rate $r$ has to be four times in two hours. Four times a $P_e=1$ and eight times a $P_e=0$ will give a $P_e=0.71$, a little lower than the maximum variation of 0.72. This can also be translated to four different customers connected to the maximum grid impedance and having a maximum inrush current once every two hours or to two customers connected to the maximum grid impedance and having a maximum inrush current once every hour. Given the transfer coefficients to the transformer (figure 6.8), the chance of having an unacceptable high $\Delta P_b$ is minimal.

It is advisable to change the national grid code. The maximum voltage variation of 3% should be skipped. Furthermore, the value of $\Delta P_b=0.8$ could be changed in $\Delta P_b=0.72$. At the connection point a inrush current equal to the current capacity of the connection could be allowed, with the restriction that the frequency of this inrush current is limited to once an hour. When the inrush currents have higher frequencies further limitation on the amplitude of this current will be necessary.

Figure 6.16: Typical Dutch low voltage system

We assume that the disturbing loads are connected to point B and C. The maximum $P_b$ at point C may not be higher than 1. The limit for the $\Delta P_b$ on the POC is:

$$\Delta P_b = \sqrt{\frac{0.91^2}{2}} = 0.72$$

At the connection point a inrush current equal to the current capacity of the connection could be allowed, with the restriction that the frequency of this inrush current is limited to once an hour. When the inrush currents have higher frequencies further limitation on the amplitude of this current will be necessary.
6.7 The lamp type and its influence

The lamp is equipment that can convert the electrical power to visible light. However, different types of lamps have different processes for converting the electrical power to visible lighting [Coa01]. The incandescent lamp converts the electrical power into electromagnetic radiation by heating the filament when electrical current passes through it. Then the electromagnetic radiation produces the visible light and some other invisible light.

The working principle of a halogen lamp is the same as an incandescent lamp. Specifically there is a small inner bulb filled with halogen in the lamp. The tungsten molecules that evaporate from the filament react chemically with the halogen molecules; this reaction results in the tungsten molecules being redeposited onto the filament surface instead of the bulb surface as happens in incandescent lamp. Thus, the halogen lamp shines brighter and has a longer lifetime than an incandescent lamp.

The fluorescent lamp has a totally different working principle from the incandescent lamp. There are two electrodes, gas and mercury, in the glass tube. A phosphor coating is also used on the inner surface of the glass tube. The electrical current, which passes through the electrodes, stimulates mercury atoms to release ultraviolet photons. These photons in turn stimulate a phosphor, which emits visible light photons. The ballast is an important component for a fluorescent lamp in order to control the current of the fluorescent lamp.

Just like the different types of lamps have different working principles, the flicker response is different for different type of lamps too. This is verified by experimental measurement in [Cai01]. The tested lamps are:

- 60 W glass incandescent bulb.
- 20 W Brilliantine pro tungsten halogen lamp.
- 15 W four foot fluorescent lamp.
- 11 W compact fluorescent lamp with electronic ballast, i.e. energy-saving lamp.
- 9 W compact fluorescent lamp (CFL) with electromagnetic ballast.

Different type of lamps produces different amount of flicker for the same voltage fluctuations. Thus, the flicker tolerance to the voltage variations must be different for different types of lamp, i.e. the voltage variations can be different when the luminance variation is the same for different types of lamp.

Due to the 230 V, 60 W incandescent bulb is used in several standards, the luminance variation of a 60 W glass incandescent bulb when applying voltage variations with
$P_{st}=1$ is selected as the standard luminance variation in [Cai01]. The modulation voltage amplitude was measured in the power quality lab of the University of Technology in Eindhoven when the luminance variation reached the same value as the standard luminance variation for different type of lamps. The flicker curves (modulation voltage amplitude versus voltage modulation frequency when $P_{st}=1$) for the 60 W incandescent bulb and an energy saving lamp are presented in figure 6.17. Only sinusoidal voltage fluctuation is used in the measurement.

The conclusion can be drawn from this figure that the incandescent bulb is more sensitive to the sinusoidal voltage variations. The energy-saving lamp is less sensitive to the sinusoidal voltage variations.

So solving the flicker problem for a specific customer can perhaps be solved by simply replacing incandescent bulbs by energy-saving lamps.

![Figure 6.17: Flicker curves for different types of lamp](image)

### 6.8 Mitigation of flicker

The effects of voltage fluctuations depend first of all on their amplitude, influenced by the characteristics of the power system and their rate of occurrence. Usually, mitigation measures are targeted at actions focused on limiting the amplitude of the voltage fluctuations at the sensitive areas within the installation or at the POC.

In choosing the mitigation solution it is helpful to analyse who has to solve the problem, the grid operator or the customer(s). The customer has to solve the problem when he is connected with sufficient short-circuit power (grid impedance below value of table 6.4) and his current exceeds the nominal current of the protection device at the POC. Another cause of flicker could be a high repetition rate, because the given
impedance in table 6.4 is valid for a repetition rate of once per hour. When a higher repetition rate has to be taken in account, the inrush currents have to be reduced.

The most appropriate solution is to decrease the inrush current. Other solutions are using dynamic or static voltage stabilisers. Dynamic voltage stabilisers are a technically viable solution for eliminating or mitigating voltage changes. Their effectiveness depends mainly on their rated power and speed of reaction. By drawing reactive power at the fundamental frequency they give a voltage decrease on the supply network. Depending on whether the reactive power is inductive or capacitive, the rms voltage value at the point of connection (POC) can be increased or reduced. Figure 6.18 shows the classification of various solutions for dynamic voltage stabilisers. They are mainly three phase devices of high rated power, designed for voltage stabilisation at the main point of a distribution system or for a specific load or group of loads at a POC.

Figure 6.18: Overview of dynamic voltage stabilisers [Pqi01]

Static compensators (other than STATCOM) employ capacitive and/or inductive passive components that are switched, eventually phase-controlled or combined with controlled core saturation. They supply the required stabilising reactive current either in discrete steps or, more often, in a continuously variable fashion. Static compensators are considered to be the most advantageous solution for improving the power supply quality, in both technical and economic terms.
If the grid impedance is too high, the problem has to be solved by the grid operator. He can use the same solution as the customer, if it is a single customer problem. The solution can even be placed with the customer but paid for by the grid operator. A more structural solution is to increase the short-circuit power at the point of connection. This can be done by connecting the load at a higher nominal voltage level or increasing the rated power of the transformer supplying the load. Another direct feeder with lower impedance is also a possible solution.

More information about flicker mitigation can be found in [Uie02].

6.9 Summary and conclusions

An analysis of the Dutch PQ-measurement programme shows that the flicker phenomenon is the only one which shows a rising trend. Furthermore, an analysis of customer’s complaints, shows that flicker is the most common problem. The reasons for this increasing trend are the increase in high-power equipment and the fact that installations are connected to the grid without looking to dynamic behaviour as inrush currents.

Different from other power quality phenomena there exists for flicker a specific requirement at the POC. Nevertheless, grid operators do not have yet a clear view on planning levels of flicker within the different voltage grids. In addition, clear limits of inrush currents and repetition rates are not well defined. When designing a grid, simple rules have to be made which are practical and easy to explain to customers.

A reasonable start for grid design is to allow a customer to have an inrush current equal to the nominal current of the protection device. With this starting point the necessary grid impedance is calculated to limit the $\Delta P_L$ to 1. An important element in arriving at a structurally good grid design is that the rules developed do not conflict with other important issues for grid design. Therefore the maximum grid impedances for solving the flicker problem were also used for defining the limits for the harmonic current on the POC.7

By choosing a planning level of 0.65 for the $P_L$ in the medium voltage network, based on the PQ-measurements done in 2005, a limit for $\Delta P_L$ as contribution of a customer is defined. The maximum variation of $P_L$ at the POC should be 0.72, taking into account the very low simultaneous use of equipment and the transfer coefficients in the low voltage grid.

In the Dutch grid code a maximum voltage variation of 3% is mentioned in combination with limits for the $\Delta P_L$ and $\Delta P_T$ for both grid operator and customer. The maximum voltage variation of 3% is impractical and can only be realised with

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7 Nevertheless, it is possible that for creating a TN system (coupling the earthing system of the grid to the earthing system of the customer) lower grid impedance is necessary.
very strong restriction on inrush currents. By putting limits on the variation of \( P_a \) and \( P_b \) enough conditions are given to protect the grid operator and/or customer against possible flicker problems.

The flicker meter and therefore the values of \( P_a \) and \( P_b \) are based on an incandescent lamp 60 W, 230 V. Several types of lamps are used nowadays and most of them are less sensitive to voltage variations. A flicker problem for a specific customer connected to the end of the grid could therefore be solved by replacing bulbs with energy-saving lamps.

Flicker is a subjective phenomenon. Consequently, it is difficult to determine the direct cost of its effect. It affects the fundamental quality of utility service – that is, the ability to provide lighting that is steady and consistent. Certainly it can affect productivity in an office or factory but the cost of flicker is usually based on the cost of mitigating it if the complaints become significant. Developments in power electronics, in particular in semiconductor device manufacturing, have enabled the practical realisation of voltage dynamic stabilisation systems of ever higher-rated power, while at the same time investment and operating costs have been reduced. The availability of equipment with the ability to execute complex control algorithms allows the implementation of different functions, including dynamic voltage stabilisation.
Bronsbergen micro grid

Power quality aspects of the supply voltage are becoming more and more important in the public grid. The quality of the supply voltage depends on the quality of the currents in combination with the “strength” of the grid. A parameter for this “strength” is the short-circuit power of the grid at the connection points. Due to the increase of several sources of dispersed generation it will be possible in the future to create micro grids. These micro grids are mostly low voltage grids with their own sources and loads which can operate autonomously. An example of a micro grid is highlighted in this chapter, which focuses on the influence of micro grids on power quality phenomena. In chapter 3 some statements are made about the influence of dispersed generation on voltage level. Most important conclusion was that voltage level control could be kept simple by controlling the voltage level at the low voltage side of the MV/LV transformer. In chapter 5 conclusions were drawn about the risk of oscillations and the harmonic distortion due to the interaction between voltage and current of inverters used to connect PV systems to the grid. In this chapter, using the measurements performed in the low voltage grid of Bronsbergen, these conclusions will be underlined. The first section describes the normal grid operation in 2006 before the creation of the micro grid situation. The second section describes shortly the micro grid concept. The third section presents the expected influence of the micro grid on the power quality phenomena. The realisation of an autonomous working micro grid will be finished in 2008. Therefore, in this thesis only the ideas and principles of the micro grid will be presented.

7.1 Bronsbergen connected to the public grid

The Bronsbergen holiday park is situated in Zutphen, the Netherlands. Solar panels have been installed on the roof of 108 of the 210 cottages in this park, as shown in figure 7.1. The total solar power installed is 315 kW peak. The nominal power of the transformer feeding all the cottages is 400 kVA. Figure 7.2 shows the total concept of the low voltage grid in the holiday park. Four outgoing feeders are used for connecting the cottages to the public grid. More detailed information is given in appendix D and [Cob11].
A programme started in June 2005 to monitor all power quality aspects in the low voltage grid. PQ measuring devices were placed in the four outgoing feeders and on the low voltage side of the transformer. During this period the active and reactive power across the feeding transformer was measured, mainly to develop the storage system for the micro grid situation. Furthermore, the measured data gives information about all power quality phenomena on the low voltage side of the transformer. To
complete the whole picture for several weeks' measurements were made in some of the cottages.

