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The DC low-voltage house

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Samenvatting

Fotovoltaïsche (PV) systemen in de woningbouw worden in de Westerse wereld vooral toegepast in combinatie met een aansluiting op het publieke elektriciteitsnet. De door zonnecellen opgewekte gelijkstroom wordt omgevormd naar de vertrouwde wisselstroom. Hierdoor is een koppeling met het elektriciteitsnet mogelijk en kan huishoudelijke apparatuur zonder problemen gebruikt worden.

Veel huishoudelijke apparatuur werkt echter intern op gelijkstroom. In deze apparatuur wordt de aangeboden wisselspanning van ongeveer 230 V omgezet naar een lage gelijkspanning, bijvoorbeeld 12 V. Het benutten van PV energie vereist in dit geval twee conversiestappen, die beide verliezen opleveren. Deze verliezen kunnen mogelijk voorkomen worden door het gebruik van een gelijkstroom-laagspanningsnet. Dit rapport gaat over de haalbaarheid van 'De gelijkstroom-laagspanningswoning' binnen vooraf bepaalde randvoorwaarden.

Het onderzoek heeft zich eerst gericht op het elektriciteitsverbruik door huishoudens. Een overstap naar voeding met gelijkstroom van huishoudelijke apparatuur is mogelijk, maar blijkt niet automatisch voor besparingen te zorgen.

Het tweede deel van het onderzoek heeft zich gericht op het gelijkstroom-laagspanningsnet. De gewenste lage systeemspanning veroorzaakt een probleem. Door spannings- en vermogensverliezen is het niet mogelijk om te voldoen aan de huidige vermogensvraag in huishoudens. Andere problemen die zich aandienen bij de realisatie van een gelijkstroom-laagspanningsnet zijn het schakelen van gelijkstroom en het begrenzen van kortsluitstromen.

De resultaten van de eerste twee delen van het onderzoek zijn gebruikt voor een vergelijking van een wisselstroom- en gelijkstroomwoning. Er wordt vastgesteld dat toepassing van gelijkstroom op laagspanningsniveau in 'Westerse' woningen niet veelbelovend is. In hiervan afwijkende situaties kan gelijkstroom echter wel interessant zijn. Voorbeelden van dergelijke situaties zijn: een afgelegen woning met een kleine vermogensvraag, de aanwezigheid van een gelijkstroomnet op wijkniveau en de voeding van bepaalde gebruikersgroepen met gelijkstroom.

Abstract

The use of photovoltaic (PV) energy in buildings is usually associated with a connection to the public electricity grid. The grid connection requires a conversion from direct current (DC) to alternating current (AC). This conversion enables both the use of standard AC household equipment and a connection to the public electricity grid.

Many household appliances, however, function internally on DC. Within the AC equipment an alternating voltage of about 230 V is transformed to a (low) DC voltage, for example 12 V. Utilising PV energy in this way involves two energy conversions with inherent energy losses. It is reasonable therefore to assume that these losses could be avoided by introducing a DC (low-voltage) grid. The feasibility of 'The DC low-voltage house' set within predefined boundary conditions is the subject of this report.

The first part of the research has focused on household energy consumption. It became apparent that DC supply of household appliances is possible, but does not automatically reduce energy losses.

The second part of the research concentrates on the DC low-voltage distribution system. It became clear that due to voltage and power losses, it will not be possible to satisfy the present power demand in households with a very low voltage distribution system. The main problems to be overcome in the design of the DC low-voltage distribution system are: switching of DC currents and limitation of short circuit currents.

The results of the first two parts of the research lead to conclusions on the feasibility of the DC low-voltage house. Observing the boundary conditions of the project, a change from AC to DC low-voltage in houses is not very promising. A large reduction of energy losses is not expected. Taking other conditions and circumstances into consideration (for example: a very small power demand, the presence of a public DC electricity grid and the supply of certain types of appliances), may lead to a more positive assessment of the DC low-voltage house.

Contents

APPENDICES

1. INTRODUCTION

The use of photovoltaic (PV) energy in buildings is usually associated with a connection to the public electricity grid. The grid connection requires a conversion from direct current (DC) to alternating current (AC). This conversion enables both the use of standard AC supplied household equipment and a connection to the public electricity grid.

Many household appliances however work internally on DC. Within the AC equipment an alternating voltage of about 230 V is transformed to a (low) DC voltage, for example 12 V. Utilising PV energy in this way involves two energy conversions with inherent energy losses. It is reasonable therefore to assume that these losses can be avoided by introducing a DC (low-voltage) grid. The feasibility of 'The DC low-voltage house' set within predefined boundary conditions is the subject of this graduation project.
The following questions should be posed:

- How effective is the installation of a PV supplied DC low-voltage network in domestic dwellings and what are the consequences?
- Does a change from AC to DC really reduce the envisaged energy losses in a PV powered system?

This report addresses these questions through a structured approach to the problems involved. The following items and issues have been discussed:

- background of the project, partners involved, general consideration on PV systems and on AC and DC power distribution (chapter 2);
- project structure, i.e. target groups, targets, project organisation, feasibility assessment criteria and boundary conditions (chapter 3).

An important factor in this evaluation is the energy consumption for an average family using modern appliances. To what extent can a DC supply satisfy domestic energy consumption and what are the consequences of installing a DC supply? Related topics such as power demand and availability of DC household appliances will also be discussed (chapter 4).

Having established a clear view of the electricity demand for an average household, including some energy conservation measures, different aspects of the electrical installation of the DC low-voltage house are considered. Theoretical aspects, a layout for the DC low-voltage grid, safety aspects and protection are then discussed (chapters 5, 6 and 7).

The feasibility of the DC low-voltage house is then assessed against the predefined criteria (chapter 8). The outcome of the feasibility assessment is strongly influenced by the predefined boundary conditions. Different boundary conditions lead to other findings on the feasibility of the DC low-voltage house (chapter 9).

The results of the research into the different features of the DC low-voltage house and the assessment of the feasibility are combined in conclusions and recommendations for further research (chapter 10).

2. BACKGROUND

2.1 Partners involved: ECN and TUE

The Netherlands Energy Research Foundation ECN is the leading institute for energy research in the Netherlands. ECN carries out basic and applied research in the fields of nuclear energy, fossil fuels, renewable energy sources, policy studies, environmental aspects of energy supply and the development and application of new materials.

One of the business units of ECN is the unit Renewable Energy. Renewable Energy carries out research in the area of renewable energy sources: solar, wind and biomass. The research into solar energy focuses on photovoltaic conversion and its applications, either as stand-alone systems or grid-connected systems. The emphasis is on technological development, which is set by the requirements of the (Dutch) manufacturing industry and utilities.

A complementary aspect is the research on renewable energy in the urban environment. In this 'demand side sector' it appears to be relatively easy to introduce renewable energy on a large scale. An example is the integration of the use of solar energy in buildings.

The ECN project 'The DC low-voltage house' originates from research to optimise the integration of PV systems in the urban environment. The project 'The DC low-voltage house' was initiated by the unit Renewable Energy and carried out by its group PV systems. The project has been carried out at ECN as a graduation project for a Master's degree at the Eindhoven University of Technology (TUE).

The graduation project was supervised by the Electrical Power Engineering group (EVT) of the department of Electrical Engineering at the TUE. The research group of Power Engineering (EG) concentrates its efforts in the field of power transmission, and distribution systems, emphasising the aspects of reliability, security and continuity. The areas in which the Power Engineering group is active include:

- analysis of transient phenomena in power systems;
- computerisation of power system protection;
- current interruption processes in switching components;
- material characteristics under high currents and voltages;
- high-voltage technology for industrial applications;
- discharge and insulation in vacuum, gases and solids;
- broad bandwidth sensors for measuring rapid phenomena;
- electromagnetic compatibility.

It should be clear that researchers with different disciplines contribute to the project 'The DC low-voltage house', including electrical engineers, civil engineers and building contractors. This report has been written for electrical engineers as well as non-electrical engineers. Therefore basic electrical rules will be discussed and simple theories will be explained. More detailed explanation is given in appendices in order to restrict the main text of this report to a manageable size.

2.2 PV systems

PV systems are solar energy conversion systems, which either supply electrical power directly to electrical equipment or feed energy into the public electricity grid. The power range extends from tens of W to several MW [1].

PV systems can be divided in two main categories:
1. grid-independent and
2. grid-connected.

Larger grid-independent or remote solar power supplies are also called stand-alone or autonomous systems [2], [3]. A typical example of the second category is a system with solar modules installed on house roofs, which is connected to the public electricity grid via a suitable converter [4], [5], [6], [7], [8].

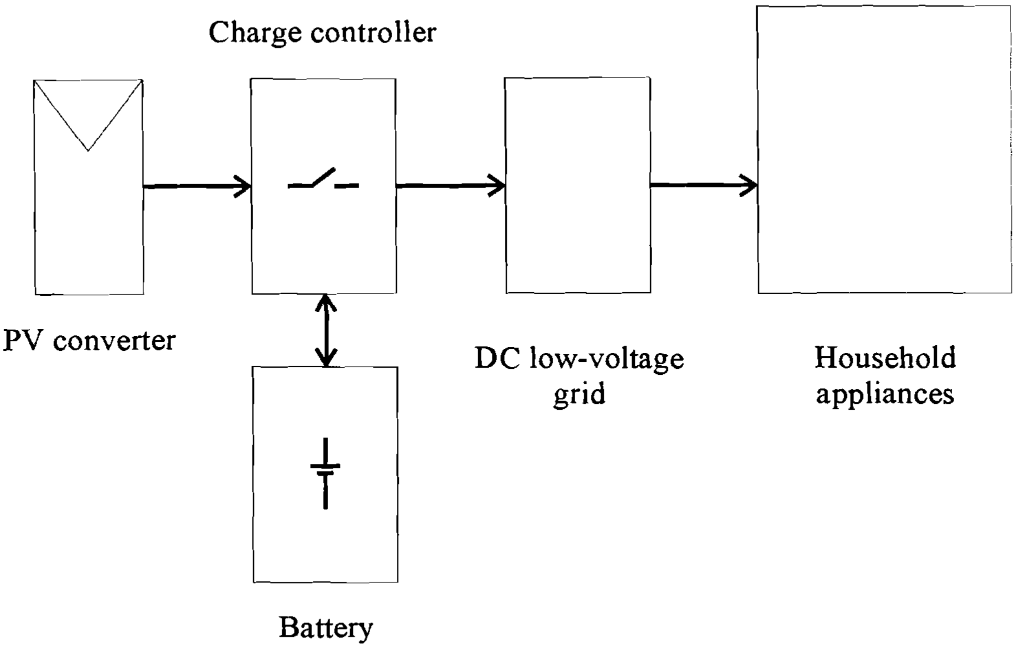


Figure 2.1: An autonomous DC low-voltage house.

A house which receives all or most of its electrical energy from solar modules installed on the roof is called a PV house. PV houses can be grid-connected or grid-independent (stand-alone). Most PV systems on Western European houses are grid connected. The project 'The DC low-voltage house' will, in the first place, concentrate on stand-alone PV houses. Figures 2.1 and 2.2 give the block diagrams of two possible implementations of a stand alone PV house. Figure 2.1 shows a stand-alone system with a DC grid: an autonomous DC low-voltage house. Figure 2.2 illustrates a house with an AC distribution system between the stand-alone PV system and the load: an autonomous AC house.

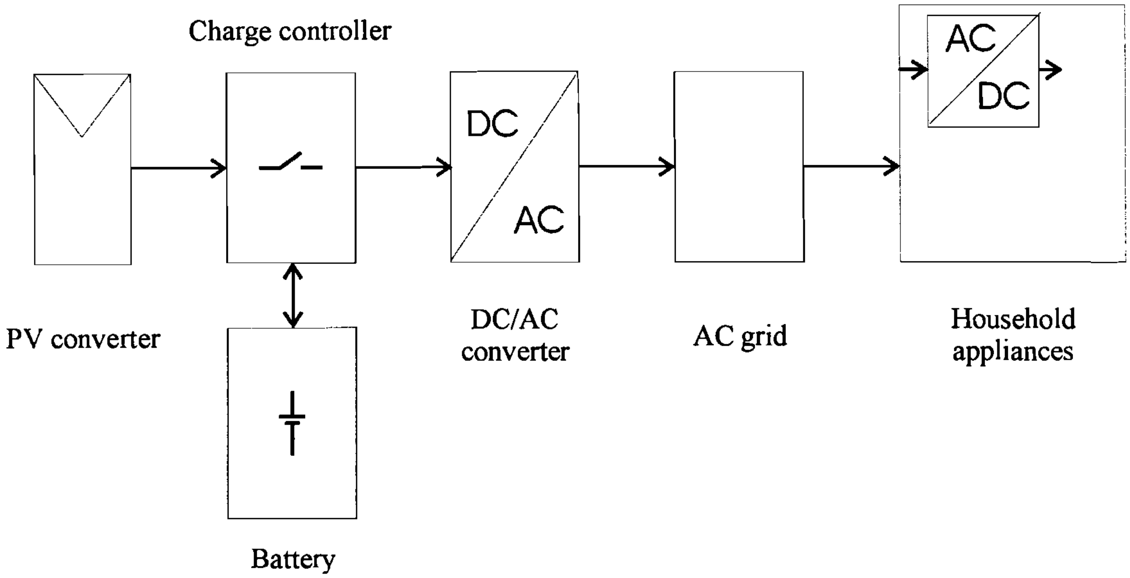


Figure 2.2: An autonomous AC house.

The main components with the accompanying energy losses of both versions of the stand-alone PV house are listed in tables 2.1 and 2.2 [9], [10], [11]. The energy losses are estimated values for commercially available equipment. The components for which the losses are indicated with '-%' are the research topics of this project.

Table 2.1: Components of an autonomous DC low-voltage house.

	PV generator	charge controller	battery	DC low-voltage grid	household appliances
Function	conversion of solar energy to electrical energy	control of energy flow to and from battery	storage of electrical energy	DC power transmission from supply to the user	conversion of DC power to heat, rotation, noise, light
DC or AC	DC	DC	DC	DC 12/24 V	DC
Losses	85%	20%		–%	–%

Table 2.2: Components of an autonomous AC house.

	PV generator	charge controller	battery	DC/AC converter	AC grid	household appliance		
Function	conversion of solar energy to electrical energy	control of energy flow to and from battery	storage of electrical energy	conversion from DC to AC	AC power transmission from supply to the user	conversion of AC power to heat, rotation, noise, light		
DC or AC	DC	DC	DC	AC	AC 220 V	AC	DC	AC/DC
Losses	85%	20%		8%	–%	–%	–%	–%

Tables 2.1 and 2.2 show that a reduction in the overall energy losses is possible by avoiding conversion losses. The AC/DC conversion inside a household appliance is necessary if this device operates internally on DC, which is the case in many appliances.

Three different kinds of supply in the interior of the AC appliance can be distinguished (this feature is being addressed in table 2.2):

1. only DC power supply (for example, a computer or a radio);
2. DC and AC power supply (for example, a television or a washing machine);
3. only AC power supply (for example, an incandescent lamp or a heater).

2.3 DC distribution a renewed interest

Nowadays AC distribution systems are usually used for the supply of electrical energy. In the past however, there were people (like Edison) who thought that DC would and should become the preferred method for electricity transport. DC and AC systems existed together for some time, but AC won the battle between these two systems, mainly due to the invention of the transformer (around 1885). This invention made a conversion of AC power from high voltage to low voltage and vice versa relatively easy. The transformer enabled the transport of AC power over large distances without unacceptable voltage losses.

Although electricity transport by means of AC is most widely used, DC distribution systems still exist or have existed for a long time (for example, on boats or for traction). Nowadays there is even a renewed interest for DC power transmission, for, among others, the following reasons:

- new developments in the area of power electronics;
- utilisation of renewable energy sources such as DC generating solar cells.

At the moment KEMA pays much attention to the potential of DC in future energy supply scenarios [12]. The high voltage DC (HVDC) link between the Netherlands and Norway is a typical example of the application of DC instead of AC. Another example is the use of medium voltage DC distribution systems for the integration of renewable energy sources in electricity distribution networks. Other developments in this area come from the ElectroMagnetic Power Technology (EMVT) association. This is a co-operation of several companies and research institutes, which concentrates its efforts on the use of power electronics in domestic applications, science and industry. One of the projects ('Future of electricity supply in densely populated areas on a small scale level') within this co-operation is engaged in DC distribution systems, where specific interest is shown for houses and ships.

The main advantages of DC power transmission in relation to the above mentioned projects are:

- reduction of energy losses;
- a relatively simple integration of renewable energy sources such as PV systems;
- a simple coupling with storage systems;
- better utilisation of the current electricity infrastructure, because of higher power densities.

An example of a low-voltage DC supply in a Western European domestic dwelling is the 'Solarhome Castricum', where a PV supplied 24 V DC system supplies most of the household appliances [13], [14]. DC power supply systems are also applied in Solar Home Systems, which are small PV powered systems used for rural electrification in developing countries [15].

3. PROJECT STRUCTURE

3.1 Target groups

The question on the feasibility of a DC distribution system in domestic dwellings which led to the project 'The DC low-voltage house' arises from three different groups: the target groups of the project:

1. associations in the area of renewable energy sources (Holland Solar);
2. users of PV systems (for example, 'Organisatie voor Duurzame Energie': ODE);
3. PV system designers and manufacturers (ECN, Shell Solar).