Figure 7.3 shows the outside light intensity (lux) during week 25 in the year 2006. The first day of this week it was a little cloudy, which of course influenced the active power produced. The active and reactive power across the feeding transformer during this week is shown in figure 7.4. The blue line (active power) is negative when the solar power systems are producing more power than needed within the park. The reactive power (black line) is capacitive (negative) when the PV inverters are connected to the grid. These moments of operation are easily to recognise in figure 7.4, every day early in the morning until late in the evening.
In the next sections each power quality aspect in the situation where the holiday park is still connected with the public grid, will be described. The interaction between current and voltage will be explained.

### 7.1.1 Voltage level

Figure 7.5 shows the voltage level on the low voltage side of the transformer. The variation of the voltage is influenced by the transmitted power across the transformer but also the variation of the medium voltage is responsible for the variation measured. The average value is beneath the nominal voltage of 230 V. The tap changer of the transformer is fixed in this way because the amount of load in the low voltage grid is less than the total power of the PV-systems installed.

![Figure 7.5: Voltage level, LV side of the transformer; week 28, 2006](image)

**Figure 7.5: Voltage level, LV side of the transformer; week 28, 2006**

![Figure 7.6: Currents at the low voltage side of the transformer, week 28, 2006](image)

**Figure 7.6: Currents at the low voltage side of the transformer, week 28, 2006**
Figure 7.6 shows the current across the transformer. The measuring device used, did not distinguish the direction (positive or negative) of the current. Nevertheless, the high values should be negative (current of the PV systems) and the small peak at the end of each day is positive (load). As can be seen, there is a great unbalance in the three currents. Looking at the phase voltages on the low voltage side of the transformer in relation to the power flows or currents across the transformer we can conclude that there is a slight relationship with the power flow across the transformer, but it is not very strong. So the voltage level at this point is mostly influenced by power flows in the medium voltage grid.

When the micro grid should work autonomously the voltage level has to be controlled and stabilized on a fixed value. The variations of the voltage in either load or generation mode are small enough to keep the voltage in the grid at each point within the given limits, which will be described in section 7.3.1.

7.1.2 Dips

In the measuring period, from June 2005 to June 2006, a considerable number of voltage dips were detected. As stated in chapter 4 the average number of dips on a site like this should be around three or four per year. In the mentioned period 53 dips were measured, an unexpected high number. The reason for this extraordinary amount was the unusual weather (wind and ice) conditions in the Netherlands on 24 and 25 November 2005. Due to galloping lines there were a lot of short circuits in the overhead lines during this period.

![Dips at Bronsbergen site, period June 2005-June 2006](image)

Figure 7.7 shows that most of the dips occurred in two phases (61%), some in one phase (25%) and a few in all three phases (14%). In eleven cases the dip in at least one
phase was beneath the ITIC curve. If the data of 24 to 28 November 2005 is removed, the rest of the data consists of three dips during the remainder of the period, in other words an average number of dips (see chapter 4). When the micro grid operates in the autonomous working state, dip problems will be very seldom, because only a fault in the low voltage grid will give a dip.

7.1.3 Flicker

The flicker level on the site is similar to the average flicker level in Dutch low voltage network. Figure 7.8 shows the flicker parameters \( P_s \) and \( P_l \) in phase 1. In the two other phases there is the same pattern and the same level of flicker. So the large unbalance due to the solar power systems in the system does not give differences in the flicker level. Measuring the flicker levels in different cottages shows no increase in values of \( P_s \) and \( P_l \), so the solar power systems and the loads on the low voltage side of the transformer do not seem to be of importance for flicker.

![Figure 7.8: Flicker parameters in phase L₁ on the low voltage side of the transformer](image)

Still, flicker phenomena will be looked at in the autonomous working state, the voltage behaviour is important for the flicker level. A control mechanism in the autonomous working state is supposed to ensure that the voltage level is kept stable.

7.1.4 Harmonic distortion

The level of harmonic distortion is higher than the average in Dutch low voltage networks. Figure 7.9 shows the total harmonic distortion (THD) during week 28.
This harmonic voltage distortion is partly due to existing background harmonic distortion and otherwise due to the distorted harmonic currents of the PV inverters. The level of harmonic distortion of the current has to be related to the rms value of the fundamental current flow. A high distortion in combination with a very low rms value of the fundamental current is not as harmful as the same distortion combined with a high level of fundamental current. Figure 7.6 shows the rms value of the current in the same period. There is certainly a strong relationship between the measured THD and the power produced by the solar power systems. The differences in the phases and the different days of the week in figure 7.6 (the currents) can also be found in figure 7.9 for the THD.

In chapter 5 was found that several aspects have to be considered when analysing the relationship between the harmonic voltage and the harmonic current, namely:

- The existing harmonic background voltage.
- The harmonic current of the inverter and the interaction between harmonic current and harmonic voltage and vice versa.
- The resonant effect that can occur due to the inductivity in the grid and the capacitors across the input of the inverters.

An example of extreme harmonic problems is, due to a combination of these aspects, present on the given site. To catch some waveforms a trigger was set on the PQ measuring equipment to store the waveform when the level of THD in the voltage was in excess of 8%. This resulted in many waveforms, mostly in the middle of the day when a lot of solar power was generated. Figure 7.10a shows an example of a form of the current in phase 1. The harmonic analysis given in figure 7.10b shows the value of each separate harmonic current in percent of the fundamental current.
This distorted current influences the quality of the voltage, which will be distorted too. The total harmonic distortion is around 8% or more when oscillation occurs (given the trigger set and the harmonic analysis made). Such a harmonic voltage is given in figure 7.11.

Keeping in mind that there was a great unbalance in the three currents, the neutral current will be high and extremely distorted with a combination of a high 11th harmonic current and a serious contribution of the 3rd harmonic current. Figure 7.12 shows this neutral current and as concluded before, the distortion is indeed extremely high. This high value of the neutral current and the extreme distortion will stress the transformer.
In the third phase also a high harmonic voltage and current with a frequency of 750 Hz (15th harmonic) was also measured. To analyse why there seems to be an oscillation problem with the 11th harmonic in phase 1, and the 15th harmonic in phase 3, we can use the diagram shown in figure 7.13, as already derived and explained in chapter 5. The harmonic voltage at the average POC can be calculated with formula (7.1).

\[ U = \frac{U_g + I(R_g + j\omega L_g)}{1 + (R_g + j\omega L_g) \cdot (G + j\omega C)} \]  

(7.1)

where:

- \( U \) = harmonic voltage at the Point of Common Coupling (PCC)
- \( U_g \) = grid background harmonic voltage
- \( R_g \) = grid resistance, including the influence of the skin-effect
- \( L_g \) = grid inductance
- \( I \) = harmonic current emission of the inverter without background distortion
- \( C \) = total capacitance (sum of load and inverter capacitance)
- \( G \) = total conductance (sum of load and inverter conductance)
The values of a single inverter are measured using the method described in section 5.2. The values of \( I_{0(h)} \), \( G_{0(h)} \) and \( G_{(h)} \) of the inverters used in this situation are shown in figure 7.14, 7.15 and 7.16 [Hes01],[Cob04].

**Figure 7.14**: Harmonic currents inverter \((U_g=0)\)

**Figure 7.15**: \( G/G_{ref} \) for measured inverter

**Figure 7.16**: \( C/C_{ref} \) for measured inverter

These values are given in units/W, so the real value can be calculated by making an estimate of the power generated in the three phases, using the total power given in figure 7.4 and the currents in figure 7.6. In figure 7.17 the second day, which was very
sunny, is shown in more detail. Also the total active power curve is divided into an estimated load and solar power curve to get a more accurate estimate of the active power of the PV systems. During the day the load is taken as a constant 50 kW.

Figure 7.17: Estimated active power of PV systems

The active power of the PV systems in the various phases can be calculated by:

\[
P_{PV,1} \approx P_{PV,2} \approx (U_p \cdot I_1) + P_I / 3 = (230 \cdot 300) + (50 \cdot 10^3 / 3) = 85 \text{ kW}
\]
\[
P_{PV,3} \approx (U_p \cdot I_3) + P_I / 3 = (230 \cdot 150) + (50 \cdot 10^3 / 3) = 50 \text{ kW}
\]

Where:
- \( P_{PV} \) = active power of the PV systems
- \( P_I \) = total active power of the load
- \( U_p \) = phase voltage
- \( I \) = phase current

To calculate possible resonance in the grid, the capacitance of the total amount of inverters can be calculated from the normalised values as follows:

\[
C_{PV,1} = (C_i / C_{ref}) \cdot C_{ref} \cdot P_{PV,1}
\] \hspace{1cm} (7.2)

\( C_{ref} = 60 \cdot 10^{-9} \text{ F/W at 230 V, 50 Hz (chapter 5, formula (5.7))} \)
\( C_i / C_{ref} = 0.12, \text{ figure 7.16} \)
\[ C_{\text{PV,1}} = 0.12 \cdot 60 \cdot 10^{-9} \cdot 85 \cdot 10^3 = 612 \cdot 10^{-6} \text{ F} \]
\[ C_{\text{PV,3}} = 0.12 \cdot 60 \cdot 10^{-9} \cdot 50 \cdot 10^3 = 360 \cdot 10^{-6} \text{ F} \]

The resonance frequency of the system can be calculated using (7.3).

\[ f_{\text{res}} = \frac{1}{2\pi \sqrt{LC}} \]  

At the point where the distortion at a POC was measured the inductance was 0.04 Ω, which was validated with the network model of figure C2.

For the given situation the \( L \) can be calculated:

\[ L = \frac{X}{2\pi f} = \frac{0.04}{314} = 0.1274 \text{ mH} \]

For the different phases the following resonance frequencies can be calculated.

\[ f_{\text{res,1}} = \frac{1}{2\pi \sqrt{0.1274 \cdot 10^{-3} \cdot 612 \cdot 10^{-6}}} = 570 \text{ Hz} \quad (\approx 11^{\text{th}} \text{ harmonic}) \]
\[ f_{\text{res,3}} = \frac{1}{2\pi \sqrt{0.1274 \cdot 10^{-3} \cdot 360 \cdot 10^{-6}}} = 743 \text{ Hz} \quad (\approx 15^{\text{th}} \text{ harmonic}) \]

The estimated values of the components are not constant, but change according to the frequency. Due to the skin-effect this is also the case with the resistance of the grid cable, as stated in section 5.4.1. Using formula (7.1), the harmonic voltage for each frequency can be calculated. Without calculating all the voltages, the oscillation problem around the 11th harmonic voltage in phase 1 and the 15th harmonic voltage in phase 3 is predictable. In the situation with inverters, working in parallel with the grid, a solution for this problem has to be found. In the autonomous working grid situation new calculations have to be made to study the possibility of resonance.

### 7.1.5 Unbalance

The last phenomenon, regarding the power quality on the site is the unbalance. We already noticed that there was a considerable unbalance in the currents (and therefore in the generated power). The question is whether this unbalance in current also gives an unbalance in the voltage. Figure 7.18 shows the unbalance of the voltage at the low voltage side of the transformer, which gives a clear answer to the question.
The pattern of the unbalance is similar to the pattern of the currents shown in figure 7.6. So the origin of the unbalance is clear. However, the level of unbalance in the voltage is not very high because the limited impedance in the medium voltage grid. In relation to the unbalance, harmonic oscillation problems in phase 1 and 3 occurred with different resonance frequencies. So it is interesting to see how we can deal with this unbalance in the autonomous working situation.

### 7.2 Bronsbergen operated autonomously

Interconnection of small generators in the low voltage distribution systems leads to a new type of power systems, the micro grid [www04]. Micro grids can be connected to the public grid or operated autonomously. Advantages of micro grids are minimisation of the overall energy consumption, lower grid losses and improvement of reliability and power quality. These advantages still have to be proved and some difficulties and drawbacks of micro grids have to be tackled. The higher costs of distributed energy resources, the lack of experience, the difficulty of controlling large numbers of micro sources are some examples of the challenges. The micro grid “Bronsbergen” is developed to analyse the predicted advantages and to find solutions for problems encountered. The micro grid will be built during 2007 and tested in 2008. In this thesis the concept will be described, the functionality of the micro grid and its components and some relations with power quality phenomena.

An autonomous working micro grid will be realised by introducing a storage system (batteries) coupled with the public grid by DC/AC inverters. The diagram with the changes to be made is given in figure 7.19. In table 7.1 an overview is given of the objectives of the micro grid, the components needed for it and its main functions.
Table 7.1: Objectives of the micro grid and functions of the components

<table>
<thead>
<tr>
<th>Objective</th>
<th>Components</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Islanded operation</td>
<td>Batteries, Inverters, Control centre</td>
<td>Keeping the energy balance. When there is more PV-power as needed in the grid the batteries will be charged. When these batteries are fully charged PV-systems have to be disconnected. When the load is higher then the PV-power, the batteries have to deliver the energy.</td>
</tr>
<tr>
<td>Automatic isolation and reconnection (In normal operation micro grid will be connected to the public grid)</td>
<td>Circuit breaker, Control centre</td>
<td>The circuit breaker has to disconnect the micro grid from the external public grid when a fault occurs on the external system. This protection device will operate as directional overcurrent detection and must not operate during an internal fault in the micro grid. Internal faults must be handled selectively by the fuse on the faulty feeder or, in case of a fault within the BIS (Battery inverters system), by a protection device in the BIS. Upon an enabling signal from the Micro grid Control Centre (MCC) the protection device must reconnect the micro grid to the external grid. For this purpose, the device will be equipped with a synchronization detection facility. The BIS must sense the voltage on the external grid and adjust the voltage and frequency of the micro grid in such a way that synchronous reconnection is possible. Reconnection must be established within one minute after it has been detected that the voltage and frequency on the external grid is within the statutory limits.</td>
</tr>
<tr>
<td>Fault protection</td>
<td>Batteries, Inverters, Circuit breaker</td>
<td>Internal fault: The BIS (Battery and inverter system) must be able to generate a fault high enough to blow a 200 A fuse within 5 s. External fault: The short circuit behaviour of the BIS should be such that it does not switch off during a fault on the incoming feeder from the public grid. The short circuit breaker has to disconnect the micro grid from the public grid.</td>
</tr>
<tr>
<td>Limiting harmonic voltage distortion</td>
<td>Inverters</td>
<td>The inverters should absorb and/or compensate harmonics within the micro grid to such an extent that each harmonic voltage from 100 Hz up to 2000 Hz complies with the planning level. The initial assumption for the planning level is equal to the average harmonic voltages in the grid.</td>
</tr>
<tr>
<td>Black start</td>
<td>BIS, Control centre, Circuit breaker</td>
<td>By an outage of the public grid the microgrid has to be disconnected from the public grid. The BIS, in combination with the control centre has to realise the black start</td>
</tr>
</tbody>
</table>
7.3 Influence of the micro grid on PQ

By creating the micro grid, power quality phenomena will be influenced. There will be a difference in the grid connected situation and the disconnected, autonomous working, situation. The influence in both cases is described below.

7.3.1 Voltage level

If the low voltage network is connected to the public grid, control of the voltage level is not needed within the control centre. The tap changer of the transformer was changed to an acceptable point to decrease the average voltage level at the connected houses. Even with the existing variation of voltage in the medium voltage network the voltage level at the end of the low voltage feeders is kept within the limits.

Calculation in the low voltage grid has shown that by using a constant voltage level at the low voltage busbar in the transformer station, the voltage variations at the end of the low voltage feeder are limited. Figure 7.20 shows the voltage profile at the end of the low voltage feeder (house no. 1, appendix D) with the maximum PV power at noon and maximum load in the evening, in accordance with figure 7.17. Therefore voltage level control in autonomous operation can be achieved by keeping the voltage at the low voltage busbar constant. No additional control is necessary.
In several houses an energy meter with additional functionalities will be installed as shown in figure 7.21. This will give the possibility to disconnect PV systems from the grid if this should be necessary in autonomous operation. This could be the case if the battery is already fully loaded and there is still a surplus of generated power. But also when the voltage might become too high which normally will never be the case.

**Figure 7.21: Special energy meter installed in several houses for disconnecting PV systems**

### 7.3.2. Dips

In autonomous operation the amount of dips will be limited and can only occur when there is a short circuit in one of the low voltage feeders. In grid-connected operation the storage system in combination with the inverters could be used for dip mitigation. The influence on the dip depth will however be small because the injected current into the medium voltage grid is limited to the protection settings of the circuit-breaker at
the low voltage side of the transformer. In a short time the maximum current could be 1000 A, which is 40 A at MV level. This current can increase the voltage with not more than a few % of the nominal voltage. To increase the possibilities for dip mitigation additional measures should be taken, for instance:

- Fast disconnecting the grid when a dip is detected, voltage control by the inverters in autonomous operating mode and connecting again to the public grid when the voltage level is restored.
- Placing a variable inductance in series with the transformer and increasing the inductance when a dip occurs.

7.3.3 Flicker

There is currently an average flicker level. Theoretically it is be possible to limit fast voltage variations using the inverters and the storage system with fast energy response. In the micro grid situation the short-circuit power is lower but there are no high inrushes or starting currents. Only sudden power variation due to clouding is possible. The time scale of these variations is a few seconds and the inverters in combination with the storage systems will be able to keep the voltage at the low voltage level constant. Therefore an increase of flicker is not likely.

7.3.4. Harmonic distortion and unbalance

In the current situation two different resonance frequencies are measured in the different phases of the power system. The unbalance in the installed PV systems (asymmetric connection to the phases) is the reason for the existence of these two resonance problems. The unbalance is also the reason for an unnecessarily high current in the neutral. Also the losses in the grid will be higher due to this unbalance. The first improvement is simply to reconnect the PV systems and balance these systems between the different phases. This will also reduce the harmonic problem to a single frequency which, in the given situation, will be around the 13th harmonic.

If the micro grid is connected to the grid, the power electronic converter can increase the damping of the grid, making it less sensitive to harmonics and oscillations. A description of a controller that emulates resistive output impedance for the controller can be found in [Mor01]. Complete compensation of harmonics will not be possible with this method, but this is not needed anyway.

When the micro grid is disconnected from the public grid, the converters can make a sinusoidal voltage which will limit the harmonic currents. By disconnection of the public grid, background harmonic frequencies will disappear. Still, new resonance frequencies can appear by introducing the converters and the storage system.
7.4 Summary and conclusions

Micro grids have their own sources of electricity and for autonomous operation controllable sources are needed. If the sources are not completely controllable at least enough storage has to be available to operate the micro grid autonomously during an acceptable time. They can operate connected to the grid and isolated from the public grid, and both operation modes have their advantages and disadvantages. In relation to power quality issues the following conclusions can be drawn:

Connected to the public grid:
- Voltage dips occurring in the MV and HV grid will be transferred to the micro grid, depending on system topology and transformer type.
- Background distortion levels of flicker, harmonics, voltage variations and unbalance will be transferred to the micro grid.
- High short-circuit power ensures that harmonic currents, inrush or starting currents are possible to some extent without high distortion of the voltage.

Isolated, in autonomous operation:
- The number of voltage dips will be minimal, only short circuits in the micro grid itself will cause voltage dips.
- Due to a limited short-circuit power the impact of the currents on the voltage will be higher and starting or inrush currents can cause voltage dips of a certain extent.
- Voltage level control in micro grids can most efficiently be organised by regulating the voltage level at the low voltage side of the transformer and keeping the voltage constant at this point.
- The implementation of a good protection philosophy in the micro grid (overcurrent and electric shock) is important because old or existing protection systems will probably not work due to the reduced short-circuit power.

Depending on the main characteristics of the micro grids different PQ limits could be introduced. These characteristics could be:

- Short circuit power of the micro grid. In all cases the short circuit power of an autonomous working micro grid will be significantly less than in the grid connected situation. This means that for example inrush currents have more impact on voltage variations. Depending on the installation and devices connected to the microgrid this might be acceptable.
- Maximum nominal power within the micro grid. The energy sources in the micro grid will be limited and keeping the balance between load and generation will be important. Introduction of storage will simplify this
problem, nevertheless constant coordination of all load and sources in the grid will be needed. Switching on and off load and sources will have a greater impact on the power quality phenomena.

- Type of customers in the micro grid (and their specific needs). For some customers the momentary high quality of service is not needed. Micro grids can be made for typical customers, where there is no need for this high quality. Special contracts with lower power quality demands could be introduced.
Conclusions and recommendations

Power quality aspects are becoming more and more important. The ERGEG public consulting paper “Towards Voltage Quality Regulation in Europe” gives a good overview of the most important issues and questions in this field. Some of them can be answered with the work achieved and described in this thesis. Within the conclusions several issues are highlighted, such as using standards, impact of dispersed generation, responsibilities and classification methods. Moreover, new research topics are recommended, in line with the results of this research and the needs of grid operators and regulators.

8.1 Conclusions

Given the nature of electricity, every party connected to the power system influences voltage quality, which means that every party also should meet certain requirements. Therefore power quality standards are set for the supply voltage and for devices. Less effort is made in developing standards for the point of connection (POC) to the grid, but several activities in this field have started. Standards are necessary to uphold today’s quality, e.g. to counteract a deterioration of the power quality of the supply voltage. Minimum quality requirements are needed for customer protection, and are necessary in order to solve disputes between different stakeholders.