3.2 Targets

'The DC low-voltage house' project aims to establish whether energy savings are feasible or not. To cover all aspects related to this principal aim of the project the following points will be addressed:

1. Information on the current average electricity consumption in households is needed. In order to supply a house with PV power, without any electricity import from the public electricity grid, the electricity consumption must be as low as possible, without loss of personal comfort. Which savings are possible in the DC low-voltage house?
2. To answer this question the feasibility of using DC supply for household appliances should be studied. An inventory is required of all available DC appliances, of the problems related to a change to DC supply of household appliances and of the possible energy savings that a change to DC supply yields.
3. The power demand in houses from household appliances must be known in advance in order to design a low-voltage DC supply system.
4. Using the data obtained on the power demand, a low-voltage DC distribution system must be designed which is able to supply all DC appliances with electrical power of sufficient quality. The energy losses in the distribution system must be sufficiently small.
5. The DC low-voltage grid must fulfil all technical and safety requirements of NEN 1010: 'Safety requirements for low-voltage installations' [16].
6. The results of the research on DC household appliances and the DC distribution system lead to conclusions on the feasibility of the DC low-voltage house. An autonomous DC low-voltage house will be compared with an autonomous AC house (figures 2.1 and 2.2); this autonomous AC house is based on a typical Dutch single-family dwelling. The criteria for determining the feasibility of the DC low-voltage house will be discussed in the next paragraph.

3.3 Organisation of the project

The structure of the project is derived from the targets set. Figure 3.1 gives a schematic view of the organisation of the project.

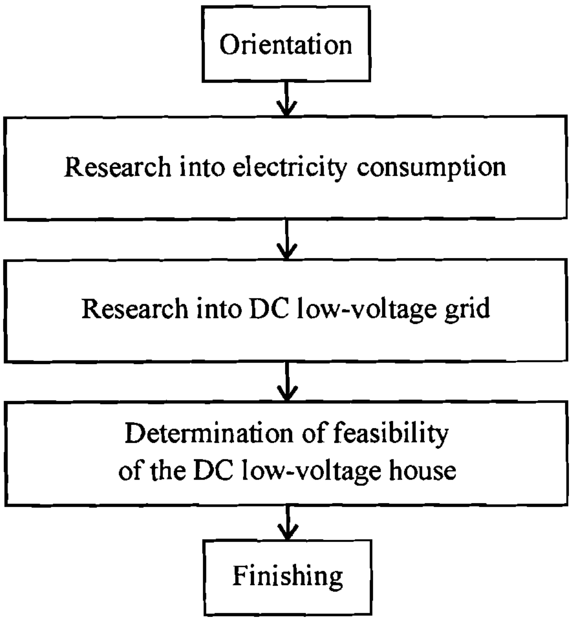


Figure 3.1: Organisation of the project.

3.4 Criteria

The following criteria will be used to determine the feasibility of the DC low-voltage house:

1. the magnitude of the reduction of energy losses in stand-alone PV supplied houses due to a change from an AC to a DC supply system;
2. the technical feasibility of the DC low-voltage house;
3. economic aspects.

For a full assessment of the DC low-voltage house, other criteria such as social and environmental aspects should also be considered. These aspects will not, however, be addressed in this report.

The technical feasibility can be assessed in different ways. The first is to take account of existing technologies and circumstances only. The major part of this report is written from this point of view. A second method to determine the technical feasibility is to assume new or continuing developments and changing circumstances. For example, one could assume that the development of power electronics will make power conversion very efficient and affordable or one could imagine a society in which DC has taken the place of AC for high-voltage and medium-voltage power transmissions. The effects of such developments on the DC low-voltage house will be considered briefly at the end of this report (chapter 9).

3.5 Boundary conditions

The boundary conditions of the graduation project are:

1. The DC low-voltage house is a stand-alone PV house: initially there is no coupling with the public AC electricity grid. The evaluation of the feasibility of the DC low-voltage house will be based on a comparison between an autonomous DC low-voltage house and an autonomous AC house.
2. The DC low-voltage house should provide the same level of comfort to the user as a normal AC house; all the demands of a typical Western European user must be satisfied.
3. The DC low-voltage system must satisfy all technical and safety requirements as laid down in NEN 1010.
4. The electricity consumption in the DC low-voltage house should be as low as possible. So only (super) efficient household appliances are to be installed in the DC low-voltage house.
5. DC low-voltage is taken to be in the range of 10 to 60 Volts.

The boundary conditions of the graduation project will strongly influence the outcome of the project. Different boundary conditions will result in another assessment of the feasibility of the DC low-voltage house (chapter 9).

4. ENERGY CONSUMPTION IN THE DC LOW-VOLTAGE HOUSE

The current level of energy consumption in households is an important issue in the context of energy saving. The average electricity consumption of Western European households and possible savings will be discussed in this chapter. The possible reduction of energy losses inside appliances resulting from a change to DC and the feasibility of DC supply of household appliances is considered as well as the availability of DC household appliances. The power demand of DC appliances, which must be known in advance in order to design a low-voltage DC supply system, is also dealt with.

4.1 Energy consumption

4.1.1 Energy consumption and energy infrastructure

The major part of the energy demand in Western European domestic dwellings is usually supplied by energy carriers such as gas and electricity. But, depending on the energy supply infrastructure, it is also possible that other energy carriers and/or other combinations are already in use or will be used in the future [17], [18], for example:

- only electricity;
- electricity and heat;
- hydrogen and electricity;

Within the framework of the DC low-voltage house, electricity consumption is most relevant, but this consumption is related to the total domestic energy supply. The total electricity consumption depends, to some extent, on which energy carrier is used for heating. Information presented in this chapter is mainly based on a traditional energy consumption pattern. Some other energy scenarios varying from a futuristic hydrogen society to, for example, a large integration of heat pumps in domestic dwellings are briefly considered later in this report (chapter 9).

4.1.2 Household electricity consumption

Table 4.1 gives a classification of household appliances sorted into 11 different application groups. The information on electricity consumption in this table is derived from a report on the (AC) electricity consumption in households in the Netherlands (BEK '95, [19]). The data for the third column are derived from electricity companies and from articles about high efficiency appliances [20], [21].

The average electricity consumption per household in the Netherlands in 1995 was 3259 kWh. This average consumption is calculated using the consumption of many different kinds of households. Households with a shop or a small company with a large energy consumption are also included in the calculation of the average electricity consumption. Therefore the average consumption of a 'standard household' living in a single-family dwelling might be smaller than 3259 kWh. Monitoring the electricity consumption of households in Amsterdam by Energie Noord West resulted in an average electricity consumption of 2600 kWh [22].

Table 4.1: Average electricity consumption of AC household appliances.

Application:	Average electricity consumption in kWh per household per year:	Electricity consumption for efficient equipment (kWh):
1. Cooling equipment (freezer, refrigerator)	599	200
2. Cooking equipment (elec. cooker, microwave oven)	138	30
3. Kitchen equipment (coffee maker, toaster)	108	108
4. Heating and warm water (electric boiler, centr.heating)	534	260
5. Cleaning (wash. machine, dryer, iron)	621	500
6. Personal care (solarium, hairdryer)	35	35
7. Interior climate (ventilation, air-conditioner)	130	130
8. Hobby (elec. drill, sewing machine)	32	32
9. Audio/video/communication (TV, tuner, CD player)	460	300
10. Lighting (light bulb, halogen lamp)	509	400
11. Remaining (doorbell, alarm system)	94	94
Total consumption:	3259	2089

4.1.3 Standby consumption

Many household appliances consume power for 24 hours a day. This energy consumption continues even when the appliance is not fulfilling its primary function. This consumption is called standby consumption or continuous consumption. Examples of these continuous consumers are the wireless telephone, the alarm clock and televisions with a standby function. All AC appliances which have a built-in transformer which stays connected to the supply even if the device is switched off will have a continuous power consumption due to the no-load losses in the transformer.

Table 4.2 gives an estimation of the standby consumption in (AC) households [19]. The standby consumption is about 10% of the average consumption per year, which is excessive if it is recognised that this continuous consumption performs no useful function. For audio/video/communication equipment, this consumption is even more than one third of the total consumption. Simple measures could eliminate a large part of this standby consumption, for example, installing a switch on the grid side of an appliance to eliminate power consumption by the appliance after it is switched off. This measure is not possible for, for example, an alarm clock, but will surely work for hi-fi equipment and halogen lighting.

The effect of DC supply of household appliances on standby consumption will be considered in the section on DC household appliances.

Table 4.2: Electricity consumption divided into 'standby' and 'on' consumption.

Application group:	On: (W)	Standby: (W)	On + standby: (W)
1. Cooling equipment	581	19	599
2. Cooking equipment	121	17	138
3. Kitchen equipment	93	16	108
4. Heating and warm water	476	58	534
5. Cleaning	615	5	621
6. Personal care	31	4	35
7. Interior climate	130	0	130
8. Hobby	30	1	32
9. Audio/video/communication	291	168	460
10.Lighting	517	10	509
11.Remaining	61	34	94
Total consumption:	2946 (90 %)	332 (10 %)	3259 (100 %)

4.1.4 Energy savings

One way to reduce electricity consumption is to eliminate or reduce standby consumption. Other savings are achieved by using efficient equipment and by not using electricity for inefficient conversion of electric energy. An example of an inefficient conversion is the use of electricity for heating applications. Avoiding this inefficient conversion also implies that an electric washing machine gets its warm water from a gas heated boiler and does not heat the water by itself. Reduction of electricity consumption by not using electricity for heating and cooking is not a 100% energy saving, because in place of electricity, gas or another (primary) energy carrier will be used.

Building efficient appliances is not a simple matter and is different for every application. Some general measures to obtain an efficient appliance are: preventing power losses in wires and electronic components, prevention of no-load losses in converters, good insulation to keep cold appliances cold (refrigerators) or warm appliances warm (ovens) and avoiding heat production due to friction.

If very efficient appliances are used and electricity is not used for heating and cooking applications, a large reduction in electricity consumption is possible. An example of possible energy savings in a normal household is demonstrated in the Solar home in Castricum [13], [14]. In this case the electricity consumption per year is reduced to below 1000 kWh.

The possible reduction of energy losses in household appliances by supplying the appliance with DC instead of AC is discussed in the next section.

4.2 DC Household appliances

4.2.1 Suitability for supply with DC and low voltage

Table 4.3: Household appliances divided according to the type of energy conversion.

Kind of energy conversion:	Examples:	AC supply	DC supply		Power demand (W):
		AC→DC converter	DC→AC converter	DC→DC converter	
1. electric energy → heat	boiler, coffee maker, light bulb, electric cooker	No	No	No	< 3500
2. electric energy → rotational or mechanical energy	washing machine, ventilator, vacuum cleaner	No			< 3500
3. electric energy → sound and vision	TV, radio, CD player, telephone	Yes	No		< 500
4. electric energy → light	fluorescent lamp, PL	No*	Yes	No	< 500

* PL needs an AC/AC converter

Table 4.3 lists the household appliances according to the type of energy conversion. The suitability for DC supply of household appliances depends on the type of energy conversion required:

- The equipment in group 1 can be supplied with DC electricity because heat generation in conductors is, in principle, the same for DC and AC. The differences between AC and DC supplied equipment in this group will not be very large. The exact value of the applied voltage is not important, but for 'large' power applications, a very low voltage is not to be recommended due to voltage and power losses inside and outside the appliance (table 4.4). Large cross-sections of the wires inside and outside the appliance will be required to prevent voltage and power losses.

Table 4.4: Voltage and power losses.

Applied voltage (V)	Load power (W)	Load current (A)	Relative voltage and power losses over resistance of:		
			100 mΩ	50 mΩ	10 mΩ
24	240	10	4.2 %	2.1 %	0.42 %
24	960	40	16.7 %	8.3 %	1.7 %
120	240	2	0.17 %	0.08 %	0.02 %
120	960	8	0.67 %	0.34 %	0.07 %
220	240	1.1	0.05 %	0.03 %	0.005 %
220	960	4.4	0.20 %	0.10 %	0.02 %

- For the household appliances in group 2, it is possible to supply energy with DC electricity, but the suitability for DC supply is not the same for all equipment. The type of motor used in the apparatus will determine whether a change from AC to DC will be possible or will require another type of motor. Collector motors which are used in vacuum cleaners and electric drills can be connected to DC. Push armature (refrigerators) and shaded-pole, capacitor motors or other types of induction motors are not suitable for connection to a DC supply. These types of motors will have to be replaced by DC motors, or otherwise a DC/AC conversion will be required. Low replaced by DC motors, or otherwise a DC/AC conversion will be required. Low voltage supply will not be a principal problem for low power motors. For larger powers, the motor needs thicker windings to prevent voltage and power losses (table 4.4), this will lead to heavier, larger and more expensive motors.

- The equipment in group 3 functions internally on different DC voltages. Supply with DC will not be a problem, but in most cases a DC/DC converter or voltage regulator is necessary to apply the correct magnitude of the voltage to the electronics inside the appliance. The appliances in this group demand a small power, therefore supply with a low voltage will in general not give many problems.

- The appliances in group 4 can be supplied with DC, but will need a DC/AC converter (electronic ballast). For 'energy-saving lamps' this electronic ballast is also needed for AC supply, so supply with DC or AC will not really make much difference. For fluorescent lighting a converter is not necessary for AC supply. DC supply will increase the cost of a fluorescent lamp because of the additional cost of a converter. Supply with low voltage seems to be no problem, although the generation of high ignition voltages requires special facilities in the electronic ballast.

Table 4.5: Overview of suitability for DC low-voltage supply and reduction of conversion losses.

Kind of energy conversion:	Suitability for DC supply:	Suitability for low-voltage:	Automatic reduction of conversion losses due to change to DC:
1. electric energy → heat	++	+/-	No
2. electric energy → rotational or mechanical energy	+/-	+/-	No
3. electric energy → sound and vision	++	+	Possible
4. electric energy → light	+/-	+	No

4.2.2 Reduction of conversion losses

At the start of the project it was expected that a change from AC to DC supply of household appliances would reduce losses due to the elimination of energy conversions inside appliances. This is not necessarily true (tables 4.3 and 4.5). Only if the internal DC voltage level used is the same as the applied DC voltage level can conversion be avoided. If the voltage levels do not match, the efficiency of the DC/DC conversion in comparison to the AC/DC conversion will determine whether a change to DC supply reduces energy losses.

Manufacturer data on converters (from Mascot, Vicor, EA and Kniel) makes it clear that typical efficiencies of DC/DC and AC/DC converters lie between 80% and 90%. The obtained data does not show a clear difference between the efficiency of DC/DC and AC/DC converters. More research into converters will be needed before any definite conclusions can be drawn on the difference between DC/DC and AC/DC converters.

The comments on the feasibility of automatic reduction of conversion losses due to a change to DC, as listed in table 4.5, are of a general nature and only concern conversion losses. It is not excluded that reduction of energy losses can be achieved for certain appliances. Therefore more research into the design of household appliances is required in order to obtain a complete overview of the consequences of DC supply.

4.2.3 Reduction of standby consumption

An example of an appliance in group 1 (tables 4.3 and 4.5) which forms an exception to the expectation that DC supply does not give an automatic reduction of conversion losses is halogen lighting. A halogen lamp demands a low DC or AC voltage (for example 24 V), therefore a transformer is necessary if 220 V AC is supplied. Supply with DC low-voltage will eliminate the required transformer, which will result in a reduction of conversion losses, and also a reduction of standby consumption.

If a DC supply makes a converter unnecessary, then in general standby consumption will be reduced or eliminated.

4.2.4 Converting AC appliances to DC appliances

There are safety aspects which should be taken into account when converting AC appliances to DC. One important aspect is the short circuit power of a DC motor. This short circuit power can be very high due to the absence of large current limiting self-inductance voltages (appendix A).

A further aspect is that transformers in AC appliances are often used to obtain a galvanic separation of the 220 V AC grid. For a low-voltage DC system this measure is perhaps not necessary, but for higher supply voltages an effective solution needs to be found for the galvanic separation between appliance and DC grid.

4.3 Power demand

The power demanded by household appliances varies from a few W to thousands of W (table 4.3). There is no reason to expect a much lower power demand for DC household appliances. The power consumed by the appliances must be taken into account in the design of the DC low-voltage network (chapter 6).

The maximum power load of devices can, for example, be limited by using rechargeable, battery operated appliances. This could be a solution for appliances which consume a high power for a short time, for example, electric drills and microwave ovens. This solution however does not really fit within the aim of energy saving: a battery system has an efficiency of only 80%. Other measures to limit the maximum power consumption will most likely have a negative influence on the performance of the household appliance. This is in contrast to the demand for equal comfort in the DC low-voltage house when compared with a typical AC house.

4.4 Availability of DC household appliances

The proportion of DC household appliances on the market is very small. Most DC appliances are produced for the yachting and camping market. It is difficult to buy a DC version of each type of household appliance. For some appliances, DC supplied versions are not available. If DC appliances are available, they are often not very modern and not very efficient. An exception to this is the development and production of DC appliances for Solar Home Systems in developing countries [23], [24], [25]. These appliances are very efficient, very reliable, have a long life and are relatively cheap. The range of appliances offered is however limited to equipment such as lighting, televisions, cooling applications and well pumps. The voltage of most of the available DC appliances is 12 or 24 V.

Because of the limited availability of DC appliances it is not expected that a change to DC instead of AC in houses can be made in a short time.

4.5 Conclusions and recommendations

4.5.1 Conclusions

- DC supply will in general not automatically give energy savings in the household appliance. Only if the applied DC voltage can be used without any voltage conversion can a reduction of energy losses be expected.
- DC supply of household appliances is possible. It depends on whether the appliance can be easily changed or adapted for DC operation. This adaptation varies from the replacement of an AC/DC converter by a DC/DC converter to a complete change of the components in the device.
- Standard voltages for existing DC appliances are 12 and 24 V. The present power demand of household appliances varies from a few W to 3500 W. To supply larger loads this voltage level is not to be recommended because of high load currents. (Loads of about 1 kW already give large voltage and power losses, a voltage level of at least 100 V seems to be necessary to supply such loads.)
- The average electricity consumption of households is about 3000 kWh per year. A large reduction of this total consumption is possible by using efficient appliances and avoiding inefficient use of electricity. But it has not become clear that a change to DC supply will automatically result in extra savings.
- The range and availability of DC appliances is limited.

4.5.2 Recommendations

- In order to obtain a complete overview of the consequences of DC supply of household appliances, more research is required into:
    1. the design of household appliances and
    2. the difference between DC/DC and AC/DC converters.