A strong recommendation in the 3rd CEER Benchmarking Report on Quality of Electricity Supply [Cee01] was that at least the most critical voltage quality parameters should be monitored and results should be published so that, in the first instance, the actual performance of networks can be determined. Monitoring the voltage quality on many places provides a huge quantity of data which has to be analysed thoroughly. This is only possible with an effective classification procedure, for which the new classification methods developed and described in this thesis can be used.
The duties and rights of all the parties involved should be clear; ERGEG proposes a general framework for sharing the responsibility between network companies, equipment manufacturers and final customers. In this field, a sound coordination among technical standards (both system-related and device-related) is of great importance. Furthermore, the interaction between voltages and currents (e.g., harmonic currents) should be explored, as well as the level of short circuit power provided by network operators, in order to clearly identify responsibilities for voltage quality disturbances. The “harmonic fingerprint” described in this thesis is developed as new technique to analyse the interaction. Each party has its own interest in the quality of supply and certainly industrial customers will be able to take their own countermeasures or pay for a higher quality of the supply voltage.

As described before, devices connected to the power system influence the voltage quality. Dispersed generation is a very typical device which influences the supply voltage at the POC, but can also change the character of the power system itself. For example, the short-circuit power will be influenced and all related aspects also. Dispersed generation connected to the power system via electronic converters influences the voltage shape. Storage systems combined with dispersed generation can improve the quality of the supply voltage, for example to decrease the flicker level, the harmonic distortion or the depth of dips.

8.1.1 Standards

There are many standards related to power quality regulation. The standard EN 50160 [Sta01] is the most important one for defining the quality of the supply voltage. European regulators are concerned about the voltage quality standards with respect to customer needs, so we can expect regulators to pay an increasing attention to voltage quality issues in the years ahead. For instance, many regulators think that stricter voltage quality standards are required; some of them have already introduced or are engaged in preparing more constraining requirements in national grid codes.

Setting more restrictive standards than those stated in EN 50160 may entail higher costs for network companies depending on the today's level of quality within each country. Voltage supply quality covers a wide range of factors. For the purpose of this thesis, the following aspects are treated:

- supply voltage variations
- rapid voltage changes
- flicker severity
- supply voltage dips
- harmonic voltages
Mostly the limits for voltage variations in EN 50160 are given for typical 95% of the time. This means that, according to EN 50160, for 8 hours every week there can be severe voltage deviations without exceeding the limits in the standard. The national Dutch regulator added a 100% criterion to the voltage level requirement which limits the voltage to –15% for the additional 5% of all 10 minutes averages values. In addition to the accepted 5% voltage drop in an installation, devices could be connected to a voltage of 80% of the nominal voltage during 5% of the time in a week. This is a big problem for customers. The manufactures will not design equipment for handling the remaining 5% of the time, which leaves the risk to the customers. The clause of 95%-of-time (applicable to most of the parameters in EN 50160) is too loose and therefore there is lack of protection of the customer.

Another critical point is also the time interval used for averaging measured values in order to verify limits of voltage variations (especially as regards supply voltage variations and flicker severity). The currently used 10 minute average is related to thermal effects and may hide some voltage variations that could damage equipment. Hence, a change of the time interval used to average measured values should be considered consistently with the 95%-of-time issue. A logical shorter time interval is 1 minute because this the maximum duration

8 Events with a lower voltage levels than –10% of the nominal voltage and with a time interval shorter than 1 minute will be recognised as a dip. In general, limits for supply voltage variations should be clear and uncontroversial.

EN 50160 does not give binding limits but only indicative (non-binding) values for dips. These values are also rather vague (e.g. “up to several hundreds”) and therefore not useful for customers, neither for claiming damages when they occur nor even for designing protection systems in an economically sound manner, or for taking appropriate countermeasures. As a preliminary step, a dip profile and a classification of voltage dips is needed. This can be done through the definition of a “voltage dip table” that classifies dips by depth and duration, in order to distinguish group of events having common severity characteristics.

With voltage dips we have to be aware that the amount of dips in the Netherlands, certainly compared with most other European countries, is small. Also there can be, due to extreme weather conditions, a year with an extreme amount of dips. And even without the extreme weather conditions the amount of dips each year has a Poisson distribution. This means that the average amount of dips can vary from year to year. By regulating dips it is advisable to use a sliding window of 5 years to calculate the average amount of dips.

---

8 Hungary and Norway are using already a 1 minute interval in their national grid codes, [CEE01].
EN 50160 is the main technical standard for voltage quality in Europe, but it is not the only one. There is also the IEC 61000 series of technical norms on electromagnetic compatibility (EMC), which is very comprehensive and includes references about limits for voltage disturbances, immunity and emission levels of electrical equipment, measurement procedures for voltage quality parameters and measurements techniques. These standards can be used for devices but in general are not meant to be used for customer connection points (POC). In the standard for devices the problem occurs that, (e.g. for harmonics) the devices are tested in lab conditions with an ideal supply voltage. In practice they are connected to a distorted voltage and their reaction is not defined. Equipment should also be tested with an average distorted supply voltage to get a certain “fingerprint” of the equipment behaviour.

Furthermore complementary instructions are needed to establish the limits of disturbances that each installation is allowed to emit to the network. For the moment this is based on:


Simultaneous use of equipment on the POC and the simultaneous use of equipment among connected customers have to be estimated to come to realistic limits for which examples are given in chapter 5 (harmonic currents) and chapter 6 (inrush currents).

8.1.2 Classification

The most critical voltage quality parameters must be monitored in order to determine the actual performance of networks. Monitoring the voltage quality on many places delivers a high amount of data which has to be analysed. Not only the actual level but also trends over the last years have to be given. This is only possible with an effective classification method where transmission of large amounts of data can be avoided. Implication of this conclusion is that data of locally measured PQ phenomena has to be stored locally. Also the first data operation to normalise and classify the power quality has to be achieved locally. Then the information can be transmitted to a central point where it is combined with other data, as shown in figure 8.1.
In first instance the classification of all power quality phenomena at dedicated locations in the grid can be displayed. Only in case when still more detailed information is wished (because of an occurring problem or a special point of interest) all measured data of a specific location could be transmitted from the local database.

It is not only in the interest of the regulator to monitor the PQ phenomena in the grid. Installations connected to the grid can change over time. Dispersed generation will be implemented, the characteristics of new devices will be different and all these developments will influence the quality of the supply voltage. Monitoring the grid is necessary to recognise problems in time; to get information about the margins in the grid and observation of the quality level.

**8.1.3 Responsibilities**

Power Quality is a shared responsibility of all interested parties: network companies (both distribution and transmission grid operators), customers and equipment manufacturers.

A sound coordination among technical standards (both system-related and device-related) is important. Limits given in EN 50160 must not be in conflict with other technical standards, for instance product standards, emission and immunity standards. Standards should not contain limits which leads to high cost of equipment without reasonable explanation. Sharing responsibilities between the parties involved is of key importance from the regulators' viewpoint.

Requirements for each power quality phenomena are needed for clarifying the responsibility of the customer. These requirements at the POC must be based on integrated grid design rules. For example the grid impedances (or short circuit powers)
used for defining requirements for flicker must be the same as for harmonic currents or other power quality phenomena.

The transmission and the distribution operators mostly contact the customer if he causes troubles in the system and he may advice the clients connected to their network on the best way to mitigate the disturbances caused by the installations on the network.

### 8.1.4 Dispersed generation

There are several Power Quality phenomena which will be influenced by dispersed generation and on the other hand dispersed generation will be affected by Power Quality.

Dispersed generation increases the voltage level. When connecting it to the low voltage network without any control, to high voltage levels may occur. Nevertheless, in almost all cases it will be possible to avoid these problems by dividing the dispersed generation over all outgoing feeders and over the total length of the feeders. The best way to regulate the voltage level is to keep the voltage level at the low voltage side of the MV/LV transformer constant. Regulating the voltage level with reactive power is not effective in the low voltage network and has its limitation also in the medium voltage network. Regulating the voltage level, by controlling the output of all dispersed generators and possibly also the loads in the low voltage network is not advisable and unnecessary complicated.

To avoid islanding dispersed generation has to be disconnected from the network if the voltage level or frequency is outside the following limits:

- $U > 106\% U_{\text{nom}}$, disconnection time: 0.1 s
- $U < 80\% U_{\text{nom}}$, disconnection time: 0.1 s
- $f < 48$ Hz, disconnection time: 2 s
- $f > 52$ Hz, disconnection time: 2 s

Measurements on PV-inverters [Ecn01] have shown disconnection by voltage dips with a remaining voltage of 60% $U_{\text{nom}}$ already within a few periods. Disconnection of dispersed generation within such short times is not necessary and even contraproducive. There are for instance several developments on ride-trough capabilities for wind generators. The upper limit of 106% of the nominal voltage is out dated and should be changed in 110%.

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9 According the Dutch National grid code, for systems with a nominal power < 5 kW. For systems with a nominal power above 5 kW the limits and disconnection times are slightly different.
Dispersed generation even could be used to some extent for mitigation of voltage dips. However, without any storage or other possibility to inject more power on the moment a dip occurs, its effect on dip mitigation will be limited.

Systems to connect dispersed generation to the network are mostly based on electronic inverters what increases the level of harmonic distortion in the network. Power Quality measurements in the Dutch low voltage grid have shown a significant increase of harmonic distortion levels on places where a high amount of PV inverters is installed [Ene03]. The characteristics of the inverters, which can be identified by making a harmonic fingerprint of the inverter, are very important for calculating the harmonic currents and harmonic voltages. There is an interaction between the harmonic currents and voltages which has to be limited. A negative $G$ (which means that the inverter is injecting harmonic active power into the grid) can lead to high harmonic currents and voltages. Capacitors at the entrance of most inverters in combination with the inductance of the grid lead to harmonic frequencies in the area where already some background distortion exist. The occurrence of very high harmonic voltages and currents can often be explained by the existence of these resonance effects. So the capacitance at the entrance of inverters (and other devices) has to be limited to keep resonance frequencies above proximally 1250 Hz.

PV inverters, connected to a distorted voltage, have given a malfunction, although the harmonic distortion was below the limits of the EN50160 [Ecn01]. Robustness of inverters has to be increased to improve reliability. Multiple zero-crossing due to harmonic voltages with high frequencies are mostly the problem why inverters disconnect from the grid.

Designing inverters which are more robust, with limited harmonic currents and even a positive interaction with the harmonic background voltage, is technical possible. Inverters can act as active filters, injecting harmonic current in contra phase into the grid, which decreases the harmonic current in the grid and decreases harmonic voltages. Making these types of inverters is more expensive and will only be done when it is regulated in standards so that all manufacturers have to deal with it.

### 8.2 Recommendations

As recommendations first some general remarks are made about developments needed regarding Power Quality issues. After that, some specific recommendations will be made about practical problems that should be solved. The last part of the recommendations indicates some future research which could be valuable to perform.
8.2.1 General remarks

Voltage quality is becoming an important issue in many countries, because of the sensitivity of end-use equipment and the increasing concern of grid operators, customers and regulators. In the last few years, research has highlighted the consequences in terms of costs for customers due to poor voltage quality. The most common power quality phenomenon, analysed in relation to costs is voltage dips. Nevertheless, other power quality phenomena also contribute to customer’s costs and this should be identified. At the moment voltage quality is still not adequately addressed by most regulators. Important reasons for regulating voltage quality are achieving the optimal level of quality and obtaining realistic reference levels. Only after setting requirements for the voltage (and current) quality it is possible to identify disturbing customers and therefore to adopt regulatory measures for these kinds of customers that provoke costs to both network operator and other customers connected nearby. Also, the reference levels are important to provide good basis for handling disputes both between network companies and customers, but also between network companies (e.g. transmission-distribution interface). There is a need to clear up the responsibility borders between different parties.

Before setting voltage quality standards, knowledge about the level of quality that is provided to the customers is important. Monitoring the voltage quality in the grid has to be expanded. To avoid analysing enormous amounts of data simple classification methods have to be used.

Less vague voltage quality standards will improve the customers’ rights regarding quality of supply, and will focus on the network companies’ ability to supply services and electricity with a satisfactory quality. Furthermore, current quality standards have to be developed to define the customers’ duties regarding the quality of the current on the POC.

Because dispersed generation becomes an integrated part of the low and medium voltage grid, network designers have to improve their design rules to make (certainly for new grids) the low and medium voltage networks “future-compatible” and “quality-optimal”.

8.2.2 Solving practical problems

Practical problems that need to be solved within the next years are:

- Avoid unnecessary disconnection of dispersed generation by voltage dips or voltage level. In most European countries this is an issue and looking to the
draft standard for micro cogeneration, there is not yet a reasonable compromise for the settings.

- Limit the capacity at the entrance of inverters (and devices in general) to avoid low resonance frequencies in the grid which could introduce high harmonic voltages and currents in the grid and as consequence malfunctioning of devices.
- Limit the interaction of harmonic currents of inverters (and devices in general) to harmonic background voltage to avoid a high level of harmonic distortion.
- Distinguish dip events according to the typical causes that provoke them and the consequences they may lead to. Especially for dips the rather vague ranges given (e.g. “up to several hundreds”) are not useful for customers. By using a “dip-profile” mitigation systems could be designed in a better way.
- Clarify the present level of voltage quality by monitoring and classifying the quality.
- Improve definitions of voltage quality parameters and measurement rules, searching for the widest international consensus as possible. Unique definitions are necessary in order to calculate or measure the parameters in a uniformly way.
- Develop grid design rules taking into account the most restricting issue, which could be for example flicker or protection to electric shock and make for the given grid configuration the requirements for the (other) power quality phenomena.

8.2.3 Future research

A general voltage quality and current quality framework has to be developed in which all duties and rights of all the parties should be taken into account to share the responsibility between network companies, equipment manufacturers and final customers. As a result better defined standards for devices and points of connection should be established. A sound coordination among these standards (power system-related, installation-related and device-related) is of great importance.

Further, characteristics of interaction between voltage and current (e.g. harmonic currents) should be explored, as well as minimum level of short circuit power provided by operators, in order to clearly identify responsibilities for voltage quality disturbances. Procedures and tools as well, should be considered in order to simply obtain a non controversial measure of disturbances, and as far as possible, a meaningful one for detecting responsibilities.

Due to the need of extended power monitoring programs more research could be done on data handling and transmission of power quality monitoring data.
Implementation of power quality into the operation and planning of networks requires advanced analysing tools.

Individual “Power Quality contracts” is a possibility for special customers. However, more research will be needed to quantify the benefits for customers and grid operators.
REFERENCES


[Cig02] Assessment of emission limits for the connection of disturbing installations to LV power systems. CIGRE-CIRED JWG C4.103, (Future IEC 61000-3-14).


IEC 60725, Considerations on reference impedance for use in determining the disturbance characteristics of household appliances and similar equipment, Draft technical report. (2004). : IEC.

IEC 61000-2-8, Environment - Voltage dips and short interruptions on public electric power systems with statistical measurement results, Technical report. (2002). : IEC.


[Sta05] IEC 61000-3-12: Limits for harmonic currents produced by equipment connected to public low voltage systems with input current > 16 A and < 75 A per phase. (2005). : IEC, Genevea, Switzerland.

[Sta06] IEC 61000-3-3: Limitation of voltage changes, voltage fluctuations and flicker in public low voltage power systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection. (2001). : IEC, Geneva, Switzerland.
IEC 61000-3-11: Limitation of voltage changes, voltage fluctuations and flicker in public low voltage power systems - Equipment with rated current \( \leq 75 \) A and subject to conditional connection. (2001). : IEC, Geneva, Switzerland.


IEC 61000-4-7: General guide on harmonics and interharmonics measurements and instrumentation for power supply systems and equipment connected thereto. (2002). : IEC, Geneva, Switzerland.


www.anwb.nl/auto/brandstofetikettering; energielabels voor personenautos (Dutch)

www.est.org.uk/myhome/efficientproducts/energylabels; EU Energy label

www.dispower.org; dispower project

http://microgrids.power.ece.ntua.gr; microgrid project

http://www.clusterintegration.org; overview of different integrated projects

http://www.eu-deep.com; eu-deep project

http://www.smartgrids.eu; smartgrids project
Appendix A: Classification and distribution

Appendix A1: Normal distribution

The normal distribution is a convenient model of quantitative phenomena in the natural and behavioural sciences. A variety of psychological test scores and physical phenomena have been found to follow approximately a normal distribution. While the underlying causes of these phenomena are often unknown, the use of the normal distribution can be theoretically justified in situations where many small effects are added together to give a score or variable that can be observed. The normal distribution also arises in many areas of statistics: for example, the sampling distribution of the mean is approximately normal, even if the distribution of the population from which the sample is taken is not normal. In addition, the normal distribution maximizes information entropy among all distributions with known mean and variance, which makes it the natural choice of underlying distribution for data summarized in terms of sample mean and variance. The normal distribution is the most widely used family of distributions in statistics and many statistical tests are based on the assumption of normality.

This distribution also applies to continuous measured power quality phenomena, in locations where a lot of customers are connected. The probability function of the normal distribution is shown in formula (A1) and figure A1.

\[
P_f(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)}
\]  

(A1)

Figure A1: Probability function of standard normal distribution

This so-called “standard normal distribution” shown in figure A1 is given by taking an average value \( \mu = 0 \) and a variance \( \sigma^2 = 1 \).
The cumulative distribution function (cdf) is defined as the probability that a variable \( X \) has a value less than or equal to \( x \), and it is expressed in terms of the density function as:

\[
F(x; \mu, \sigma) = \int_{-\infty}^{x} \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(t - \mu)^2}{2\sigma^2}\right) dt
\]  

(A2)

The standard normal cdf, conventionally denoted as \( \Phi \), is just the general cdf evaluated where \( \mu = 0 \) and \( \sigma = 1 \), resulting in:

\[
F(x; 0,1) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{t^2}{2}\right) dt
\]  

(A3)

Figure A2 shows this standard normal cdf. The arrows indicate that 95% of all values are beneath the average and 1.65 times the standard deviation.

![Figure A2: cdf of the standard normal distribution](image)

Every normal distribution can be converted to a standard normal distribution by changing the variables to:

\[
Z \equiv (X - \mu)/\sigma, \quad \text{so} \quad dz = \frac{dx}{\sigma}
\]

yielding to:

\[
P(x)dx = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}
\]  

(A4)

Conversely, if \( Z \equiv N(0,1) \), then

\[
X = \sigma Z + \mu
\]  

(A5)

The standard normal distribution has been tabulated and the other normal distributions are simple transformations of the standard one. Therefore, one can use
tabulated values of the cdf of the standard normal distribution to find values of the cdf of a general normal distribution

The values of the cdf can be found in table A3. As an indication, the values of the 95% (1.65) and the 99.9% (3.1) of all values are shown in colour.

| Table A3: Table of cdf of the standard normal distribution |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Z               | 0.01            | 0.02            | 0.03            | 0.04            | 0.05            |
| 0.0            | 0.500000        | 0.500000        | 0.500000        | 0.500000        | 0.500000        |
| 0.1            | 0.539824        | 0.543795        | 0.547758        | 0.551717        | 0.555670        |
| 0.2            | 0.579263        | 0.583166        | 0.587064        | 0.590954        | 0.594835        |
| 0.3            | 0.617911        | 0.621719        | 0.625616        | 0.629512        | 0.633372        |
| 0.4            | 0.655422        | 0.659097        | 0.662757        | 0.666402        | 0.670031        |
| 0.5            | 0.691462        | 0.694974        | 0.698468        | 0.701944        | 0.705402        |
| 0.6            | 0.725474        | 0.729069        | 0.732571        | 0.735963        | 0.738894        |
| 0.7            | 0.758036        | 0.761148        | 0.764238        | 0.767305        | 0.770356        |
| 0.8            | 0.788145        | 0.79103        | 0.793892        | 0.796731        | 0.799546        |
| 0.9            | 0.81594         | 0.818589        | 0.821214        | 0.823814        | 0.826391        |
| 1.0            | 0.841345        | 0.843752        | 0.846138        | 0.848495        | 0.850830        |
| 1.1            | 0.864334        | 0.866643        | 0.870762        | 0.872857        | 0.874928        |
| 1.2            | 0.88493         | 0.88686         | 0.888767        | 0.890651        | 0.892512        |
| 1.3            | 0.903199        | 0.904902        | 0.906562        | 0.908241        | 0.909877        |
| 1.4            | 0.919243        | 0.92073         | 0.922216         | 0.923641        | 0.925066        |
| 1.5            | 0.93193         | 0.934478        | 0.935744        | 0.936992        | 0.93822         |
| 1.6            | 0.945201        | 0.946301        | 0.947384        | 0.948449        | 0.949497        |
| 1.7            | 0.955435        | 0.956367        | 0.957284        | 0.958185        | 0.959071        |
| 1.8            | 0.96407         | 0.964852        | 0.965621        | 0.966375        | 0.967116        |
| 1.9            | 0.971284        | 0.971933        | 0.972571        | 0.973197        | 0.973831        |
| 2.0            | 0.977275        | 0.977784        | 0.978308        | 0.978822        | 0.979325        |
| 2.1            | 0.982136        | 0.982571        | 0.982997        | 0.983414        | 0.983823        |
| 2.2            | 0.986907        | 0.986447        | 0.986791        | 0.987126        | 0.987455        |
| 2.3            | 0.989276        | 0.989556        | 0.98983         | 0.990097        | 0.990358        |
| 2.4            | 0.991982        | 0.992204        | 0.992425        | 0.992664        | 0.992857        |
| 2.5            | 0.995379        | 0.995936        | 0.996132        | 0.996297        | 0.996457        |
| 2.6            | 0.995547        | 0.995803        | 0.996031        | 0.99618         | 0.996345        |
| 2.7            | 0.996533        | 0.996663        | 0.996833        | 0.996928        | 0.997071        |
| 2.8            | 0.997445        | 0.997523        | 0.997699        | 0.997744        | 0.997882        |
| 2.9            | 0.998134        | 0.998613        | 0.998625        | 0.998805        | 0.998811        |
| 3.0            | 0.998658        | 0.998694        | 0.998736        | 0.998773        | 0.998817        |
| 3.1            | 0.999032        | 0.999064        | 0.999096        | 0.999126        | 0.999155        |
| 3.2            | 0.999313        | 0.999336        | 0.999359        | 0.999381        | 0.999402        |
| 3.3            | 0.999517        | 0.999533        | 0.999566        | 0.999596        | 0.999617        |
| 3.4            | 0.999663        | 0.999675        | 0.999687        | 0.999698        | 0.999709        |
| 3.5            | 0.999767        | 0.999778        | 0.999789        | 0.999807        | 0.999816        |
| 3.6            | 0.999841        | 0.999847        | 0.999853        | 0.999858        | 0.999864        |
| 3.7            | 0.999892        | 0.999896        | 0.99990  | 0.999904        | 0.999908        |
| 3.8            | 0.999928        | 0.999933        | 0.999936        | 0.999939        | 0.999943        |
| 3.9            | 0.999952        | 0.999954        | 0.999956        | 0.999958        | 0.999959        |
| 4.0            | 0.999968        | 0.99997  | 0.999971        | 0.999972        | 0.999973        |

-191-
Appendix A2: Classification of THD and unbalance

The classification of voltage magnitude variations and flicker is described in chapter 2. All other phenomena which can be measured continuous can be translated in the same classification. By using the formula for normalising (2.1) the borders for the specific phenomena can be calculated and the classification can be made. Figure A3 shows the classification for the THD with a limit of 8% (for low and medium voltage grids in the Netherlands) with some LV measuring results as example. Figure A4 shows the classification for unbalance with a limit according the national Dutch grid code of 2%.