5. THEORETICAL ASPECTS OF DC DISTRIBUTION

In order to transport electricity from the point of generation to the user, an electrical distribution system is needed. For the DC low-voltage house this distribution network is the DC grid, which connects the PV-elements and battery system to the household appliances. This chapter provides some basic information on DC distribution.

5.1 AC versus DC

The essential differences between DC and AC are expressed in figure 5.1, which shows voltage and current as a function of time for two different power sources. In figure 5.1 (b) the power source is a DC voltage source. DC means direct current: the voltage and current do not fluctuate with time. AC means alternating current. For an AC voltage source the current and voltage change (sinusoidally) with time, as can be seen in figure 5.1 (a). The current and voltage pass through zero twice every period, this means 100 times per second for a frequency of 50 Hz. Because of this continuous change of polarity, magnetic and electric fields are built up and broken down every period. This results in another visible difference between AC and DC which is illustrated in figure 5.1: the phase shift between voltage and current. This phase shift is present in AC circuits, but does not exist in DC circuits.

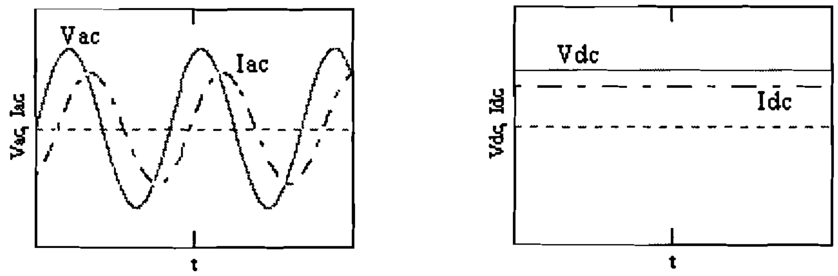


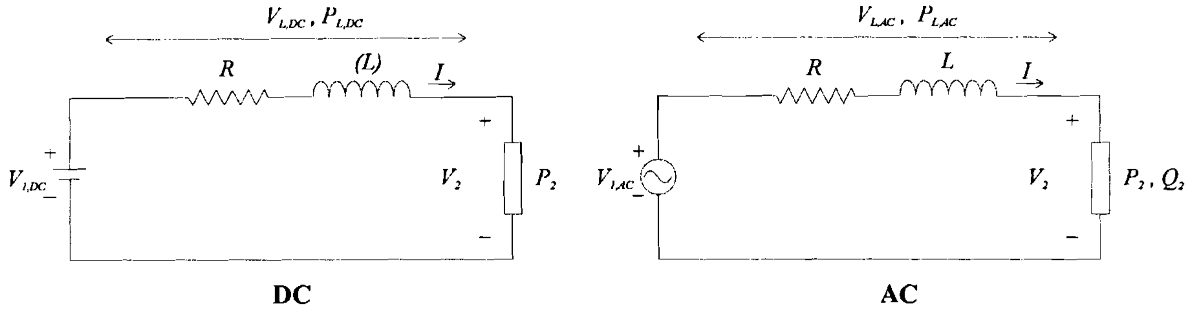
Figure 5.1: Voltage as function of time for AC (a) and DC (b).

The phase shift φ between the voltage and current in an AC circuit is determined by the load connected to the power source. For a pure resistive load there will be a phase shift of zero. For an inductive load the current lags the voltage. For a capacitive load, the current leads the voltage. The phase shift caused by the load is expressed in the power factor, which is equal to cos φ. The power factor is 1 for a resistive load. For an inductive or capacitive load, the power factor is smaller than 1.

5.2 Power transport in DC and AC circuits

To demonstrate the difference between DC and AC in relation to power and voltage losses in a distribution network, the following example is given. For the circuits of figure 5.2 the current, voltages, active and reactive power and power losses are calculated. The only difference between the circuit is the type of source. The left circuit has a DC power source, the right circuit is supplied from an AC power source.

In both cases the active power dissipated by the load is P_2. The branches in the circuit are characterised by a resistance R and a reactance $X=\omega L$. The capacitance of the link between source and load is neglected. The load (for example, a heater or lamp) has a power factor cos φ. The voltage applied to the load is the same for DC and AC (RMS value): V_2.



R:	conductor resistance	$V_{L,DC}$:	voltage losses in DC circuit
L:	conductor inductance	$V_{L,AC}$:	voltage losses in AC circuit
$V_{1,DC}$:	DC source voltage	$P_{L,DC}$:	power losses in DC circuit
$V_{1,AC}$:	AC source voltage	$P_{L,AC}$:	power losses in AC circuit
V_2:	voltage at the load terminals		
P_2:	active load power		
Q_2:	reactive load power		

Figure 5.2: DC and AC equivalent circuits.

Table 5.1: Voltage, current and power for DC and AC circuits.

DC	AC
$P_{2,DC} = P_{2,AC} = P_2$ $V_{2,DC} = V_{2,AC} = V_2$	$P_{2,AC} = P_{2,DC} = P_2$ $V_{2,AC} = V_{2,DC} = V_2$
$P_2 = V_2 \cdot I_{DC} \rightarrow I_{DC} = \frac{P_2}{V_2}$ (5.1a)	$P_{2,AC} = V_2 \cdot I_{AC} \cdot \cos\varphi = P_2 \rightarrow$ $\rightarrow I_{AC} = \frac{P_2}{V_2 \cdot \cos\varphi}$ (5.1b)
$V_{L,DC} = V_{1,DC} - V_2 = I_{DC} \cdot R = \frac{P_2}{V_2} \cdot R$ (5.2a)	$V_{L,AC} = V_{1,AC} - V_2 =$ $= \sqrt{(\frac{P_2}{V_2} \cdot R + \frac{Q_2}{V_2} \cdot X)^2 + (\frac{P_2}{V_2} \cdot X - \frac{Q_2}{V_2} \cdot R)^2}$ (5.2b)
$P_{L,DC} = P_{1,DC} - P_2 = V_{1,DC} \cdot I_{DC} - V_2 \cdot I_{DC} =$ $= I_{DC}^2 \cdot R = \left(\frac{P_2}{V_2}\right)^2 \cdot R$ (5.3a)	$P_{L,AC} = I_{AC}^2 \cdot R = \left(\frac{P_2}{V_2}\right)^2 \cdot \frac{1}{\cos^2\varphi} \cdot R$ (5.3b)

Table 5.1 gives the equations for the voltages, currents and powers in the circuits of figure 5.2. Using the equations of table 5.1 and assuming equal active power consumption (P_2) and applied voltage (V_2) for the DC and AC circuit, the following conclusions can be drawn:

- If the power factor of a load is smaller than 1, the AC current is larger than the DC current. For the same active power consumption, the AC current must be larger. This leads to higher voltage and power losses in the conductors.
- Power and voltage losses increase with rising load power.
- Power and voltage losses increase with decreasing system voltage.

The next comparison identifies the difference between electricity transport in a DC or an AC circuit with regard to power losses in the conductors. In this comparison the active power consumption is still assumed to be equal for both circuits, but the applied voltages are no longer equal.

$$\frac{P_{L,DC}}{P_2} = \frac{P_2}{\frac{V_{2,DC}^2}{R}} = \frac{P_{L,AC}}{P_2} = \frac{P_2}{\frac{V_{2,AC}^2}{R}} \cdot \frac{1}{\cos^2 \varphi} \quad \Rightarrow \quad V_{2,AC} \cdot \cos\varphi = V_{2,DC}$$

As long as: $V_{2,DC} > V_{2,AC} \cdot \cos\varphi$, voltage and power losses in the DC circuit will be smaller than in the AC circuit. This is an advantage of DC in comparison to AC for electric power transmission.

5.3 Very low voltage versus low voltage

Equations 5.1a and 5.1b show that the current increases if the same power is transported at a lower voltage level. Due to this current increase, the voltage and power losses in the conductors will increase (equations 5.2 and 5.3). A simple comparison of a system with a very low voltage and a system with low voltage (for example, 24 V and 220 V respectively) illustrates that voltage losses and power losses will be considerably larger in the very low voltage system. This becomes even more evident if relative voltage losses are considered (table 4.4). Calculations later on in this report will demonstrate the problems which arise when a very low voltage is used in an electrical installation (chapter 6).

In addition to the problem of voltage losses, another problem related to the voltage division in networks will arise in DC low-voltage circuits. This problem is the limitation of short circuit currents and will be discussed in the next section.

5.4 Short circuits

The most likely reason for a fault current in the system is a short circuit. Short circuits occur in all electrical systems. For the reliable operation of electrical power systems it is necessary to protect them against short circuits (chapter 7). It is not possible to eliminate short circuits in electrical systems, but with good protection the effects of short circuits and other faults in electrical distribution systems can be minimised.
For the circuit in figure 5.3 the short circuit current is calculated. The load-current is neglected and the source is assumed to be an ideal DC voltage source.

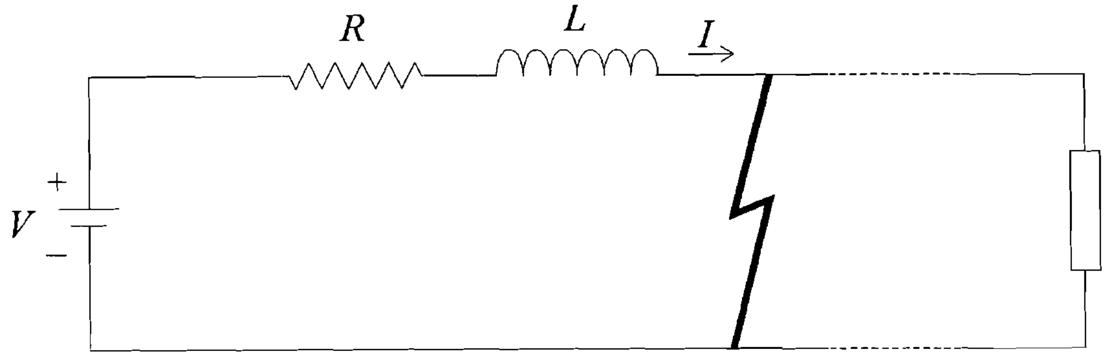


Figure 5.3: DC circuit.

The short circuit current is:

$$i(t) = \frac{V}{R} - \frac{V}{R}\cdot e^{-\frac{R}{L}t} \qquad (5.4)$$

where:

- V: system voltage (V)
- R: equivalent system resistance (W)
- L: equivalent system inductance (H)

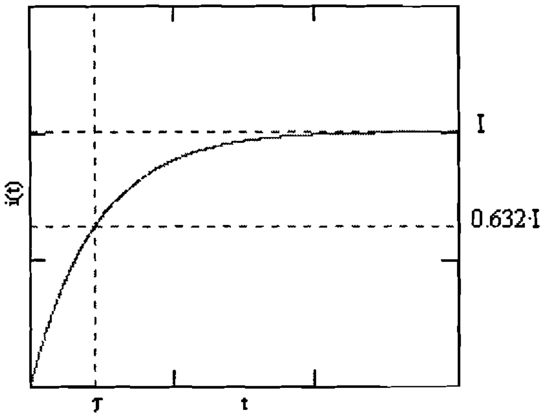


Figure 5.4: Typical short circuit current in DC system.

Figure 5.4 gives the typical shape of the short circuit current in a DC system corresponding to equation 5.4. The sustained value of the short circuit current is equal to $I_{sc,DC} = \frac{V}{R}$.

The time constant which is the ratio of L and R is a measure for the rate of rise ($\frac{di}{dt} = \frac{V}{L}$) of the short circuit current. The rate of rise and the time constant tell us how quickly the current rises to the sustained short circuit current after the occurance of a short circuit. At $t=\tau$ the short circuit current is approximately 63% of its maximum value.

For calculating the sustained value of the short circuit current, only the equivalent resistance of the circuit is needed. If we also wish to calculate the time constant and the rate of rise of the short circuit current, then the equivalent inductance of the circuit must be known.

If the circuit of figure 5.3 is supplied by an AC source, the (RMS) value of the sustained short circuit current becomes equal to:

$$I_{sc,AC} = \frac{V}{\sqrt{R^2 + (\omega L)^2}} \text{.}$$

Compared to the magnitude of the DC short circuit current, the AC short circuit current is smaller: in AC circuits the short circuit current is limited due to self-inductance voltages. These self-inductance voltages do not give large voltage losses in normal circumstances. Since AC systems usually contain transformers, the magnitude of the circuit self-inductance (ωL) is relatively high compared to the magnitude of the system resistance (R). This causes an effective limitation of the short circuit current.

The presence of current limiting self-inductance voltages is an important advantage of AC circuits in comparison to DC circuits.

5.5 Interrupting DC currents

Interrupting DC circuits needs special consideration because of the problems which can arise when switching DC currents [26], [27], [28], [29]. When circuits are switched or interrupted, the stored energy in the circuit inductances will attempt to expend itself through an electric arc. Due to the absence of zero-crossings, interrupting DC arcs is more difficult than interrupting AC arcs.

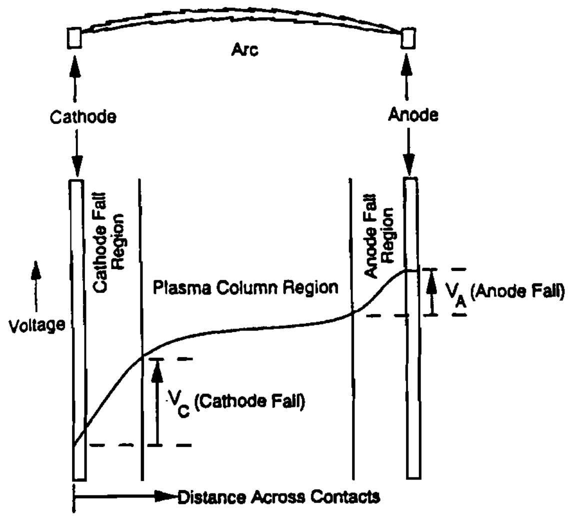


Figure 5.5: Voltage-distance characteristic of stationary arc.

A short stationary arc has a typical voltage arc to arc length characteristic as shown in figure 5.5. The minimum voltage drop across the arc is equal to the sum of the voltage drops within the cathode and anode fall regions. This voltage drop is approximately 15 V.

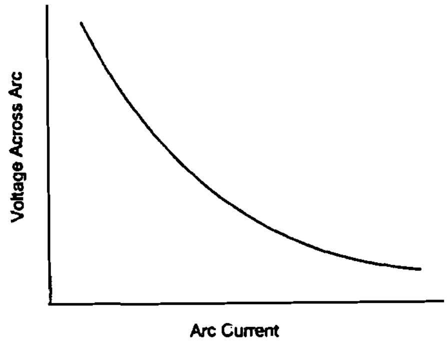


Figure 5.6: Voltage-current characteristic of stationary arc.

Figure 5.6 illustrates the current-voltage characteristic of a stationary arc, known as the negative differential resistance characteristic. To interrupt the circuit and clear the arc, it is necessary to increase the voltage to a point at which the arc is unstable and where conductivity of the arc is low. The major contributor to conductivity which is influenced in interruption devices is the temperature in the plasma region.

In switches an electric arc is formed as the contacts open. In order to extinguish and clear the arc it is necessary to raise the voltage across the arc and/or decrease the conductivity by reducing the temperature in the plasma region.

The problem which arises when DC current is interrupted is one of the major points of attention in the design of DC systems. It is not only a problem when DC currents have to be switched, but it also increases the risk on fire and burns due to electric arcs. Protection of the DC system will be considered in one of the next chapters (chapter 7).

5.6 Corrosion

Corrosion [30] is a typical problem of DC systems in the open air. But also inside domestic dwellings it can be a problem, for example, in humid areas. The problem of corrosion is considerably larger in DC systems than in AC systems. The reason for this is the continuous presence of a redox potential in DC circuits between the active and return conductor. Therefore, one of the two conditions for corrosion is always fulfilled. The other condition is the presence of an electrolyte. This electrolyte is usually water in combination with gas, acids or salts.

Prevention of corrosion is possible by, for example, good separation of the electrolyte and the conductors or contacts by insulation.

6. THE DC DISTRIBUTION SYSTEM

This chapter will consider the design of the DC low-voltage distribution system. The design of the DC low-voltage grid must fulfil the following requirements:

1. Transport of DC electrical energy from the source to the user with minimum energy losses.
2. The DC electrical installation must be safe for the user.
3. The voltage quality of the supplied energy must be high enough to guarantee proper functioning of the household appliances which are connected to the DC grid.
4. The cost of the entire DC electrical installation must be comparable to the cost of an AC installation.
5. Control of the electricity supply to the appliances must be simple.
6. The DC low-voltage network must be easy to install and maintain.

Following the description of the design, calculations are performed to determine the behaviour of the DC grid under rated operation conditions and in fault situations. These calculations will be used to check whether all requirements are fulfilled.

6.1 Safety requirements for the DC low-voltage installation

The electrical installation of the DC low-voltage house will have to meet the requirements in NEN 1010 'Safety requirements for low-voltage installations' [16]. The most important information and requirements in NEN 1010 in direct relation to the design of the DC low-voltage installation are:

- The conditions which determine the wire diameter are:
    1. highest tolerable temperature of conductors;
    2. permissible voltage drop;
    3. expected electromechanical forces caused by short circuits;
    4. other mechanical forces to which conductors could be exposed;
    5. maximum impedance at which the short circuit protection still works.
- The fact that voltages below 120 V DC are, under normal circumstances, touch safe.
- The fact that systems with a nominal voltage below 60 V DC do not need special measures to protect against direct and indirect touch.
- The requirement that conductors must be protected against overcurrents and short circuits.
- The requirement that voltage losses in conductors should not cause malfunctioning of household appliances. (For 220 V AC installations the maximum allowed voltage drop is 5% of the nominal voltage.)

Protection of the DC low-voltage system and the user is discussed in chapter 7.

6.2 Components of the DC distribution system

The DC low-voltage distribution system will in general contain the same elements as an AC distribution system. This section discusses the most important components of the DC grid and describes their suitability for use in a DC system. Important requirements for a particular component as laid down in NEN 1010 will also be given.

6.2.1 Conductors

There will be no insuperable problems on using wires for DC. Special attention must be paid to the insulation of the conductors to prevent arcs and corrosion. Standard insulation of wires as used in AC installations should be sufficient to prevent these problems. If thick wires are required in the DC low-voltage system, problems concerning the maximum number of conductors in conduits may arise (NEN 1010, 522.8.1.5). The thickness of the wires must be in accordance with the above listed requirements (section 6.1).

6.2.2 Switches

Switching DC gives problems because of the absence of zero-crossings. For AC these zero-crossings make extinguishing arcs very simple, for DC, special measures must be taken to extinguish the arc. The DC ratings of standard AC switches are unknown for most switches, although one manufacturer gives 24 V, 10 A as the DC rating for a standard AC switch.

A very low system voltage will facilitate switching DC, higher system voltages will make it more difficult to extinguish arcs. Because of this problem, switches for DC will be considerably larger and more expensive than AC switches if the same system voltage (220 V) is used.

Another sort of switch: the solid state switch, does not give the problem of arcing. But this switch must still be able to dissipate the energy which is released with the interruption of the DC current. A disadvantage of the solid state switch is the voltage drop across this device if it is conducting.

More research is required into switches for DC systems in domestic dwellings and especially the use of AC switchgear in DC networks [31].

6.2.3 Contacts and joints

For making contacts and joints in DC systems, problems may arise due to corrosion (chapter 5). Special attention must be paid to contacts and joints in humid areas, moisture free enclosures may be necessary.

If a system has large currents then a low contact resistance is required in order to prevent overheating of contacts and joints. If the wire diameter is considerably larger than the standard 2,5 mm^2 for AC house installations, it will not be possible to use standard equipment for making joints.

6.2.4 Outlets and plugs

Outlets and plugs should be rated for the system voltage and the maximum load current. Plugs may not fit in outlets of other voltages. Outlets may not be accessible by plugs of other voltages. This implies that different types of plugs and outlets are needed for the DC low-voltage house. Other types of plugs and outlets are available, so this will not give rise to any problems. Available outlets and plugs for DC are rated for 10 A, 24V.

Arcing between outlet and plug is a potential danger in the DC low-voltage house. A problem may arise when a plug is connected to an appliance which draws high (starting) currents. To prevent arcing between plug and outlet, a switch in the outlet may be necessary to change the place of interruption to one which does not give any danger to the user.

6.3 Layout of the DC grid

6.3.1 The single-family dwelling

A typical Dutch single-family dwelling will be used as the 'standard AC house' to make a comparison between DC and AC. It is therefore necessary to study the distribution grid of a single-family dwelling (appendices B and C). The arrangement of the groups in AC house distribution networks is based on a radial grid. This means that there is only one link between a load and the source. Most often PVC conduits are used to carry the wires. Connections with switches, outlets and light points are made in central junction boxes.

The layout of the DC network will also be based on a radial grid. Other grid types can also be considered [32], but for domestic applications these have no particular advantage. There is no significant reduction in wire lengths if for example a ring circuit or a meshed grid is used. Furthermore, the protection of such systems is rather more complex than for a radial grid.

The wires in a 16 A, 220 V AC house installation, except the switch-wires, have a cross-section of 2.5 mm^2. For switch-wires a cross-section of 1.5 mm^2 is used. The maximum power load per group is about 3.5 kVA. A single-family dwelling typically contains 3 to 5 groups. The maximum admissible voltage loss is 5% of the nominal voltage. The maximum length of wires is about 40 m. Table 6.1 summarises the characteristics of a standard AC house distribution system.

Table 6.1: Main characteristics of typical AC house installation.

Standard AC house	
System voltage:	220 V
Maximum current/ max. load per group:	16 A / 3.5 kVA
Wire cross-sections:	2.5 mm^2 / 1.5 mm^2
Maximum voltage loss/ maximum length:	5% / 40 m

6.3.2 Power per group, system voltage and wire cross-sections

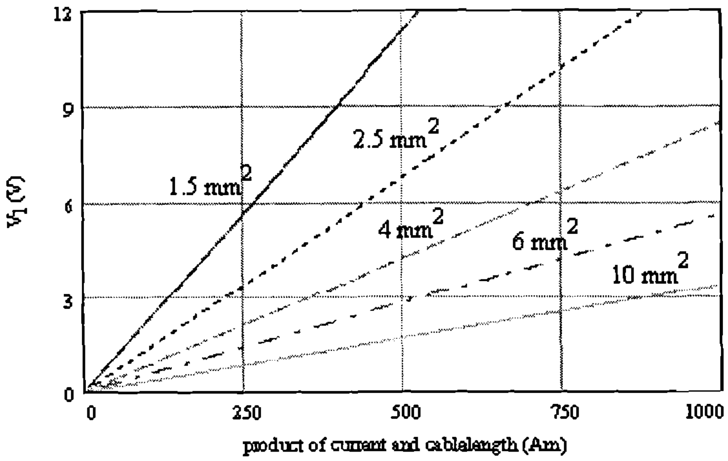


Figure 6.1: DC voltage losses in relation to the product of current and cable length.

The problem of voltage losses is illustrated in figure 6.1. This figure shows the voltage losses for a certain wire cross-section as a function of the product of current and cable length.

For example, for a current of 20 A and a wire length of 40 m, the voltage losses vary from approximately 3 V to 12 V for wire cross-sections of 10 and 2.5 mm^2 respectively. These voltage losses are absolute values, if they are related to the nominal system voltage, the relative voltage losses are obtained. It becomes clear that the relative voltage losses are larger for a 24 V system in comparison to a 220 V system. This presents a problem in the design of the DC low-voltage house.

Table 6.2 gives maximum current, power load and wire length for different copper cross-sections at a system voltage of 24, 120 and 220 V. The maximum current load is limited by the maximum tolerable conductor temperature of 70 °C. The maximum length is calculated according to a maximum voltage loss of 5%.

Table 6.2: Maximum current, power load and wire length for different copper cross-sections (based on NEN 1010; table 6.42-C1 and 52-E1).

Cross-section (mm^2)	Maximum current (A)	Maximum power (W)			Max. length (m)		
		24 V	120 V	220 V	24 V	120 V	220 V
1.5	14	336	1680	3080	3.8	19	34.8
2.5	19.2	460.8	2304	4224	4.6	23	42.2
4	25.6	614.4	3072	5632	5.5	27.5	50.4
6	32.8	787.2	3911	7216	6.5	32.5	59.6
10	45.6	1094.4	5472	10032	7.7	38.5	70.6
25	80.8	1939.2	9696	17776	10.9	54.5	99.9
50	120.8	2899.2	14496	26576	14.6	73	134

Table 6.2 shows that for transporting larger powers (> 500 W) problems arise:

- In typical houses, wires easily reach lengths of 30 m and more. If a system voltage of 24 V is chosen, it is not easy to keep voltage losses below 5% for wires longer than 30 m.
- Even with a power limit of 500 W and a cross-section of 10 mm^2, wires cannot be longer than 17 m if a maximum voltage loss of 5% is desired.
- If a wire length of 50 m is demanded at 500 W peak load, a cross-section of 30 mm^2 is required to reduce the voltage losses to a maximum of 5%.
- If a wire length of 50 m is demanded and the cross-section of the conductors is 6 mm^2, then the maximum power load is limited to 100 W.
- If the wire cross-section is 6 mm^2, the maximum load is 500 W and wire lengths of 50 m are used, then voltage losses up to 5.9 V (25%) must be accepted.

The power limits and the related voltage losses result in limits for the DC household appliances in a very low voltage system. These appliances may not exceed the maximum power and may not be very sensitive to voltage variations.

The voltage losses mentioned above are caused by nominal load currents. Voltage losses due to starting currents have not yet been treated. If a DC motor of 200 W draws a starting current of 5 times the nominal current, starting currents of approximately 40 A will flow through the system for a very short time. In a system with 6 mm^2 wires and a wire length of 40 m, this current will result in a momentary voltage loss of 9 V.

These voltage dips also put limitations on the DC appliances which are connected to the DC grid. It is not recommended to use equipment which is sensitive to voltage dips in a system where voltage drops are very common. Such equipment (an incandescent lamp or a computer) is better connected to a separate group.

In addition to voltage losses in conductors, the supply of the DC grid can also be a source of voltage variations. The voltage of a battery system can vary greatly due to battery charge and discharge. How the system voltage is influenced by the voltage of the PV-system depends on the coupling of DC grid and PV-system. If a DC-DC converter is used, it is possible to deliver a constant voltage to the DC low-voltage network.

6.3.3 Design of the DC low-voltage system

Three system layouts for the DC low-voltage distribution network will be discussed in this paragraph. Each layout represents a different solution for the problems of voltage losses and limited power consumption as mentioned in the previous section (table 6.3):

- The first layout is a system with a voltage of 24 V and wire cross-sections of 6 mm^2. In this system the household appliances are limited to a small power consumption and must be tolerant to large voltage variations.
- The second layout has a system voltage of 120 V. This layout uses a higher system voltage to prevent voltage losses and to make transmission of larger powers possible.
- The third layout is a combination of the first two designs.

Table 6.3: Main characteristics of designs for the DC house installation.

The DC low-voltage house			
Layout:	1	2	3
System voltage:	24 V	120 V	24 & 120 V
Max. current/ max. load per group:	20 A/ 480 W	20 A/ 2400 W	20 A, 480 & 2400 W
Wire cross-sections:	6 mm^2	4 mm^2	6 & 4 mm^2
Max. voltage loss/ max. length:	20 %/ 40 m	10 %/ 60 m	20 % & 10 %/ 40 m & 60 m
Conductors:	1 active cond. 1 return cond.	1 active cond. 1 return cond.	2 active cond. 1 return cond.
Appliances:	only low power appliances	no special requirements	low power appliances for 24 V, 'high' power appliances for 120 V

Figure 6.2 gives a schematic representation of the first layout. This figure shows a busbar which feeds several user groups. Each group is protected (2) against overcurrents and short circuits. The busbar is connected to the source. The source is also protected (1).

The two main reasons for selecting a voltage of 24 V in the first design are:

1. the availability of DC appliances for this voltage;
2. the fact that 24 V is a frequently used voltage in PV and battery systems.

A 12 V DC system also has these advantages, but the problems with voltage losses will increase by at least a factor 2 if 12 V is chosen as system voltage. So the choice between 12 and 24 V is not very difficult.

The wire cross-sections are chosen at 6 mm^2 to reduce voltage losses to not more than 20 % for wire lengths up to 40 m. Smaller cross-sections could perhaps be used after the central junction boxes. If it is certain that most appliances will not demand larger powers than 200 or 300 W, it will be possible and furthermore more economical to use smaller wire cross-sections after the central junction boxes.

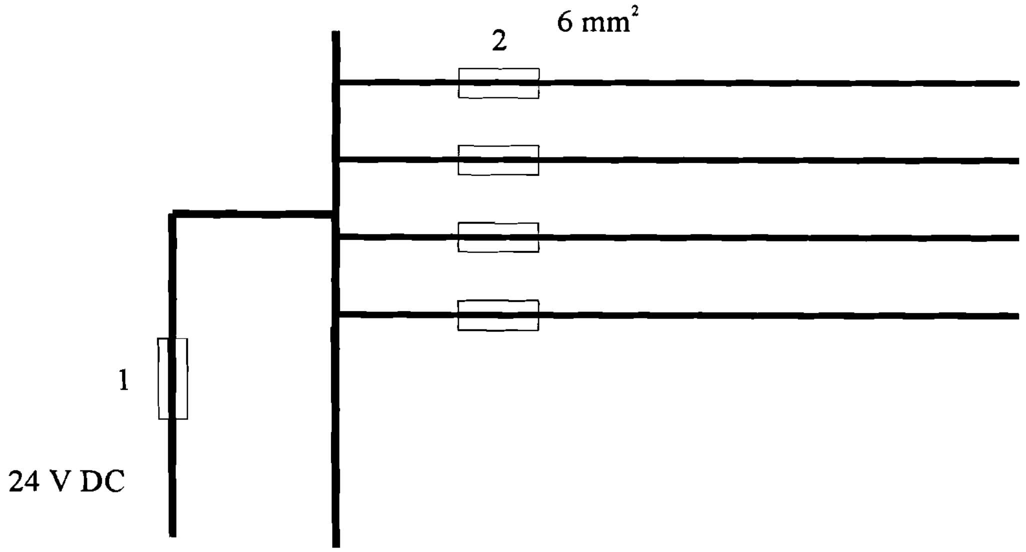


Figure 6.2: Schematic representation of layout 1.

The system voltage of the second layout (figure 6.3) was chosen to make possible transport of larger powers without unacceptable voltage losses. There are no very good reasons for a voltage of precisely 120 V. The most important argument for this choice is the fact that systems with a voltage below 120 V DC do not have to be protected against indirect touch. A search has been made to find out if there is a voltage at which DC motors are often supplied. It appeared that DC motors are available for many voltage levels. So there is no good reason to choose a voltage lower than 120 V to facilitate the supply of DC appliances. A voltage higher than 120 V can be considered. If a DC low-voltage distribution network at district level is available it seems logical to use the voltage level of that network in the DC low-voltage house.

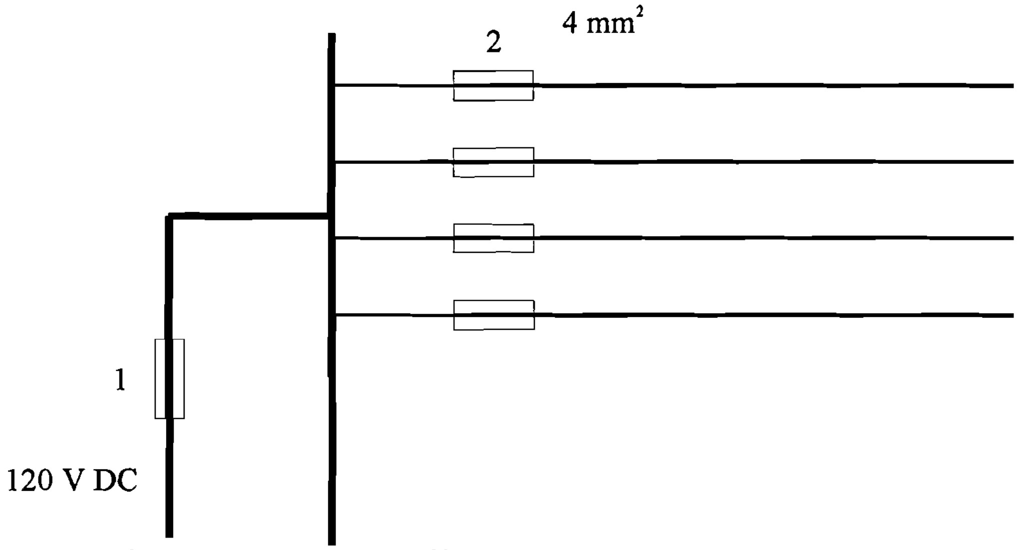


Figure 6.3: Schematic representation of layout 2.

Figure 6.4 shows layout 3. The DC low-voltage grid operates at two voltages. Different active conductors must be used for every system voltage. The neutral conductor needed as return conductor can be separate or combined for the two voltages. The layout in figure 6.4 shows a combined return conductor for both voltages.

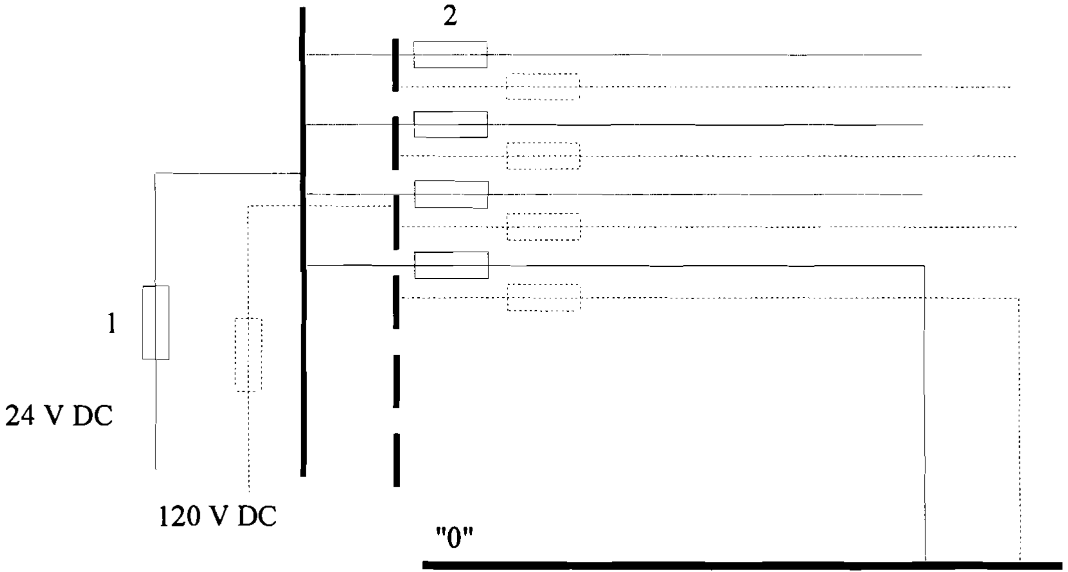


Figure 6.4: Schematic representation of layout 3.

A voltage of 24 V is supplied for low power applications. Appliances within this group must have the following features: low energy consumption, low power and peak power load (<100 W) and be tolerant to variations of the supplied voltage. The voltage of 120 V is provided for efficient appliances which demand larger powers. Table 6.4 shows some examples of appliances that can be supplied by 24 V or 120 V.
As in layout 1, the cross-sections of the wires in the second and third design may perhaps be smaller after the central junction boxes.

Table 6.4: Appliances for 24 V and 120V.