![Figure A3: Classification of THD](image)

![Figure A4: Classification of unbalance](image)
Appendix B: Dip calculations

B1: The low voltage grid

To analyse possible dips we start at the end of the grid, looking at the results of a short circuit in the low voltage grid. Figure B1 shows a model of the grid, used for calculations. The estimated short circuit power on the MV side is 50 MVA. In the grid three different cross-sections are used.

![Figure B1: Model of the low voltage grid](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>$R$</th>
<th>$X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV-grid</td>
<td>0.32 mΩ</td>
<td>3.18 mΩ</td>
</tr>
<tr>
<td>Transformer</td>
<td>4.6 mΩ</td>
<td>15.3 mΩ</td>
</tr>
<tr>
<td>50 mm$^2$ Al</td>
<td>0.067 Ω/km</td>
<td>0.085 Ω/km</td>
</tr>
<tr>
<td>95 mm$^2$ Al</td>
<td>0.333 Ω/km</td>
<td>0.082 Ω/km</td>
</tr>
<tr>
<td>150 mm$^2$ Al</td>
<td>0.214 Ω/km</td>
<td>0.079 Ω/km</td>
</tr>
</tbody>
</table>

Figure B1 shows the value of the short circuit current in relation to place where the fault occurs along the outgoing cable. The short circuit current decreases as the fault occurs at further away along the cable. This means that the remaining voltage at the low voltage busbar in the transforming substation will increase as the short circuit takes place further away along the cable.
The short circuit current is calculated with the formula:

\[
I_{sc} = \frac{U_L / \sqrt{3}}{\sqrt{(R_s + R_c)^2 + (X_s + X_c)^2}}
\]  

(B1)

Where:

- \(R_s\) = resistant of the source (MV grid and transformer)
- \(R_c\) = resistant of the cable
- \(X_s\) = inductance of the source (MV grid and transformer)
- \(X_c\) = inductance of the cable
- \(U_L\) = the line voltage (the voltage between active phases, assumed to be 400 V)

The values for the remaining voltage on the MV side of the transforming substation and the low voltage side of the transforming substation (The PCC in figure B3) can be estimated with [Bol01]:

\[
U_{dip} = \frac{Z_F}{Z_s + Z_F} U_{nom}
\]  

(B2)

Where:

- \(U_{dip}\) = remaining voltage
- \(Z_s\) = total impedance in the short circuit
- \(Z_i\) = impedance before the location where \(U_{dip}\) is calculated

-194-
The results of calculation with power factory are shown in figure B4 and B5. In general the following conclusions can be drawn:

- Only 10% of the short circuits in low voltage cables will lead to dips at the MV bar of the transforming substation.
- Around 90% of short circuits in low voltage cables will lead to dips at the LV busbar of the transforming substation.

So, short circuits in low voltage cables often lead to a voltage dip at the POC of customers connected to the same transformer and always lead to an interruption for customers connected to the same feeder.
B2: The medium voltage grid

To analyse voltage dips occurring in a medium voltage grid, we start with a general medium voltage grid as (partially) shown in figure B6.

The medium voltage grid in the Netherlands is mostly a meshed grid, but operated radial. The average number of transforming substations on a medium voltage feeder is around ten and the average number of feeders on a substation around twenty. In the example shown in figure B6 we can see:

- Two feeders which can be connected, but are operated radial (opening of the ring at busbar 10).
- Only one protection device at the beginning of the feeder (box).
- The distance between the transforming substations is taken as 2 km.
Another common option is the medium voltage grid as shown in figure B7. At the beginning of the feeder a coil is mounted, with an inductance of 0.3 Ω. Furthermore, an additional protection device is implemented in the middle of the feeder. The protection settings of the circuit breakers are given in figure B8.

![Figure B7: Medium voltage grid with coil and second protection device](image)

For the dip calculation, the impedances of the grid (cable and coil) and the short circuit power at the main substation have to be known. Also the failure rate of the grid is needed in order to find the number of dips. For this example, the following estimations are made:

- Short circuit power at main substation: 500 MVA
- Impedance MV cable (2 km): $R = 0.25 \, \Omega$, $X = 0.17 \, \Omega$
- Failure rate of cable 2.5/100 km/year which is the average value in the Dutch grid [Wol01]

The source impedance at the main substation can be calculated as:

$$Z_s = \frac{U_L^2}{S_{sc}} = \frac{10.000^2}{500 \cdot 10^6} = 0.2 \, \Omega$$

$$X_s = 0.995 \cdot 0.2 \approx 0.2 \, \Omega$$

$$R_s = 0.1X = 0.02 \, \Omega$$

Where $U_L$ again is the line voltage.

For this example the short circuit current at the end of each cable is calculated using formula (B1) and the short circuit power at each transforming substation, using the following formulae:

---

10 This ratio between $X$ and $R$ of the source impedance is commonly used in practice as an average value. On places where the short circuit power is lower than 100 MVA a higher $R/X$ ratio should be used.
\[ S_{sc} = U_L \cdot \sqrt{3} \cdot I_{sc} \]  

(B4)

with \( R_c \) and \( X_c \) being the cable impedances up to the substation for which the calculations are made.

The dip magnitudes at the transforming substations can be calculated by using formula (B2).

Where:

- \( Z_S \) = the source impedance from generator or external network to busbar 0
- \( Z_F \) = the short circuit fault impedance from busbar 0 to fault location.
- \( U_{nom} \) = the source nominal voltage

Voltages dips can also conveniently be expressed in terms of short circuit powers (fault levels). For a nominal line voltage \( U_L \), the short circuit power \( S_F \) at the fault location is:

\[ S_{sc,F} = \frac{U_L^2}{Z_S + Z_F} \]  

(B5)

\( S_{sc,0} \) is the short circuit power available on busbar 0:

\[ S_{sc,0} = \frac{U_L^2}{Z_S} \]  

(B6)

The voltage dip magnitude\(^{11} \) on busbar 0 can be written as:

\[ U_{dip} = 1 - \frac{S_F}{S_0} \]  

(B7)

\(^{11}\) In addition to magnitude drops, voltage dips also cause supply voltage phase shifts. Sensitive loads such as solar panel inverters have been shown to malfunction because of phase shifts [ECN01]. If source and short-circuit impedances are written in terms of resistance and reactance,

\[ Z_S = R_s + jX_s \]
\[ Z_F = R_f + jX_f \]

the phase shift on busbar 0 can be written as

\[ \Delta \phi = \arctan \left( \frac{X_f}{R_f} \right) - \arctan \left( \frac{X_s + X_f}{R_s + R_f} \right) \]
Figure B8 shows the short circuit current at the main substation and each transforming substation. Also, the settings of the protection devices are given in this figure. This information is needed to establish the duration of the dip.

![Figure B8: Short circuit current at each transforming substation in the grid](image)

In figure B9 the short circuit power at each transforming substation is given.

For the calculation of the dips we assume a short circuit at the end of each cable section of 2 km, with a failure rate of 0.05 each year (using the average failure rate of 2.5/100 km/year). All the calculations are listed in table 4.2, with the columns representing the following data:

- **Column 1:** The number of the substation.
- **Column 2:** The resistance in the short circuit for a fault in the given substation.
- **Column 3:** The inductance in the short circuit for a fault in the given substation.
- **Column 4:** The impedance in the short circuit for a fault in the given substation.
- **Column 5:** The short circuit current for a short circuit in the given substation.
- **Column 6:** The short circuit power in the given substation.
- **Column 7:** The remaining voltage at the substation (number 0).
- **Column 8:** The remaining voltage at substation 4, given a short circuit in the same feeder.

The remaining voltage is the voltage at the POC (busbar 4) during the short circuit. If the remaining voltage is zero due to a short circuit on the substation or due an interruption a hyphen is placed in the table.
Figure B9: Short circuit power at each transforming substation