24 V: for all low power applications	**120 V: for all other applications**
(super) efficient appliances with a maximum power demand of 480 W per group: • lighting: PL and TL • computers • audio • video • TV • other low power appliances	*(super) efficient appliances with power demands up to ±2000 W:* • vacuum cleaner • washing machine • dryer • iron • coffee maker • toaster

The way in which the conductors are constructed does not necessarily have to be the same as in standard AC house installations. In these AC low-voltage installations all conductors are insulated and are most often carried by PVC conduits. Layouts 1 and 2 will also use this kind of construction. Layout 3 will use another construction. There will be no PVC conduits but a copper duct will be used to carry the active conductors. The copper duct is used as return conductor for both the 24 V and the 120 V circuit. The copper duct can also serve as protective conductor to prevent touching of hazardous voltages. Protection aspects are considered in the next chapter.

6.4 Modelling of the DC system

The DC system can be divided into three parts: the source, the DC grid and the load. Modelling of these parts will be needed to perform load flow and short circuit calculations. The modelling of the DC system will result in three equivalent circuits which are based on the three layouts of the previous section. The equivalent circuits will not show much similarity with the groups of the single-family dwelling (appendix C). The reason for this is that the models need to be simple to make the calculations easier to perform, easier to explain and better applicable to different system layouts.

6.4.1 Modelling of the source

The model which represents the DC source depends on the type of source which is used to supply the DC system. For the autonomous DC low-voltage house this source will most probably be a battery system of 24 V. To supply a voltage of 120 V, it is questionable whether a 120 V battery system is the best solution. Series connection of many batteries can give problems [33]. Therefore, it may be better to use a DC-DC converter for the 120 V supply. However, in this chapter it is assumed that a battery system supplies the 120 V system.

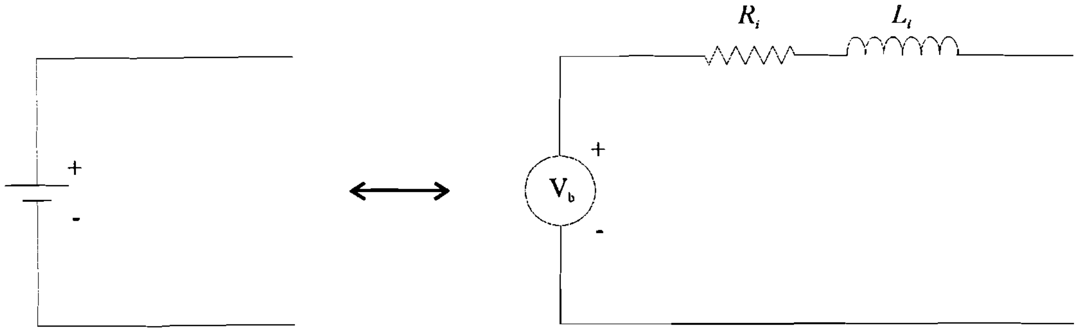


Figure 6.5: Equivalent circuit of battery system.

The equivalent battery circuit is shown in figure 6.5. The parameters which characterise the battery system are not constant. They vary, for example, with the state of charge of the battery, the age of the battery and the temperature. A complete model of the battery system which takes all possible circumstances into account is very complex. To perform the load flow and short circuit computations, a complete battery model is not needed. With the following assumptions it will be possible to execute the calculations.

- The battery only discharges to 70% of its capacity. Therefore the voltage will not drop below approximately 97% of its nominal voltage. So a 24 V battery system will not drop below 23.2 V in normal circumstances.
- If the battery is charged, it is assumed that the battery voltage is about 1.16 times the nominal voltage (14 V for a 12 V battery).
- The internal battery resistance is not the same for each type of battery and is related to the capacity of the battery. Therefore we have to know the required capacity of the battery system in the DC low-voltage house.

  The internal resistance of the battery system was calculated for a system which has a capacity of 0.5 kAh. In the calculations data of two different battery manufacturers are used (more detailed description of calculations: appendix D). The calculations have resulted in a minimum and a maximum internal resistance for the 24 V and the 120 V battery system. For 24 V, the minimum internal resistance is 2 mΩ, the maximum internal resistance is 6 mΩ. The minimum and maximum internal resistances for the 120 V battery system are 10 mΩ and 30 mΩ respectively.

  The internal battery inductance is calculated using [34]. In this article the battery resistance and inductance of a battery system are calculated and a $\frac{L}{R}$ of 6 ms is obtained. This result will be used for the battery model in this report. For the 24 V battery system, this results in a minimum inductance of 12 μH and a maximum inductance 36 μH. For the 120 V battery system the minimum and maximum inductance values are 60 μH and 180 μH respectively.

The minimum and maximum values show that it is not possible to determine the exact values for the internal resistance and inductance of the source. The minimum and maximum values are used to illustrate in which range the battery impedance can be expected. Table 6.5 gives the parameters of the battery system used in the calculations.

Table 6.5: Battery parameters.

System voltage	V_b (V)		R_i (mΩ)		L_i (µH)	
	min	max	min	max	min	max
24 V	23.2	28	2	6	12	36
120 V	116	140	10	30	60	180

6.4.2 Modelling of the DC grid

The DC grid is modelled as shown in figure 6.6. The resistance and inductance of the circuit depend on the length of the wires, on the cross-section of the wires and the layout of the system.

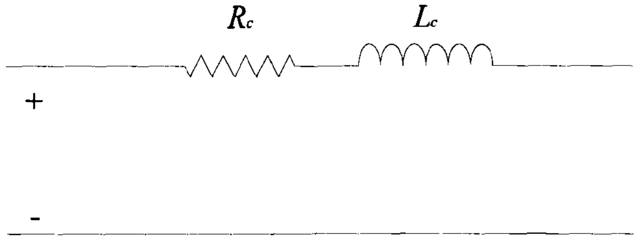


Figure 6.6: Equivalent circuit for wires.

The calculation of the conductor impedances is demonstrated in appendix E. Table 6.6 gives the inductance and resistance for 2.5, 4 and 6 mm^2 wires. Table 6.7 gives the inductance and resistance for wires which are carried in a copper duct of 19.8x22 mm, the copper duct is used as the return conductor (layout 3). The inductance values in table 6.7 should be multiplied by the length of the wire or the copper duct, but not by the total conductor length. The total circuit resistance is obtained by adding the resistance of the wire (active conductor) to the resistance of the copper duct (return conductor).

Table 6.6: Resistance and inductance values for different wire cross-sections.

wire cross-section (mm^2)	R_c (W/m) 20 °C (min)	R_c (W/m) 70 °C (max)	L_c (µH/m) min	L_c (µH/m) max
2.5	0.0069	0.0080	0.31	0.62
4	0.0043	0.0050	0.30	0.57
6	0.0029	0.0033	0.28	0.52

Table 6.7: Resistance and inductance values for wires in copper duct.

wire cross-section (mm^2)	R_c (W/m) 20 °C (min)	R_c (W/m) 70 °C (max)	L_c (µH/m)
2.5	0.0069	0.0080	0.50
4	0.0043	0.0050	0.46
6	0.0029	0.0033	0.42
Copper duct 19.8x22 mm	0.00075	0.00087	

6.4.3 Modelling of the DC household appliances

For the load flow calculations, the household appliances are modelled as loads which draw a constant current from the DC distribution network. Modelling the loads for short circuit calculations is more complicated. Some appliances will contribute to the short circuit current if a fault occurs in the system. The influence of loads on short circuit currents in the DC system will not be taken into account during the short circuit calculations. However, appendix A shows that the contribution of DC appliances to the short circuit current may not be ignored.

6.4.4 The models as used for the calculations

Figure 6.7 gives the equivalent circuit of the DC system which is used for layouts 1 and 2. A similar equivalent circuit can also be drawn for layout 3. The only difference is the presence of another active conductor. In this case faults are possible between an active conductor and the return conductor and between both active conductors. Tables 6.8, 6.9 and 6.10 give the values of the resistances and inductances as used in the calculations.

For every layout, calculations will be performed with the maximum load current flowing through the circuit. These calculations are used to establish the level of the voltage and power losses in the DC low-voltage distribution system.

Short circuits can arise anywhere in the DC system. The magnitude of the short circuit current will vary with the location in the distribution network. To give an idea of the short circuit currents which can occur in the system, the minimum and maximum fault current will be calculated for several locations in the system. The locations where the faults occur are: at the source terminals, halfway round the distribution network and at the maximum distance between source and load. The maximum distance which is used in the calculations is 40 m. So $l_1=l_2=20$ m. These locations are illustrated in figure 6.7.

The maximum short circuit current is calculated using the maximum source voltage and minimum resistance of the link between source and short circuit. The minimum short circuit calculation is performed with minimum source voltage and maximum resistance. In all calculations the impedance between source and busbar is neglected.

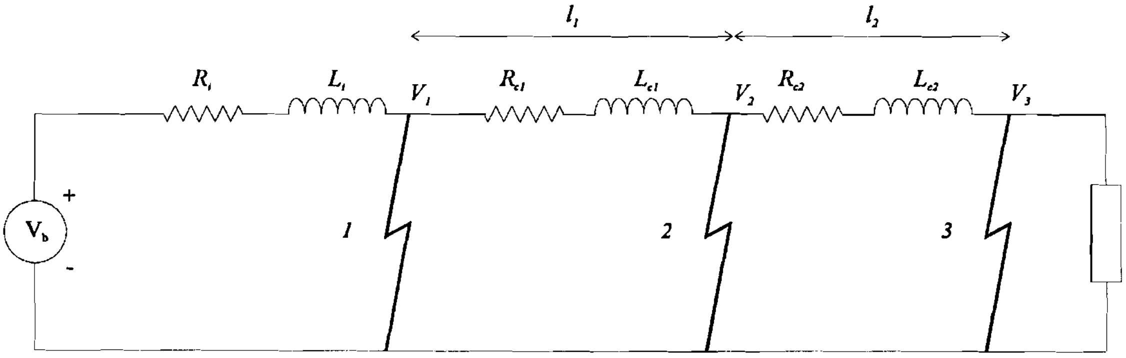


Figure 6.7: Equivalent circuit with short circuit locations for layouts 1 and 2.

Table 6.8: The values used for the short circuit calculations in layout 1.

Layout 1	V_b (V)	R_i (mΩ)	L_i (μH)	R_{c1} (mΩ)	L_{c1} (μH)	R_{c2} (mΩ)	L_{c2} (μH)
min	23.2	2	12	115	11.3	115	11.3
max	28	6	36	133	20.9	133	20.9

Table 6.9: The values used for the short circuit calculations in layout 2.

Layout 2	V_b (V)	R_i (mΩ)	L_i (μH)	R_{c1} (mΩ)	L_{c1} (μH)	R_{c2} (mΩ)	L_{c2} (μH)
min	116	10	60	172	11.9	172	11.9
max	140	30	180	200	22.8	200	22.8

Table 6.10: The values used for the short circuit calculations in layout 3.

Layout 3		V_b (V)	R_i (mΩ)	L_i (μH)	R_{c1} (mΩ)	L_{c1} (μH)	R_{c2} (mΩ)	L_{c2} (μH)
24 V	min	23.2	2	12	72	8.3	72	8.3
	max	28	6	36	84	8.3	84	8.3
120V	min	116	10	60	101	9.1	101	9.1
	max	140	30	180	117	9.1	117	9.1

6.5 Load flow and short circuit calculations

6.5.1 Results of load flow calculations

The results of the load flow calculations are the voltages at different locations in the circuits of figure 6.7 if the nominal current flows through the circuit. With these voltages and the related voltage losses, the power losses in the circuits are calculated. The results are given in tables 6.11, 6.12 and 6.13 for layouts 1, 2 and 3 respectively. The minimum values for the voltages in the tables are calculated using the minimum value of the supply voltage V_b) and the maximum values for conductor resistance and load current. The maximum values are calculated using maximum source voltage, maximum load current and minimum resistance values. The maximum voltage losses and power losses are calculated by assuming maximum load at maximum distance (40 m) from the source.

Table 6.11: Results of load flow calculations for layout 1.

Layout 1	V_1 (V)	V_2 (V)	V_3 (V)	$V_{l,max}$ /V_{nom}	$P_{l,max}$ (W)	$P_{l,max}/P_{nom}$
min	23.1	20.4	17.7	23 %	109	23 %
max	28.0	25.7	23.4			

Table 6.12: Results of load flow calculations for layout 2.

Layout 2	V_1 (V)	V_2 (V)	V_3 (V)	$V_{l,max}$ /V_{nom}	$P_{l,max}$ (W)	$P_{l,max}/P_{nom}$
min	115.4	111.4	107.4	7 %	172	7 %
max	139.8	136.4	132.9			

Table 6.13: Results of load flow calculations for layout 3.

Layout 3		V_1 (V)	V_2 (V)	V_3 (V)	$V_{l,max}$ /V_{nom}	$P_{l,max}$ (W)	$P_{l,max}/P_{nom}$
24 V	min	23.1	21.4	19.7	15 %	70	15 %
	max	28.0	26.5	25.1			
120V	min	115.4	113.1	110.1	4.4 %	106	4.4 %
	max	139.8	137.8	135.8			

6.5.2 Results of short circuit calculations

The results of the short circuit calculations are listed in tables 6.14, 6.15 and 6.16. The short circuit currents given in the tables are related to short circuits at the locations which were described in the previous section (figure 6.7). So I_{sc1} is the current flowing from the source to the fault location during a short circuit at point 1: directly before the source terminals, or at the busbar. In addition to the short circuit current, the voltage at the central busbar or source terminals during a short circuit has also been calculated. $V_{1,2}$ for example is the voltage at the busbar during a fault at location 2 in the DC system. The other columns give the time constants corresponding to the calculated short circuit currents. The minimum values were calculated using maximum resistance and minimum source voltage. The third row gives the results of the computations with maximum voltage and minimum resistance.

Table 6.14: Results of short circuit calculations for layout 1.

Layout 1	I_{sc1} (kA)	I_{sc2} (kA)	I_{sc3} (kA)	τ_1 (ms)	τ_2 (ms)	τ_3 (ms)	$V_{1,2}$ (V)	$V_{1,3}$ (V)
min	3.8	0.17	0.085	6.0	0.17	0.25	22.0	22.6
max	14.0	2.3	0.12	6.0	0.47	0.64	27.6	27.8

Table 6.15: Results of short circuit calculations for layout 2.

Layout 2	I_{sc1} (kA)	I_{sc2} (kA)	I_{sc3} (kA)	τ_1 (ms)	τ_2 (ms)	τ_3 (ms)	$V_{1,2}$ (V)	$V_{1,3}$ (V)
min	3.8	0.50	0.27	6.0	0.34	0.40	98.8	106.7
max	14.0	0.77	0.40	6.0	1.0	1.1	133.3	136.6

Table 6.16: Results of short circuit calculations for layout 3.

Layout 3		I_{sc1} (kA)	I_{sc2} (kA)	I_{sc3} (kA)	τ_1 (ms)	τ_2 (ms)	τ_3 (ms)	$V_{1,2}$ (V)	$V_{1,3}$ (V)
24 V	min	3.8	0.26	0.13	6.0	0.23	0.33	21.4	22.3
	max	14.0	0.38	0.19	6.0	0.56	0.67	27.3	27.7
120V	min	3.8	0.79	0.44	6.0	0.54	0.61	89.5	101.0
	max	14.0	1.3	0.66	6.0	1.4	1.5	129.0	134.3

6.5.3 Interpretation of the calculations

The results of the load flow calculations show that voltage losses in a very low-voltage system (layout 1) will be large, even if relatively small powers (<500 W) are transported. In addition to these large voltage losses, which are acceptable if the household appliances can resist them, the power losses are also large. The power losses can amount to 23 % of the demanded load power. Table 6.12 shows that a higher voltage reduces the relative voltage and power losses considerably. The results of the calculations for layout 3 demonstrate even smaller losses in the system. This decrease is due to the large cross-section of the copper duct which serves as the return conductor.

The following points can be concluded from the short circuit calculations:

1. The short circuit current for a fault close to the source is very large. Currents up to 14 kA can flow in the system during faults close to the supply terminals.
2. The minimum short circuit current in a 24 V system is small for a fault at the end of the distribution network. This current is just 3 or 4 times the rated current of the system.

3. The voltage at the busbar does not decrease very much during short circuits in the grid, due to the low impedance between source and busbar. Only if faults occur close to the system supply, will the voltage at the busbar decrease to a very low level. If the impedance between source and busbar increases, the voltage at the busbar will decrease more sharply during a short circuit. To keep the voltage in other, non faulted groups at an acceptable level during short circuits, the source impedance and the impedance between source and busbar must be low.
4. The time constant for the short circuit currents is small. The rate of rise of the short circuit currents is high.
5. A small increase in the circuit resistance will cause a considerable decrease in the short circuit current if the system voltage is low.

6.6 Conclusions

There are two important points which can be concluded after research into the DC low-voltage distribution system:

1. Due to voltage and power losses, it will not be possible to satisfy the present power demand in households by using a very low-voltage distribution system. This problem can be avoided by using a higher system voltage or by limiting the power demand of household appliances.
2. Interrupting DC currents is not as easy as interrupting AC currents. Therefore standard AC installation switches cannot automatically be used in the DC low-voltage house.

If the requirements of the DC low-voltage distribution system as mentioned at the beginning of this chapter are considered, then the following observations can be made:

1. The DC low-voltage distribution system does not seem to be the most optimum coupling between source and the user if energy losses are considered.
2. If the DC electrical installation is carefully constructed, the safety of the installation is able to satisfy all requirements laid down in NEN 1010.
3. The use of a very low voltage for transport of electrical energy will result in large voltage losses. This puts limits on the household appliances which can be connected to the DC grid. From this point of view the quality of the supplied energy is not very high.
4. The cost of the installation will be considered briefly in chapter 8. It can already be concluded that the DC low-voltage distribution systems need more (copper) and heavier (switches) installation materials than an AC installation for the same performance.
5. It seems to be possible to reach the same comfort as in AC installations by the control of the electricity supply, although switching of DC currents can give rise to problems.
6. Because non-standard installation materials need to be used, the construction of the DC low-voltage house is perhaps not as simple as the installation of an AC distribution system.

7. PROTECTION FOR SAFETY

This chapter discusses safety aspects and protection against overload and short circuit currents for the DC systems (layouts 1, 2 and 3) as presented in the previous chapter. The consequences of other system configurations, for example, higher system voltage and coupling with a public distribution grid will briefly be considered.

7.1 Protection against electric shock

The user must be protected against dangerous touch voltages. The touch voltage is the voltage experienced in the case of an insulation defect between two simultaneously touchable parts. Two cases can be considered:

1. direct touch: touch of active parts;
2. indirect touch: touch of metal frames which become live due to a fault.

7.1.1 Protection by extra low voltage

Figure 7.1 shows the maximum switch off time in relation to the touch voltage. It illustrates how long a voltage can be touched without any serious physical damage. It shows that voltages below 120 V DC and 50 V AC do not form a direct danger to people. Contact with DC voltage gives a smaller body current than touch of AC voltage. Therefore DC is safer in relation to body currents which may cause physical damage, for example, a heart attack.

It becomes clear that protection against electric shock is possible by using a very low system voltage (NEN 1010; 411.1). If the nominal voltage is below 60 V, no special measures are necessary to protect against direct touch. Otherwise, live parts need to be insulated. As long as the system voltage does not exceed 120 V DC, protection against indirect touch is not needed.

For the layouts presented of DC systems in the previous chapter (figures 6.2, 6.3 and 6.4) protection against electric shock is achieved by using a system voltage below 120 V. No special measures such as earth protection or protective conductors are required. The systems may be earthed or not, the only requirement is that the system must be separated safely from higher voltage (>120 V) systems. This requirement becomes very important if the system is connected to a public electricity grid.

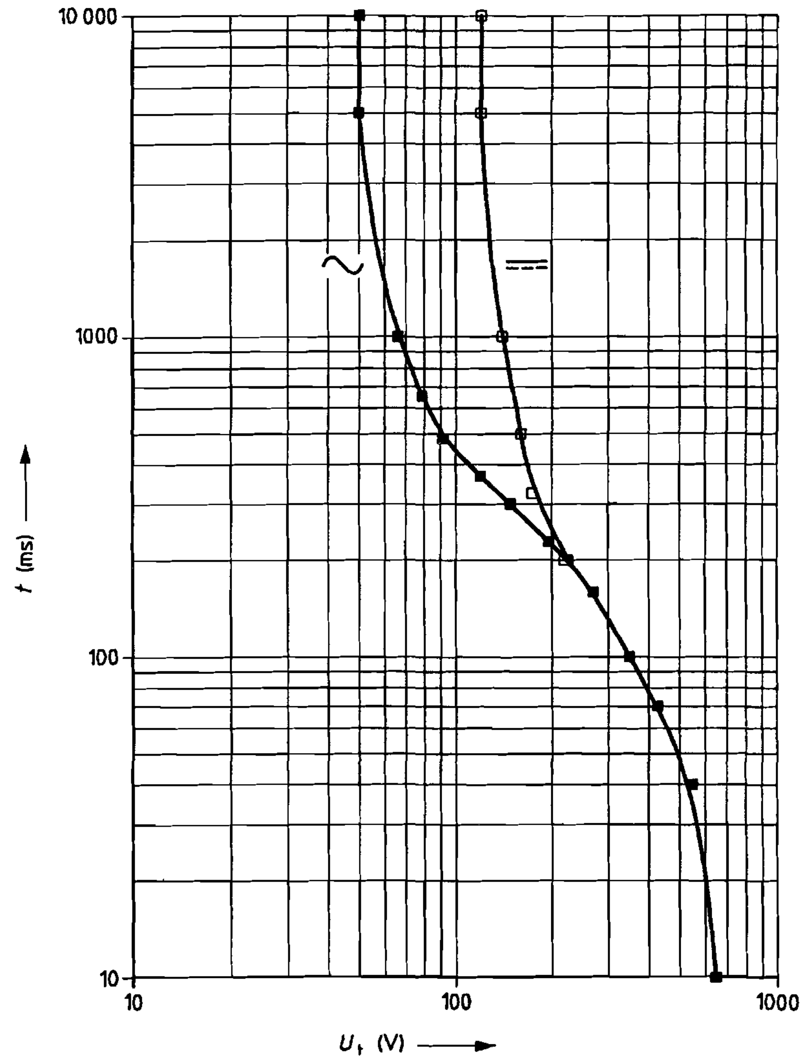


Figure 7.1: Maximum switch off time in relation to the touch voltage.

7.1.2 Protection for safety in case of higher system voltage

For system voltages above 120 V DC special measures are required to protect against electric shock (NEN 1010; 412 and 413). Earth protection and insulation must be present to protect against direct and indirect touch.

7.1.3 Protection against other hazards

In relation to dangerous body currents DC is safer than AC, but this does not automatically imply that the use of DC is safer than AC. Other hazards, especially the risk of fire and burns seem to be a larger problem in DC systems, because of the problems with interruption of DC currents and arcs. Fast clearing of faults in the DC system is required in order to limit the risk of fire and burns, this will be discussed in the next section.

7.2 Protection against overcurrent

The DC low-voltage system must be protected against short circuits and overload currents. Figures 6.2, 6.3 and 6.4 show the locations of the protection devices in the system. Each group has a protection device (fuse or circuit breaker) just behind the 24 V or 120 V busbar. There is also a protection device which protects the source and serves as a backup for the group protection.

7.2.1 Requirements for the protection of the DC system

The following points should be taken into account in the design of the protection of the DC low-voltage networks according to layouts 1, 2 and 3:

1. The protection must be selective.
   A fault in a group should not lead to a disconnection of another group. Only the circuit breaker of the group (2) in which the short circuit occurs may trip. In normal circumstances protection device 1 should only react on a fault between the source and circuit breaker 2. So this protection device should not trip immediately on a short circuit in one of the connected groups. Only if the group protection fails should the backup circuit breaker trip. This means that there must be a delay on this protection device to ensure that it does not open its contacts before the group circuit breaker or fuse can clear the fault.
2. A fault in a certain group should not lead to tripping of devices in other groups.
   Faults such as short circuits in a certain group should, if possible, not lead to a disturbance of other groups. If this is not possible, the consequences for other groups must be minimised.
3. Fast clearing time to prevent a large voltage drop in the system.
   A high short circuit current might lead to a voltage drop at the source terminals. This voltage drop will influence the complete DC low-voltage network. The protection device must be fast enough to prevent voltage dips which cause tripping of equipment in other groups than the faulted one. A large voltage drop will also influence the short circuit current in the system. If this current decreases, fault clearing can be delayed or might even not take place.
4. Fast clearing time to limit the risk of fire and burns due to open arcing. It is desirable to clear the fault before the maximum value of the short circuit current is reached. Limitation of the short circuit current is considered briefly in the next paragraph.
5. Rise of resistance during a short circuit might influence the short circuit current.
   A resistance rise in the protection device (this is possible in a fuse) will decrease the short circuit current with the same possible consequences as described in point 3.
6. Maximum starting currents which can be allowed.
   Starting currents may not lead to tripping of devices. This limits the maximum starting currents allowed in the system.
   If different cross-sections are used the maximum admissible current is determined by the smallest cross-section. This is important for the protection against overcurrents.
7. In a system with two different voltage levels (layout 3), faults in one circuit may influence the other circuit. If a combined zero conductor is used, a ground fault in the 24 V part will also influence the 120 V part.

7.2.2 Limitation of short circuit current

The short circuit calculations showed that very large (14 kA) short circuit currents can occur in the DC low-voltage system. Limitation of these currents is possible by:

- Using protection devices that switch off the short circuit current before the maximum value is reached. This method for short circuit current limitation requires very fast protection since risetimes of the calculated short circuit currents are very small (a time constant of 6 ms for the largest current). Fuses and circuit breakers will not be able to guarantee fault clearing within 6 ms. Electronic protection will be necessary in this case. Increasing the risetime by using current limiting coils may enable the use of fuses and circuit breakers to limit the short circuit current. However, the stored energy in these coils will make the interruption of DC currents more difficult, which is a disadvantage of this solution.
- Increasing the circuit resistance, this will decrease the sustained value of the short circuit current. This solution will increase the problems with voltage losses in the DC low-voltage system and is therefore not to be recommended.
- Using DC/DC converters to supply the DC low-voltage grid. In general, the presence of a transformer in DC/DC converters limits the short circuit current. In addition to this current limiting effect, DC/DC converters often have a very fast protection against small over currents. This very fast protection may give problems in providing a selective adjustment of the protection. The use of DC/DC converters is contradictory to the aim of the project: avoiding losses in converters by eliminating conversions.

Not limiting the short circuit currents means that the system must be able to resist these currents for the time that is required to switch them off. More research into limitation of short circuit currents and the dangers of allowing high short circuit currents in the DC low-voltage system is required.

7.2.3 Protection devices for DC

Two articles on the use of protection devices in DC systems were found:

1. 'Applying low-voltage circuit breakers in DC systems' [35];
2. 'Selective protection in AC and DC low-voltage networks with small short circuit currents' [36].

The first article describes the possibility of using the standard moulded case circuit breaker (MCCB) for AC installations, for DC systems. Most manufacturers provide multipliers to convert the AC trip curve to a DC tripping characteristic. A survey of manufacturers of protection devices yielded 1 manufacturer (Merlin Gerin) that provides such multipliers (appendix F).

Conversion of the AC curve is necessary, because the time-current characteristic of a circuit breaker is not exactly the same for AC as for DC:

- In the long time delay region, the time-current characteristic is exactly the same, because tripping in this region is related to the RMS value of the current.
- In the transition region, an electromagnet causes tripping of the circuit breaker. The magnetic force is equal to the square of the instantaneous value of the current flowing through the protection device. Therefore the AC trip curve in this region is shifted from the DC trip curve. The multipliers which are provided by the manufacturer must

be used to convert the AC time-current characteristic in this region to a DC characteristic.

- In the instantaneous region, the clearing time as given for AC will also satisfy DC.

The second article considers the use of fuses and electronic protection devices for selective protection of AC and DC low-voltage networks with small short circuit currents. The most interesting conclusions in relation to the DC low-voltage house are:

- The rise of resistance of fuses during short circuits may lead to a considerable decrease of the short circuit current in very low voltage networks (24 V).
- For small short circuit currents, the difference between the minimum and maximum fault clearing time is very large. This large time difference makes selective adjustment of protection devices very difficult.
- For a very fast and selective protection of low-voltage networks with small short circuit currents, electronic protection devices are preferable to fuses.

7.2.4 Tuning of the protection devices

The results of the short circuit calculations can be used for the tuning of the protection devices. The requirements which result from these calculation are separated into requirements for the source protection (1) and the group protection device (2).

Requirements for the source protection (1):

1. All faults which occur between source terminals and the group protection must be cleared. The fault current is high: from 3.8 kA to 14 kA for faults close to the source terminals. The protection device, the source and the conductors close to the source must withstand these currents and the related electromagnetic forces.
2. The protection device should not trip immediately on faults which should be cleared by the group protection. Therefore a delay on the tripping mechanism is needed to obtain a good selectivity. This delay may not be too long, because large short circuit currents must be switched off before the conductor reaches an inadmissible temperature. Faults in the order of 10 kA should be cleared within 30 ms for conductors with a wire cross-section of about 15 mm^2. If smaller wire cross-sections are used for the link between source and busbar, the short circuit current must be interrupted faster to prevent overheating of the conductors. A short fault clearing time will result in a bad selectivity between the source and the group protection.
3. Overcurrents and short circuits which are not switched off by the group protection should be cleared by the source protection. in this case circuit breaker 1 serves as a backup for the group protection. The magnitude of these overcurrents varies from the rated source current to the minimum short circuit current of 3 to 4 times the nominal current.

Requirements for the group protection (2):

1. All faults in the group must be cleared. The minimum short circuit current is 3 to 4 times the rated current for the 24 V system of layout 1. The maximum current is in the order of 14 kA for short circuits just behind the protection device. All fault currents between 3 (for layout 1) or 7 (layouts 2 and 3) times the nominal current up to currents of about 14 kA must be switched off immediately without any intentional delay. If a minimum short circuit current of 3 times the nominal current makes good tuning of the protection too difficult, the maximum length of the wires must be

decreased. The appliances connected to the distribution system may not have starting currents higher than the minimum short circuit current.

2. Overload currents must be switched off, but not immediately to prevent the interruption of starting currents. The magnitude of these currents varies from the nominal current to the minimum short circuit current.
3. The resistance of the protection device should not increase before the fault is cleared. Therefore fuses probably will not be a good option for use in very low-voltage networks [36]. Because of the low supply voltage in these systems, a slight increase of the circuit resistance may decrease the short circuit current considerably.

7.3 Conclusions and recommendations

- Protection against electric shock can be achieved by using a system voltage below 120 V.
- For protection against overcurrents, the use of circuit breakers, or even better electronic protection devices is preferred.
- Problems arise with limitation of short circuit currents and selective adjustment of the protection devices. More research into these problems is required.

8. FEASIBILITY OF THE DC LOW-VOLTAGE HOUSE

The results of research into electricity consumption in households and research into DC low-voltage distribution are used to make a comparison between an autonomous DC low-voltage house and an autonomous AC house. This chapter compares:

1. energy losses and
2. costs.

The outcome of the comparisons contributes to conclusions on the feasibility study on the DC low-voltage house.

8.1 Comparison of energy losses

8.1.1 Power losses in the converter and distribution system

Table 8.1 Relative losses in the converter and distribution system.

			relative losses in converter between battery and distribution system	relative power losses in the distribution system P_l/P, P=480 W	total power losses
autonomous AC house			8%	0.5%	8.5%
autonomous DC low-voltage house	lay-out 1		0%	11.5%	11.5%
	lay-out 2		0%*	0.7%	0.7%*
	lay-out 3	24 V	0%	7.5%	7.5%
		120 V	0%*	0.5%	0.5%*

* 8% losses must be added when a DC/DC converter is present

Table 8.1 shows the losses in the converter and the distribution system of the autonomous DC low-voltage house and the autonomous AC house (figures 2.1 and 2.2). The losses in the household appliances are not listed, since the research into DC appliances did not result in useful data about differences in the efficiency of DC and AC supplied appliances.

The losses in the distribution system are calculated using equations 5.3a and 5.3b and assuming a load of 480 W and a distance of 20 m between load and source. The real energy losses in the distribution system can be different for several reasons:

- The losses are calculated assuming a distance of 20 m between source and load. In reality this distance will vary between 0 and 40 m.
- The power losses are calculated assuming a load of 480 W. The real power demand varies between 0 and the maximum power allowed in the system. In table 8.2 the power losses for smaller loads are listed.

Table 8.2 Losses in the distribution system.

		relative power losses in the distribution system	
		P_l/P, P=200 W	P_l/P, P=100 W
AC house		max 0.2%	max 0.1%
DC low-voltage house, lay-out 1		max 4.6%	max 2.3%
DC low-voltage house, lay-out 2		max 0.3%	max 0.1%
DC low-voltage house, lay-out 3	24 V	max 3.1%	max 1.5%
	120 V	max 0.2%	max 0.1%

8.1.2 Evaluation of energy losses

It can be concluded that, in layout 1, the use of DC low-voltage instead of AC is only attractive in terms of reduced energy losses when the power demand is low (< 480 W). For layouts 2 and 3 a reduction of energy losses of about 8% is possible, if no converter between the battery and the distribution system is needed.

8.2 Comparison of costs

Table 8.3: Costs of installation materials for different layouts.

		Wire length (m)				Copper duct (m)	PVC conduit (m)	Cost
		wire cross-sections (mm^2)				*dimensions (mm)*	*diameter (mm)*	
		1.5	*2.5*	*4.0*	*6.0*	*19.8x22*	*16.0*	
autonomous AC house		79	334	0	0	0	138	ƒ 330.-
DC low-voltage house	1	0	0	0	276	0	138	ƒ 910.-
	2	0	0	276	0	0	138	ƒ 606.-
	3	0	0	138	138	138	0	ƒ 1892.-

Table 8.4: Cost of wire, conduit and duct.

Material		Cost
Wire:	1.5 mm^2	ƒ 0.32 /m
	2.5 mm^2	ƒ 0.50 /m
	4.0 mm^2	ƒ 1.68 /m
	6.0 mm^2	ƒ 2.80 /m
PVC conduit:	16.0 mm	ƒ 1.00 /m
Copper duct:	19.8x22 mm	ƒ 9.20 /m

The estimated costs of copper and PVC conduit for the autonomous DC low-voltage house and the autonomous AC house are listed in table 8.3. Table 8.4 gives the prices which were used for these calculations. The lengths of the wires and conduits are based on the plan of the single family dwelling (appendix C). It is assumed that the autonomous DC and AC houses use the same number of groups and number of outlets and light points per group.

The total cost of an electrical installation is more than the cost of wire and conduits:

- Additional expenses are incurred for other installation materials such as switches, distribution boxes, outlets and protection devices and for the fitting of the electrical installation. Appendix G shows the price of an electrical installation for a standard single-family dwelling. This price will be equal to the price of the distribution system of an autonomous AC house. The total costs amount approximately to *ƒ*3500,-. These expenses will probably be higher for the DC system than the AC system. More research is required before an assessment of these extra costs can be made.
- For the autonomous AC house additional costs are incurred for a DC/AC converter. This converter increases the price by approximately *ƒ*6000,- to *ƒ*10,000,- for an AC/DC converter in the power range from 3.5 to 5 kW (Mastervolt).

It can be concluded that taking account of the cost of installation materials (table 8.3) the autonomous DC low-voltage house is more expensive than the autonomous AC house. These extra costs may however be compensated by the elimination of costs for a converter.

8.3 Feasibility of the DC low-voltage house

- One of the conditions formulated at the start of the project was the requirement on the level of comfort in the autonomous DC low-voltage house: this must be equal to the comfort of a standard AC house. The level of comfort provided by the different designs of the DC low-voltage house is not adequate in the case of a DC low-voltage house using a very low voltage (24 V, layout 1). A very low voltage makes it impossible to satisfy the power demand in modern households, without using very thick conductors (> 25 mm^2).