Table B2: Calculated values in given example

<table>
<thead>
<tr>
<th></th>
<th>2: R(Ω)</th>
<th>3: X(Ω)</th>
<th>4: Z(Ω)</th>
<th>5: I(kA)</th>
<th>6: S(MVA)</th>
<th>7: V&lt;sub&gt;dp&lt;/sub&gt;(p.u.)</th>
<th>8: V&lt;sub&gt;dp&lt;/sub&gt;(p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.02</td>
<td>0.20</td>
<td>0.200</td>
<td>28.7</td>
<td>497</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>0.27</td>
<td>0.37</td>
<td>0.458</td>
<td>12.6</td>
<td>218</td>
<td>0.56</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.52</td>
<td>0.54</td>
<td>0.750</td>
<td>7.70</td>
<td>133</td>
<td>0.73</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>0.77</td>
<td>0.71</td>
<td>1.047</td>
<td>5.51</td>
<td>95</td>
<td>0.80</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>1.02</td>
<td>0.88</td>
<td>1.347</td>
<td>4.29</td>
<td>74</td>
<td>0.85</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>1.27</td>
<td>1.05</td>
<td>1.648</td>
<td>3.50</td>
<td>61</td>
<td>0.87</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>1.52</td>
<td>1.22</td>
<td>1.949</td>
<td>2.96</td>
<td>51</td>
<td>0.89</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>1.77</td>
<td>1.39</td>
<td>2.251</td>
<td>2.57</td>
<td>44</td>
<td>&gt;0.9</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>2.02</td>
<td>1.56</td>
<td>2.552</td>
<td>2.26</td>
<td>39</td>
<td>&gt;0.9</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>2.27</td>
<td>1.73</td>
<td>2.854</td>
<td>2.02</td>
<td>35</td>
<td>&gt;0.9</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>2.52</td>
<td>1.90</td>
<td>3.156</td>
<td>1.83</td>
<td>32</td>
<td>&gt;0.9</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>2: R(Ω)</th>
<th>3: X(Ω)</th>
<th>4: Z(Ω)</th>
<th>5: I(kA)</th>
<th>6: S(MVA)</th>
<th>7: V&lt;sub&gt;dp&lt;/sub&gt;(p.u.)</th>
<th>8: V&lt;sub&gt;dp&lt;/sub&gt;(p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.02</td>
<td>0.50</td>
<td>0.500</td>
<td>11.5</td>
<td>200</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>0.27</td>
<td>0.67</td>
<td>0.722</td>
<td>7.99</td>
<td>138</td>
<td>0.72</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.52</td>
<td>0.84</td>
<td>0.988</td>
<td>5.84</td>
<td>101</td>
<td>0.79</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>0.77</td>
<td>1.01</td>
<td>1.270</td>
<td>4.55</td>
<td>79</td>
<td>0.84</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>1.02</td>
<td>1.18</td>
<td>1.560</td>
<td>3.70</td>
<td>64</td>
<td>0.87</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>1.27</td>
<td>1.35</td>
<td>1.853</td>
<td>3.11</td>
<td>53</td>
<td>0.89</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>1.52</td>
<td>1.52</td>
<td>2.150</td>
<td>2.69</td>
<td>47</td>
<td>&gt;0.9</td>
<td>0.27</td>
</tr>
<tr>
<td>7</td>
<td>1.77</td>
<td>1.69</td>
<td>2.447</td>
<td>2.36</td>
<td>41</td>
<td>&gt;0.9</td>
<td>0.36</td>
</tr>
<tr>
<td>8</td>
<td>2.02</td>
<td>1.86</td>
<td>2.746</td>
<td>2.10</td>
<td>36</td>
<td>&gt;0.9</td>
<td>0.43</td>
</tr>
<tr>
<td>9</td>
<td>2.27</td>
<td>2.03</td>
<td>3.045</td>
<td>1.90</td>
<td>33</td>
<td>&gt;0.9</td>
<td>0.49</td>
</tr>
<tr>
<td>10</td>
<td>2.52</td>
<td>2.20</td>
<td>3.345</td>
<td>1.73</td>
<td>30</td>
<td>&gt;0.9</td>
<td>0.53</td>
</tr>
</tbody>
</table>
The first 10 rows are for the situation without coils and without second protection device. In this situation every dip calculated will occur in 19 feeders on a substation (not in the feeder with the short circuit because of the fact that this feeder will be switched off). So, the amount of dips on busbar 4 for the used POC is 0.05 multiplied by 19, which are 0.95 dips/year. A short circuit at the end of the cable to transforming substation 1 will lead to a remaining voltage of between 50-60% of the nominal voltage. A short circuit at the end of the cable to station 2 will lead to a remaining voltage of between 70-80% of the nominal voltage. All short circuits at station 3, 4, 5 and 6 will result in a remaining voltage of between 80-90% of the nominal voltage. All these short circuits will be disconnected by protection device 1, in a disconnection time of 0.3 s. Table B3 shows the number of dips in the MV grid, without a coil and without a second protection device.

Table B3: Number of dips due to short circuits in MV grid without coil and without second protection device

<table>
<thead>
<tr>
<th>kV</th>
<th>0.01-0.02</th>
<th>0.02-0.1</th>
<th>0.1-0.5</th>
<th>0.5-1</th>
<th>1-2</th>
<th>2-5</th>
<th>5-10</th>
<th>10-20</th>
<th>20-60s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>0.8</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
</tr>
</tbody>
</table>

The same kind of calculation can be made for the situation with coil and with a second protection device. The advantage of the coil is limiting the short circuit current and therefore reducing the depth of the dip. The protection device improves the reliability of the grid, but has some disadvantages in terms of dips. For instance a short circuit at transforming substation 5 will lead to a deep dip at transforming substation 4. Again, a short circuit in the first 5 stations of the 19 parallel feeders will be seen as a dip in all feeders except the faulted feeder. A short circuit in the stations after the second protection device will be seen as a deep dip in the sound part of the faulted feeder. The result of the calculation of the situation with coil and second protection device are summarized in table B4.

The disadvantages of the second protection device on the dip phenomena are clearly shown. The duration of the dips is higher, due to the necessary selectivity of the two protection devices in series. Furthermore, there are a number of dips which will be very deep, occurring with a short circuit in the same feeder as the station under consideration.
Faults in the MV grid can be divided in three groups of faults with the given occurrence [Pro01]:

- 25%: three phases to earth faults
- 25%: two phases to earth faults
- 50%: one phase to earth faults

It is important to study how these faults (and the corresponding dip) transfer to the LV side, because this is the place where most devices are connected to.

**Two phases to ground faults**

A two phases to ground fault causes an asymmetric short circuit current. Therefore, a voltage dip due to a two phases to ground fault will also have an asymmetric characteristic. An equivalent circuit for a two phases to ground fault using symmetrical components is shown in figure B10.

**Figure B10: Symmetrical components decomposition of a two phases to ground fault**
Source and fault impedances are dependent on grid components and short circuit conditions. The phase voltages $V_A$ to $V_C$ for a fault between phases B, C and ground can be assumed that $E=1$ (per unit value of nominal voltage) now be written as [Bol01]:

$$V_A = 1 + \frac{(Z_{s2} - Z_{s1})(Z_{s0} + Z_{f0})}{D} + \frac{(Z_{s0} - Z_s)(Z_{s2} + Z_F)}{D} \quad (B8)$$

$$V_B = a^2 + \frac{(Z_{s0} + Z_{f0})(aZ_{s2} - a^2Z_{s1})}{D} + \frac{(Z_{s2} + Z_{f2})(Z_{s0} - a^2Z_{s1})}{D} \quad (B9)$$

$$V_C = a + \frac{(Z_{s0} + Z_{f0})(a^2Z_{s2} - aZ_{s1})}{D} + \frac{(Z_{s2} + Z_{f2})(Z_{s0} - aZ_{s1})}{D} \quad (B10)$$

In which:

$$D = (Z_{s0} + Z_{f0})(Z_{s1} + Z_{f1} + Z_{s2} + Z_{f2}) + (Z_{s1} + Z_{f}) (Z_{s2} + Z_{f}) \quad (B11)$$

The non-faulted phase voltage $V_A$ depends on the differences between the negative and positive sequences of the source impedance and the zero and positive sequences of the cable impedances. Since the modelled zero sequence impedance is larger than the positive sequence impedance, a two phase to ground fault between phases B and C will cause an over-voltage in phase A.

All impedances depend on the short circuit distance. The phase voltages of phases A to C on the MV busbar as a function of short circuit distance are depicted in figure B11. As expected, phase A is subject to a serious over-voltage with a magnitude ranging from 1.4 to 1.5 p.u.
Dips on the MV busbar do not necessarily result in unacceptable dips at the end-user terminal. Since end-users in the Dutch situation, are mostly connected to the MV grid by a Dy5 transformer, only dips in MV line voltages will be transferred to the lower voltage level. To illustrate this, a vector plot of the phase voltages on the MV busbar as well as on the end-user terminal is shown in figure B12. Simulation results of LV phase voltages are plotted in figure B13.

As expected, only an end-user connected to phase b experiences a voltage dip in the case of a two phases to ground short circuit. Evidently, two phases to ground faults occurring at a distance greater than ten kilometres from the substation do not result in unacceptable voltage dips experienced by an end-user.

Figure B11: MV dip magnitude due to two phases to ground faults

Figure B12: Vector plot of two phases to ground short circuit.
Figure B13: LV dip magnitude due to 2 phase ground faults

Single phase to ground faults

Single phase to ground faults only cause dips of a serious magnitude in the case of a grounded grid. Figure B14 shows the decomposition of an equivalent circuit using symmetrical components. The faulted phase is A.

Figure B14: One phase to ground fault symmetrical components decomposition

The phase voltages expressed in positive, negative and zero-sequence impedances are obtained using:

$$V_A = 1 - \frac{Z_{S1} + Z_{S2} + Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \quad \text{(B12)}$$
According to (4.10) the faulted phase is subject to a serious reduction in voltage. Less straightforward is the voltage behaviour in the non-faulted phases. In general, phases B and C maintain their original positions, as indicated by the $a^2$ and $a$ values respectively. However, a strong deviation in voltage may occur in the case of relatively high zero-sequence impedance. Normally, the positive-sequence source impedance $Z_{S1}$ and negative-sequence source impedance $Z_{S2}$ have a rather equal value. If the zero-sequence source impedance $Z_{S0}$ is considerably larger than the positive and negative-sequence source impedances, the non-faulted phase voltage increases during a single phase to ground fault. In order to clarify this, a vector plot of phase voltages $V_A$, $V_B$ and $V_C$ is depicted in figure B15.

\[
V_B = a^2 - \frac{a^2 Z_{S1} + a Z_{S2} + Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \tag{B13}
\]

\[
V_C = a - \frac{a Z_{S1} + a^2 Z_{S2} + Z_{S0}}{(Z_{F1} + Z_{F2} + Z_{F0}) + (Z_{S1} + Z_{S2} + Z_{S0})} \tag{B14}
\]

Figure B15: Vector plot of single phase to ground short circuit (green vectors are the voltages before the short circuit)

MV phase voltages as a function of single phase to ground short circuit distance are shown in figure B16.
Although single phase to ground faults result in voltage dips in the MV grid, these dips are often not experienced by an LV end-user. This is because the primary $\Delta$ winding of the end-user Dy5 transformer blocks all zero-sequence voltage components. Therefore voltage dips at MV level are not transferred to lower voltage levels.

So, the total influence of short circuits in the MV grid on the dip profile of a specific customer depends on:

- The number of feeders leaving the main substation.
- The length of feeder cables.
- The protection philosophy.
- The grid configuration (earthing, application coils).
- The failure rate of components.
- The type of faults.

All these factors make it difficult to predict the dip profile for specific customers. Nevertheless, some guidance about the number of dips, the depth and the duration can be given.
Appendix C: Impedances of cables in relation with frequency

The cable model discussed in this appendix can be used for almost all types of cables. However, it is specified for two of the most common cables used by Continuon for medium voltage and low voltage networks.

The configuration of a three-phase cable is shown in figure C1, where impedances, voltages and currents are identified.