- The other two layouts for the autonomous DC low-voltage house seem to be able to provide a satisfactory level of comfort, although the following reservations must be made:
    1. There are no DC appliances available for 120 V. So, in particular for layout 2 a complete new range of DC appliances for 120 V must be created. The third layout has the advantage that all available low power (< 480 W) DC appliances operating on 24 V can be used. This enables the use of very efficient DC appliances which have been developed for Solar Home Systems.
    2. Technical problems such as interrupting DC currents and corrosion have to be dealt with very carefully to maintain a safe and fault free operation of the electrical installation.

- Looking at the energy reduction due to a change to DC, layouts 2 and 3 are only of interest if no DC/DC converter is needed to supply the 120 V distribution system. The feasible reduction of losses in comparison to the autonomous AC house is approximately 8 %. For larger energy savings a reduction in losses in the DC household appliances is necessary. Research into household appliances demonstrated that DC supply does not automatically result in reduction of energy losses.

- From the economics aspect the autonomous DC low-voltage house seems to be more comparable to the autonomous AC house, if the costs of the total electrical installation are considered. This is only true if the DC low-voltage house does not need a DC/DC converter between the battery system and the DC low-voltage grid.

The above points demonstrate that there is no clear cut case for a change from AC to DC within the boundary conditions made at the start of the project. The next chapter will discuss some other conditions and circumstances which deviate from the original boundary conditions of the project.

9. OTHER CONDITIONS AND CIRCUMSTANCES

The comments on the feasibility of the DC low-voltage house are strongly influenced by the boundary conditions formulated at the start of the project. The following sections will briefly consider some other conditions and circumstances.

9.1 Coupling with a public electricity grid

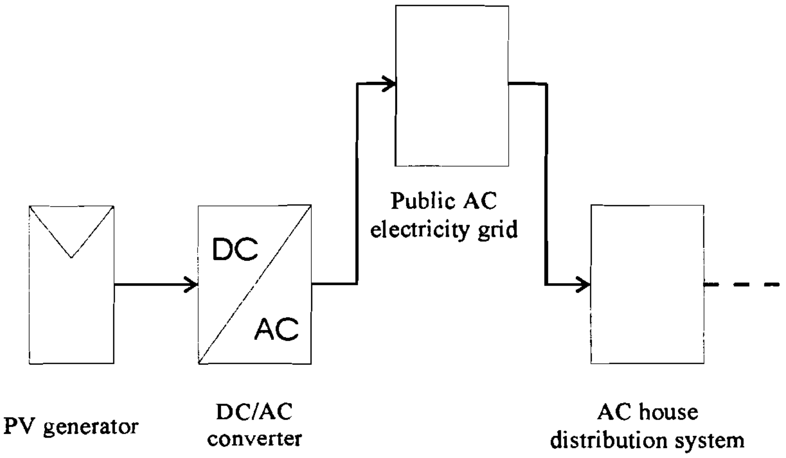


Figure 9.1: Coupling of the PV system with a public AC grid.

Figures 9.1, 9.2a and 9.2b show different arrangements for a coupling between a PV system and a public electricity grid. The coupling with a public AC grid (figure 9.1) is a simple representation of the way most PV systems are now installed in Western Europe. Figure 9.2a shows the same layout, but the public AC grid has been replaced by a public DC grid. The first two grid connected systems do not have the losses of a battery system (20 %). Furthermore, a grid connected system has the advantage that the electricity supply does not run the risk of being interrupted due to a loss of production of solar power. If a public electricity grid is available, it is obvious that a PV house is connected to this grid.

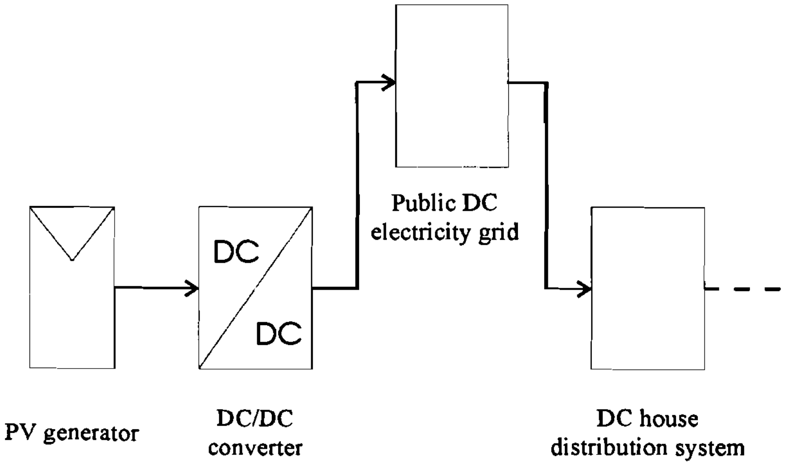


Figure 9.2a: Coupling of the PV system with a public DC grid, without a battery system.

Figure 9.2b illustrates an integration of the grid connected DC system in figure 9.2a and the autonomous DC low-voltage house according to layout 3. This system combines the advantages of both systems. It has the disadvantage of battery losses and converter losses, but the battery losses can be minimised if the battery capacity is chosen to be very small (this is not possible in autonomous systems). Additional advantages of this system are:

- The battery can perform peak shaving, by supplying stored energy during peak loads and storing energy during periods of low energy consumption.
- The battery provides a backup system for the electricity supply from the public electricity grid, the grid provides a backup for the PV system in times of low solar radiation.
- Since the battery can serve as a backup system, it may be possible to accept a lower reliability and more voltage variations in the public electricity grid. This enables a cheaper construction of the public electricity grid.

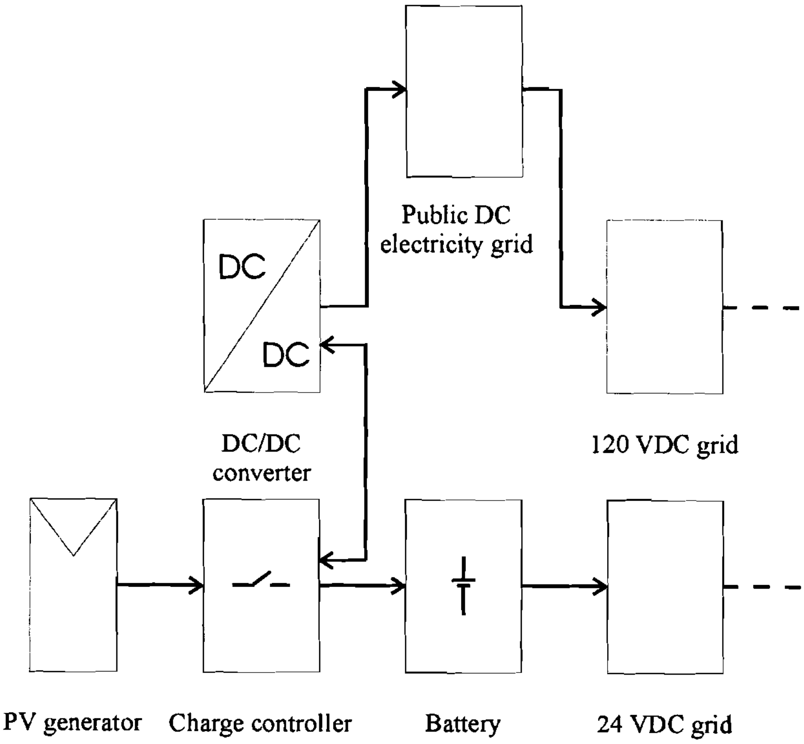


Figure 9.2b: Coupling of the PV system with a public DC grid, with a battery system and two system voltages (layout 3).

9.2 Solar Home Systems

Solar Home Systems need not satisfy the power demand of a modern household in a Western European country, but must satisfy the power demand of a household in a developing country. This power demand is much smaller, especially for places without a public electricity grid. In these places Solar Home Systems are often used to provide an electricity supply. Solar Home Systems are PV powered systems which fulfil only the most basic energy demands by supplying appliances such as lighting, well pumps, television, fans and cooling. Very efficient appliances are being developed especially for these Solar Home Systems. To obtain a cheap, efficient, easy maintainable and reliable system with a long life, a DC low-voltage system appears to be the best option. Solar Home Systems most often operate on a voltage level of 12 or 24 V.

9.3 Supply of one type of appliance

Instead of supplying the whole range of household appliances, the range could be limited, for example, to supply groups to which, for example, only lighting, heat pumps, air conditioning, computers or cooling are connected. This results in the following advantages:

- A DC voltage can be chosen to suit both the appliance and the PV system for optimum coupling between the PV system and the appliances. If a voltage is chosen to match the voltage level inside the appliance, a converter is not necessary and a reduction of conversion losses is possible.
- Power demand for appliances such as air conditioning follows the supply of solar energy. This is very useful in matching the energy demand to the energy production of the PV system. Such an optimum relationship may reduce the volume of the required energy storage system.
- For appliances which require a high quality of the supplied voltage, supply with DC may be a good option. The reason for this is that a DC distribution system enables a relatively simple connection to a DC backup system (for example, a battery) at every location in the system. In uninterruptable power supply systems (UPS systems) DC is often used for a connection with a backup system. Figure 9.3 shows a typical layout of an UPS system in an AC distribution system. An advantage of a DC distribution system is that the two converters may not be necessary. However, if a galvanic separation between backup system and the DC grid is required, a DC/DC converter will be necessary.

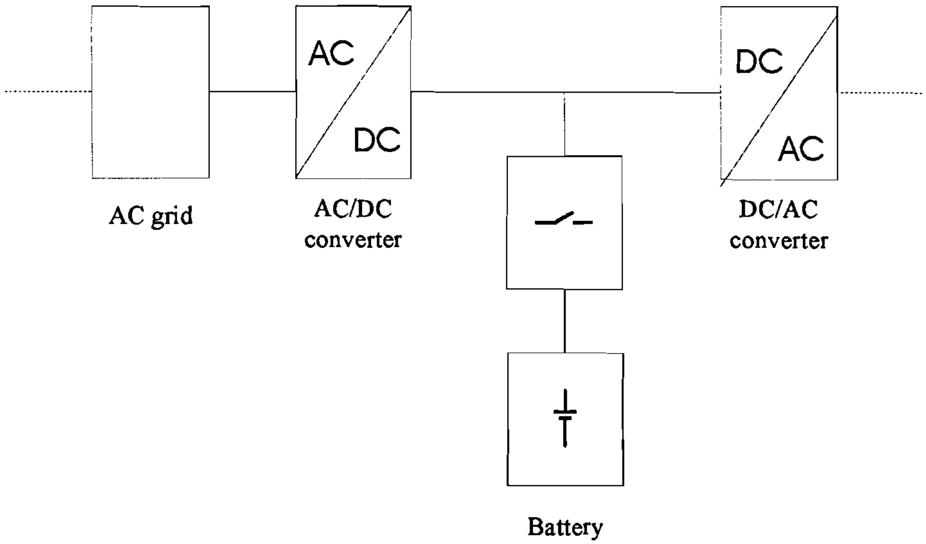


Figure 9.3: Typical layout of an UPS system.

9.4 Availability of very efficient converters

Assuming that very efficient converters are available then the elimination of conversion losses can no longer be the purpose of using DC instead of AC. Other aspects should then form the basis for using DC, for example:

- quality of the supplied voltage;
- reduction of electromagnetic interference,
- coupling of various electricity sources and storage systems to the electricity grid;
- reduction of reactive power losses.

9.5 Conclusions and recommendations

- Broadening of the boundary conditions and taking other circumstances into account, may lead to a different assessment on the feasibility of the DC low-voltage house.

- Further research into using DC in domestic dwellings should not only concentrate on reducing energy losses.

10. CONCLUSIONS AND RECOMMENDATIONS

The main conclusions from the research into the DC low-voltage house can be divided into three parts corresponding to the organisation of the project:

1. **Conclusions resulting from the research into the energy consumption of households:**
    - A change from AC to DC supply will in general not automatically result in energy savings in the household appliance.
    - DC supply of household appliances is possible. It depends on whether the appliance can be easily changed or adapted for DC operation.

2. **Conclusions resulting from the research into the DC low-voltage distribution system:**
    - Due to voltage and power losses, it will not be possible to satisfy the present power demand in households with a very low voltage distribution system, without using very large wire cross-sections.
    - The main problems which have to be considered in the design of the DC low-voltage distribution system are: switching of DC currents and limitation of short circuit currents.

3. **Conclusions regarding the feasibility of the DC low-voltage house:**
    - If the original boundary conditions of the project are held to, a change from AC to DC low-voltage in houses is not very promising. A large reduction of energy losses is not expected.
    - Taking other conditions and circumstances (for example: a very small power demand, the presence of a public DC electricity grid and the supply of certain types of appliances) into account, may lead to a more positive assessment of the DC low-voltage house.

Recommendations:

- In order to obtain a complete overview of the consequences of DC supply of household appliances, more research is required into:
    1. the design of household appliances and
    2. the difference between DC/DC and AC/DC converters.
- Further research into using DC in domestic dwellings should not only concentrate on reducing energy losses but should take other conditions and circumstances into account.

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Appendix A: Short circuit current of DC motor

Figure A.1 shows an equivalent circuit of a DC motor before and during a short circuit. The variable resistance is used to control the motor. If the DC motor is on its nominal speed, the resistance is small. In figure A.1 only 2% of the total voltage drop about the motor load is present over the variable resistance. The nominal current is equal to:

$$I_{DC} = \frac{0.02 \cdot V}{R} .$$

When a short circuit occurs in the system, 98 % of the nominal system voltage will be present over the small resistance (R) in the circuit. This causes a high short circuit current of approximately 50 times the nominal current:

$$I_{sc,DC} = \frac{0.98 \cdot V}{R} \approx 50 \cdot I_{DC} .$$

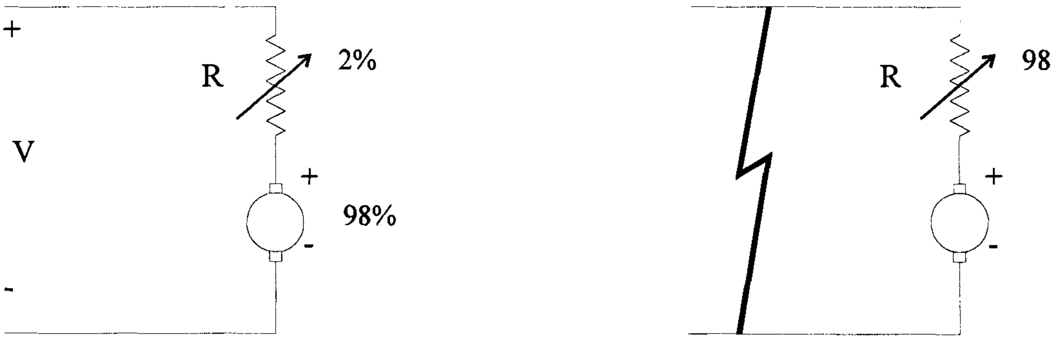
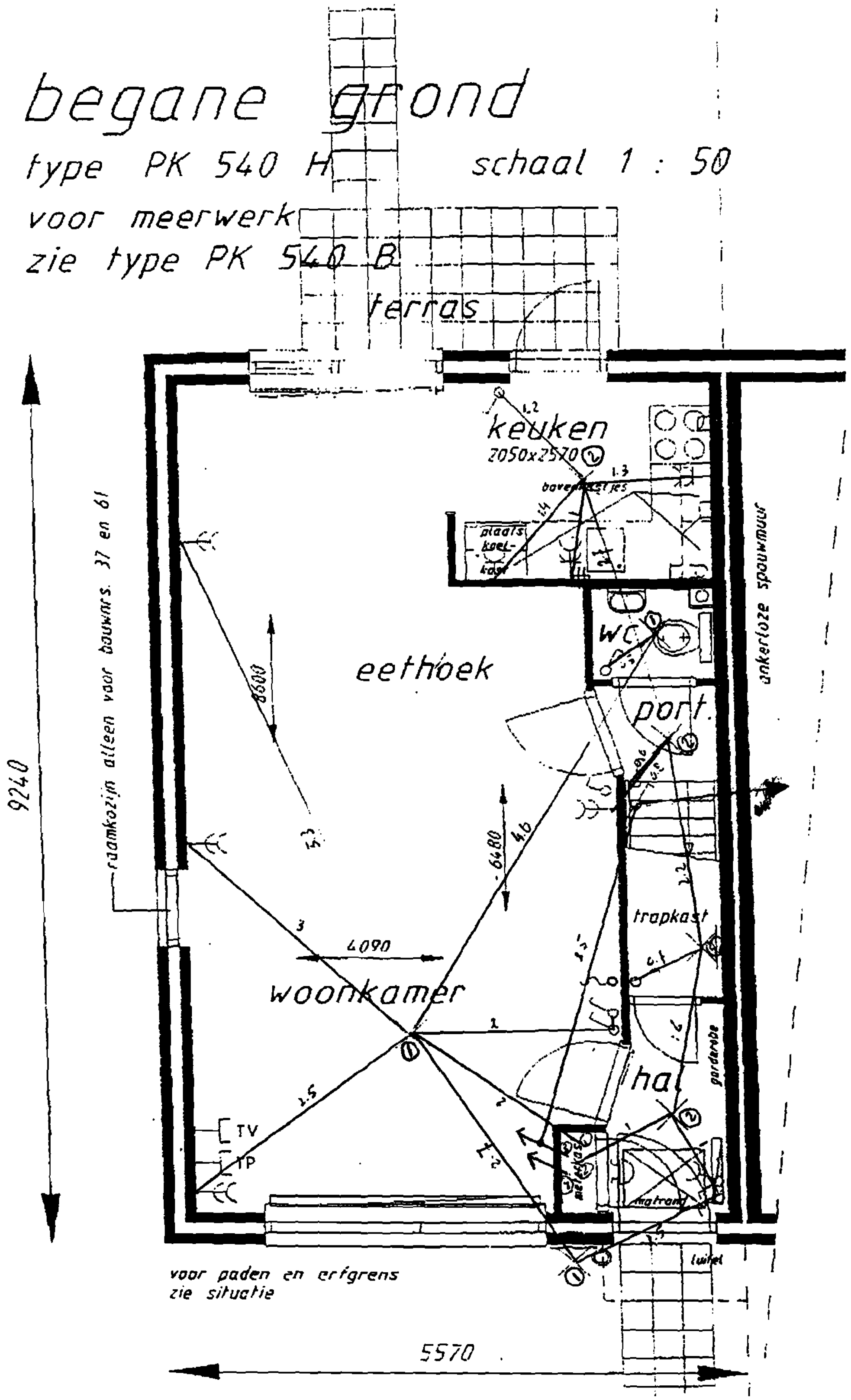


Figure A.1: Equivalent circuit of DC motor, before and during a short circuit.