![Figure C1: Three-phase cable with earth return](image)

In order to find symmetric impedances, all wires are grounded at the remote point a'-b'-c', which implies that:

\[
I_d = -(I_a + I_b + I_c) \quad \text{(C1)}
\]

\[
V_a - V_d = 0, \quad V_b - V_d = 0, \quad V_c - V_d = 0 \quad \text{(C2)}
\]

The voltage drop equations in the direction of the current flow are as follows:

\[
\begin{bmatrix}
V_{a'} \\
V_{b'} \\
V_{c'} \\
V_{d'}
\end{bmatrix} =
\begin{bmatrix}
I_a \\
I_b \\
I_c \\
I_d
\end{bmatrix} =
\begin{bmatrix}
Z_{aa} & Z_{ab} & Z_{ac} & Z_{ad} \\
Z_{ba} & Z_{bb} & Z_{bc} & Z_{bd} \\
Z_{ca} & Z_{cb} & Z_{cc} & Z_{cd} \\
Z_{da} & Z_{db} & Z_{dc} & Z_{dd}
\end{bmatrix}
\begin{bmatrix}
V_{a'} \\
V_{b'} \\
V_{c'} \\
V_{d'}
\end{bmatrix} \quad \text{(C3)}
\]

These equations are the “basic voltage equations” [Kad01]. The impedance of the cable is usually thought of as the ratio of the voltage to the current “looking into” the cable at one end. Therefore a voltage reference is selected at the left end of the cable and (C3) is solved for the voltages \(V_a, V_b\) and \(V_c\).

Since \(V_c = 0\), the fourth equation of (C3) is subtracted from the first:

\[
V_a - (V_d - V_a) = (Z_{aa} - 2Z_{ad} + Z_{dd})I_a + (Z_{ab} - Z_{ad} - Z_{bd} + Z_{dd})I_b + (Z_{ac} - Z_{ad} - Z_{dc} + Z_{dd})I_c \quad \text{(C4)}
\]
For convenience this result is written as:

\[ V_a = z_{aa} I_a + z_{ab} I_b + z_{ac} I_c \]  \hspace{1cm} (C5)

with newly defined impedances \( z_{aa}, z_{ab}, \) and \( z_{ac}. \)

Note that when \( I_b = I_c = 0, \) \( z_{aa} \) is exactly the impedance for a single cable with earth return. If the above operation is repeated for phases b and c, the result is:

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \begin{bmatrix}
z_{aa} & z_{ab} & z_{ac} \\
z_{ba} & z_{bb} & z_{bc} \\
z_{ca} & z_{cb} & z_{cc}
\end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix}
\]  \hspace{1cm} (C6)

where it is noted that \( z_{ba} = z_{cb}, \) due to reciprocity of the mutual impedances. The impedance elements of (C6) and (C2) relate to each other as:

**Self impedances:**

\[
z_{aa} = Z_{aa} - 2Z_{ad} + Z_{dd}
\]

\[
z_{bb} = Z_{bb} - 2Z_{bd} + Z_{dd}
\]

\[
z_{cc} = Z_{cc} - 2Z_{cd} + Z_{dd}
\]  \hspace{1cm} (C7)

**Mutual impedances:**

\[
z_{ab} = Z_{ab} - Z_{ad} - Z_{bd} + Z_{dd}
\]

\[
z_{bc} = Z_{bc} - Z_{ad} - Z_{bd} + Z_{dd}
\]

\[
z_{ac} = Z_{ac} - Z_{ad} - Z_{cb} + Z_{dd}
\]  \hspace{1cm} (C8)

To examine these impedances further the elements of the matrix in (C6) are split up into their real and imaginary parts. These impedances will be called the basic impedances

**Basic self impedances:**

\[
z_{aa} = R_a + j\omega L_a
\]

\[
z_{bb} = R_b + j\omega L_b
\]

\[
z_{cc} = R_c + j\omega L_c
\]

\[
z_{dd} = R_d + j\omega L_d
\]  \hspace{1cm} (C9)
Basic line-to-line mutual impedances:
\[ z_{ab} = j\omega L_{ab} \]
\[ z_{bc} = j\omega L_{bc} \]
\[ z_{ca} = j\omega L_{ca} \]  

(C10)

Basic line-to-earth mutual impedances:
\[ z_{ad} = j\omega L_{ad} \]
\[ z_{bd} = j\omega L_{bd} \]
\[ z_{cd} = j\omega L_{cd} \]  

(C11)

This leads to:
\[ z_{aa} = (R_a + R_d) + j\omega(L_a - 2L_{ad} + L_d) \]
\[ z_{bb} = (R_b + R_d) + j\omega(L_b - 2L_{bd} + L_d) \]
\[ z_{cc} = (R_c + R_d) + j\omega(L_c - 2L_{cd} + L_d) \]  

(C12)

To acquire an impedance matrix for each harmonic up to the 50th according to formula (C6), a single-phase current injection is applied as shown in figure C2.

**Figure C2: Cable model with current injection phase a and d**

Voltages \( V_{a}, V_{b}, V_{c}, \) and current \( I_{c} \) are recorded in a measurement with an injection of a sine waveform current for each harmonic. Self and mutual impedance at order \( h \) for phase a are calculated as follows:

\[ z_{h,aa} = \left. \frac{V_{h,ad}}{I_{h,a}} \right|_{I_{h}=I_{c}=0} \]
\[ z_{h,ba} = \frac{V_{h,bd}}{I_{h,a}} \bigg|_{I_y=I_z=0} \]

\[ z_{h,ca} = \frac{V_{h,cd}}{I_{h,a}} \bigg|_{I_y=I_z=0} \]

This is repeated for a current injection under B and C until the entire matrix is known. The measurement setup used for this measurement is displayed in figure C3.

Figure C3: Measurement setup for determining cable characteristics

The measurement results are split up into the results for the medium voltage cable and the low voltage cable. In this thesis only the final results are given in chapter 5. More information can be found in [Hoo01].
Appendix D: Bronsbergen micro grid

Figure D1 shows the holiday park with the cottages.

![Micro grid site](image)

**Figure D1:** The micro grid site.

Figure D2 shows some photos of holiday houses with PV system installed on the roof.

A programme started in June 2005 to monitor all power quality aspects in the low voltage grid. PQ measuring devices were placed in the four outgoing feeders and on the low voltage side of the transformer. During this period the active and reactive power across the feeding transformer was measured, mainly to develop the storage system for the micro grid situation. Furthermore measured data gives information about all power quality phenomena on the low voltage side of the transformer (see photos, figure D3).

Figure D4 shows the configuration used to make the calculation in the Bronsbergen micro grid. There are four LV feeders. All loads and PV systems of three LV feeders are lumped as one total POC. One LV feeder is modelled, where several of the houses (loads and PV systems) are lumped across the length of the cable.

The autonomous working micro grid will be realised during the coming years and the project will be finished and evaluated in 2010. It will be made for research purposes only, because there is no specific need to improve the average interruption time of around 28 minutes/year and the average interruption frequency of 0.33/year.

For holiday houses there is no need to improve the quality of supply. This site was chosen as location for a micro grid only because of the PV-systems had already been
installed and because of the willingness to cooperate and interest in renewable energy of the owners of the park.

Figure D2: Some of the houses with PV systems

Figure D3: PQ-measurement devices installed in the substation
Figure D4: model used for calculations in Bronsbergen micro grid
Appendix E: Abbreviations and symbols

Abbreviations

AC Alternating current
AFE Active Front End
CENELEC European Committee for Electrotechnical Standardisation
CFL Compact Fluorescent Lamp
CHP Combined Heat Power
CVT Constant Voltage Transformer
DG Dispersed Generation
DTE Dienst Toezicht Energie (national Dutch Regulator)
DVR Dynamic Voltage Restorer
EMC Electric Magnetic Compatibility
EMF Electric Magnetic Force
EPRI Electric Power Research Institute, USA
HV High Voltage
IEC International Electrotechnical Committee
IOP Innovatief Onderzoeks Programma (Initiative Research Program)
ITIC Information Technology Industry Council
LPQI Leonard Power Quality Initiative
LV Low Voltage
MV Medium Voltage
PC Personal Computer
PCC Point of Common Coupling
PFC Power Factor Correction
POC Point Of Connection
PQ Power Quality
PVC Polyvinylechloride
RMS Root Mean Square
SARFI System Average RMS Variation Frequency Index
SMES Superconducting Magnetic Energy Storage
SMPS Switch Mode Power Supply
STAV Standard Average
THD Total Harmonic Distortion
UNIPEDE International Union of Producers and Distributors of Electric Energy
UPS Uninterruptible Power Supply
XLPE Cross linked Polyethylene
Symbols

\begin{align*}
C & = \text{capacitance} \\
C_i & = \text{capacitance inverter} \\
C_{\text{ref}} & = \text{capacitance corresponding to nominal voltage} \\
dc & = \text{relative steady-state voltage change} \\
p_{\text{dc}} & = \text{the maximum relative voltage change} \\
E & = \text{voltage per unit, nominal voltage defined as 1} \\
F & = \text{shape factor of voltage variation} \\
f & = \text{frequency} \\
f_{\text{res}} & = \text{resonance frequency} \\
G & = \text{conductance} \\
G_{\text{ref}} & = \text{conductance corresponding to nominal voltage} \\
I & = \text{current} \\
I_{\text{eq}} & = \text{current equipment} \\
I_{\text{sc}} & = \text{short circuit current} \\
l & = \text{compatibility level of phenomena} \\
L & = \text{inductance} \\
m & = \text{the actual level of phenomena} \\
N & = \text{number of customers, connection, systems, harmonics or other discontinuous occurrences} \\
P & = \text{active power} \\
P_{\text{lt}} & = \text{long term flicker severity} \\
P_{\text{p}} & = \text{chance of occurrence} \\
P_{\text{s}} & = \text{short term flicker severity} \\
PWHD & = \text{partial weighted harmonic distortion} \\
Q & = \text{reactive power} \\
r & = \text{the normalised power quality aspect} \\
R & = \text{resistant} \\
r & = \text{repetition rate per minute} \\
RMSE & = \text{mean square root of the error} \\
R_{\text{sc}} & = \text{short circuit ratio} \\
S & = \text{short circuit power} \\
SST & = \text{sum of squares of the regression} \\
SST & = \text{sum of squares around the average} \\
T & = \text{transformation ratio or transfer ratio} \\
THD_{\text{i}} & = \text{total harmonic distortion current} \\
THD_{\text{u}} & = \text{total harmonic distortion voltage} \\
U & = \text{voltage} \\
U_{\text{c}} & = \text{declared voltage or contracted voltage} \\
U_{\text{dp}} & = \text{remaining voltage}
\end{align*}
\(U_L\) = line voltage
\(U_{nom}\) = nominal voltage
\(U_p\) = phase (to neutral) voltage
\(V\) = voltage per unit
\(V_{dip}\) = remaining voltage per unit
\(X\) = reactance
\(X\) = normal distribution variable
\(x\) = normal distribution value
\(Y\) = standard normal distribution variable
\(Z\) = impedance
\(Z_0\) = impedance at resonance frequency
\(\sigma\) = standard deviation within given distribution

Index

\(PV\) = photovoltaic
\(g\) = grid
\(MV\) = medium voltage
\(LV\) = low voltage
\(T\) = transformer
\(b\) = harmonic order
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Sjef Cobben
List of publications

Curriculum vitae

Sjef Cobben was born in Nuth, Netherlands, in 1956. He received the Bachelors degree in Electrical Engineering from the Technical University of Heerlen in 1979. In 2002 he received the Masters degree in Electrical Engineering from Eindhoven, University of Technology (TU/e).

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