For AC motors, the short circuit current is typically limited to about 6 times the nominal current due to the voltage drop over the self-inductance of the motor windings (L):

$$I_{sc,AC} = \frac{V}{\sqrt{R^2 + (\omega L)^2}} .$$

Appendix B: Plan of single family dwelling



verdieping

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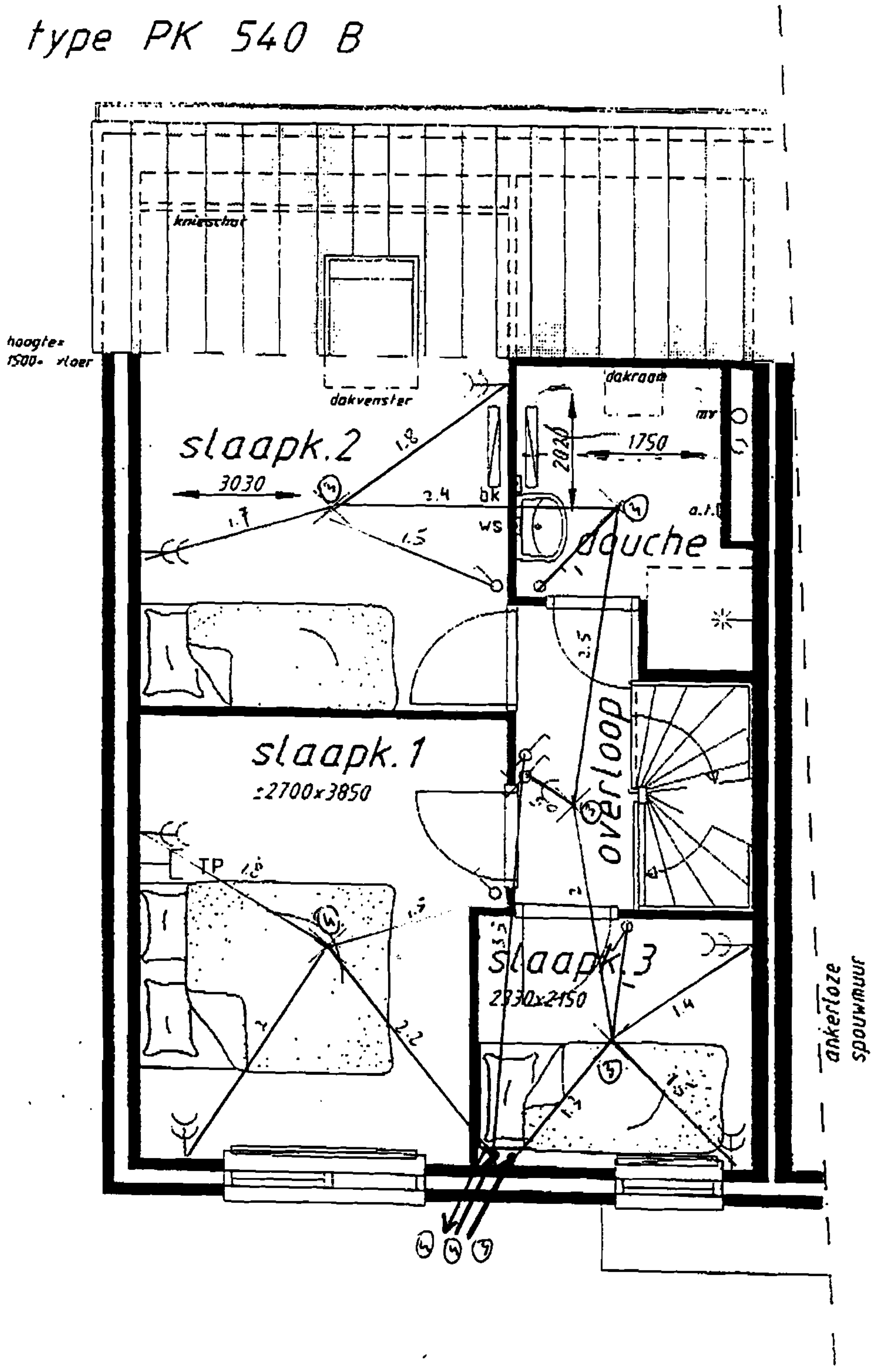
voor meerwerk
zie type PK 540 B



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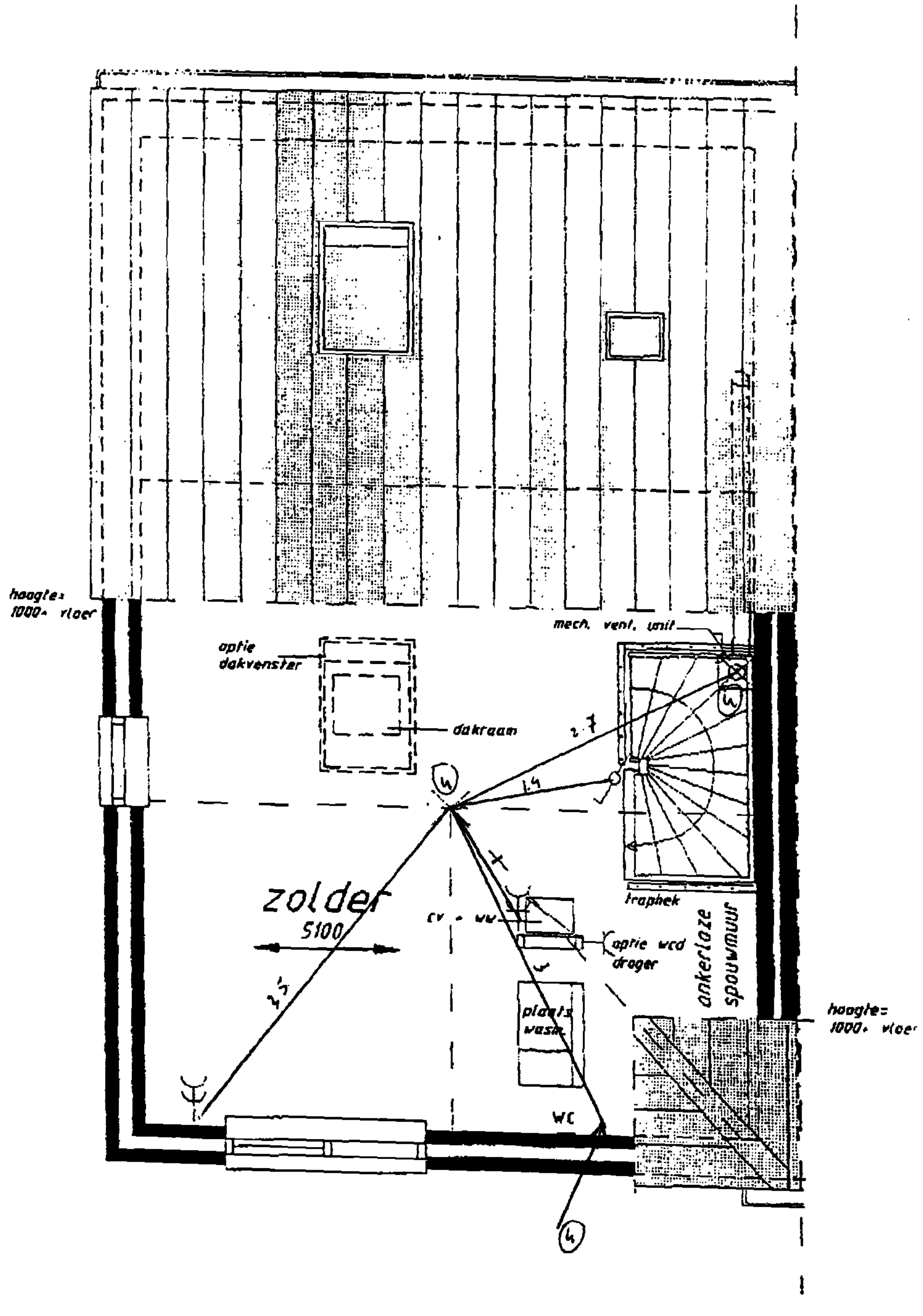
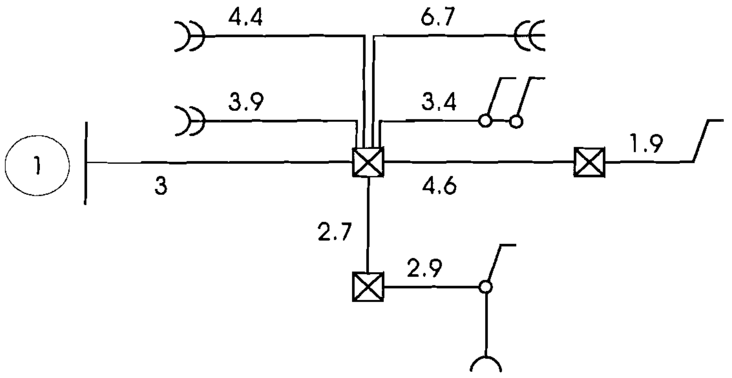
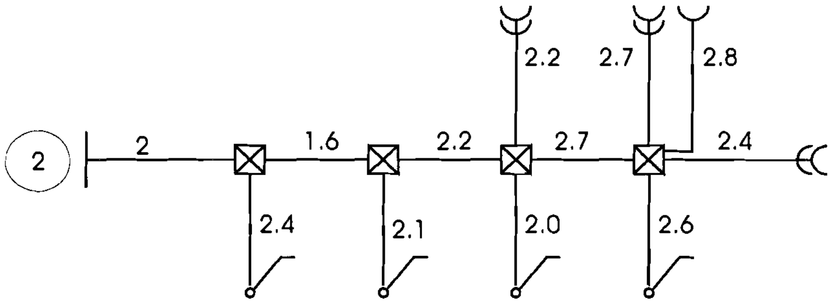
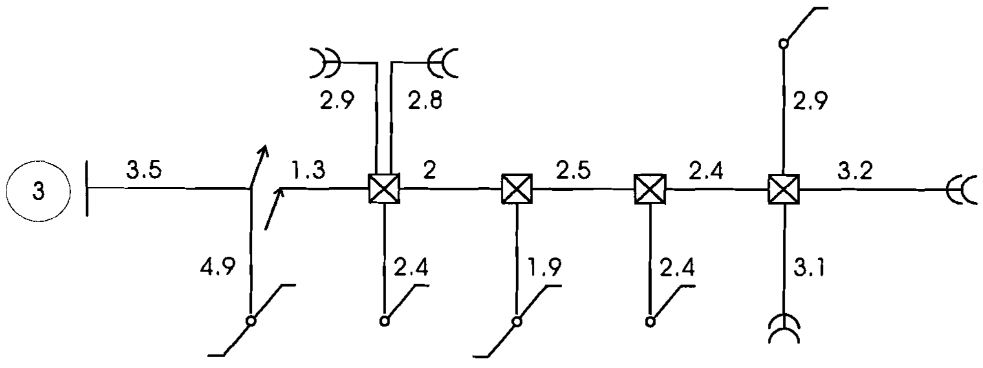
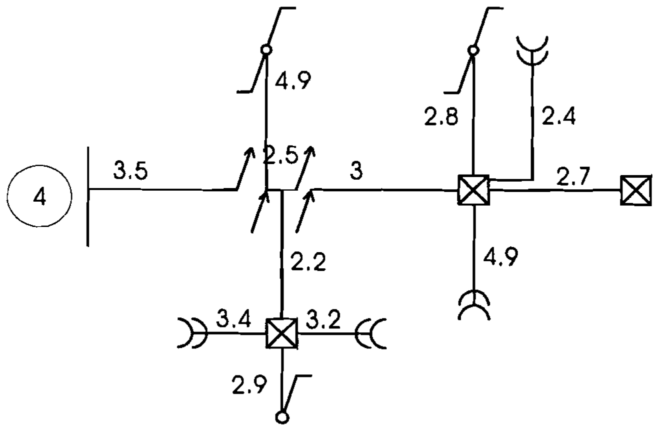


Appendix C: Plan of electrical groups of single family dwelling









The numbers in the figures give the distances (in m) between the components (central junction boxes, switches and outlets) of the groups.

Appendix D: Calculation of battery parameters

Battery capacity

The battery capacity needed for a 24 V DC system which consumes about 1000 kWh per year is calculated (the yearly consumption is based on the consumption in the solar home in Castricum [13], [14]). It is assumed that the energy consumption is divided equally over the year. The batteries are expected to contain enough energy to supply electricity for 3 days without being charged by the PV-system. This means that an energy storage of $\frac{3}{365}\cdot 1000 = 8.2$ kWh is needed. If the battery system is not further discharged than 70% of its capacity, the battery capacity has to be $\frac{8.2}{0.7} = 12$ kWh. For a 24 V battery this results in a capacity of C=0.5 kAh.

The internal resistance can be calculated with the help of manufacturers' data about batteries. The internal resistance for a 24 V battery system with a capacity of approximately 0.5 kAh is calculated for two different battery types in the following examples.

Battery resistance

Example 1: The internal resistance of a 24 V 0.5 kAh battery system when using the Kobe HP65-12 battery.

The Kobe HP65-12 battery has a terminal voltage of 12 V, a rated (20 hr) capacity of 65 Ah and an internal resistance (R_b) of 8 mΩ. The maximum discharge current is 500 A for 5 s. The charging voltage is about 14 V. To build a 24 V 0.5 kAh battery system, 8 parallel strings with 2 HP65-12 batteries on a string must be connected. Figure D.1 shows the construction of this battery system.

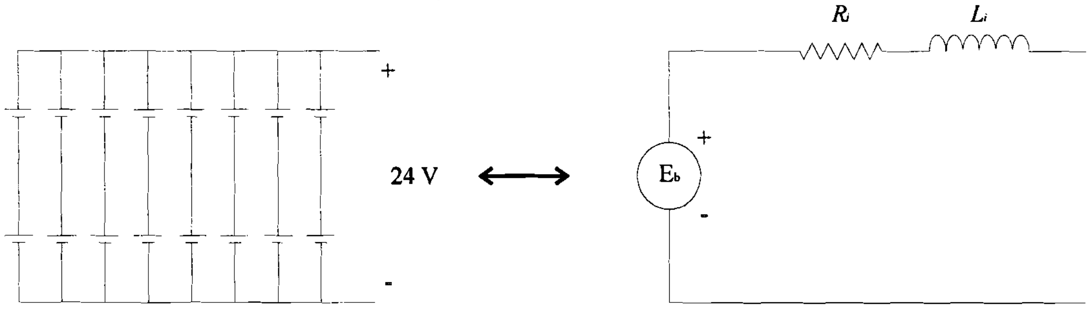


Figure D.1: 24 V 0.5 kAh battery system using the HP65-12.

The internal resistance of the battery system is equal to: $R_i = \frac{2R_b}{8} = \frac{2\cdot 8}{8} = 2$ mΩ. The short circuit power is $P_{sc} = \frac{E_{bat,\max}^2}{R_i} = \frac{28^2}{2\cdot 10^{-3}} = 392$ kW. The short circuit current at a short circuit at the battery terminals is: 14 kA.

Example 2: The internal resistance of a 24 V 0.5 kAh battery system when using Oldham lead/acid batteries.

The battery system is constructed by connecting 12 battery cells in series. Each battery cell has a nominal voltage of 2 V. The cell capacity is 545 Ah (12 hr). Figure D.2 shows the series connection of the battery cells. The internal resistance of each cell is R_b=0.5 mΩ.

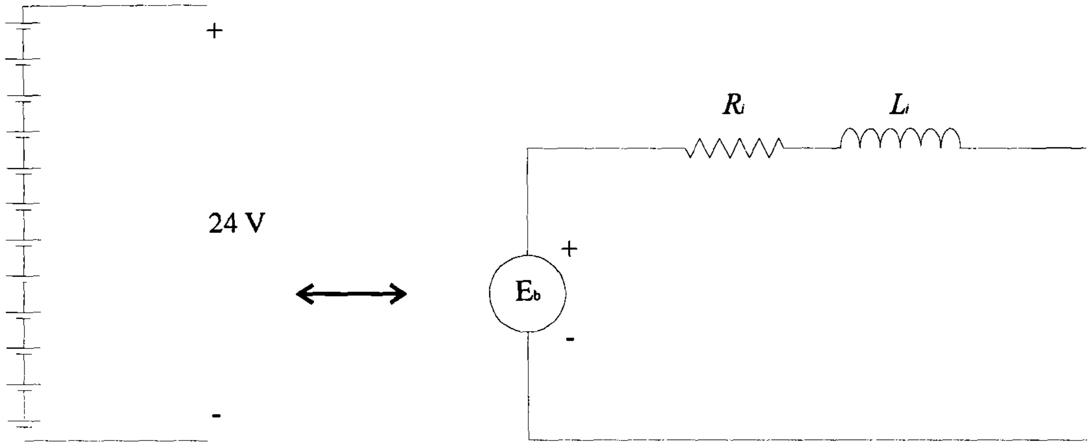


Figure D.2: 24 V 0.5 kAh battery system using Oldham lead/acid batteries.

The internal resistance of the battery system is equal to: $R_i = 12 \cdot R_b = 12 \cdot 0.5 = 6$ mΩ. The short circuit power is $P_{sc} = \frac{E^2_{bat,\max}}{R_i} = \frac{28^2}{6 \cdot 10^{-3}} = 131$ kW. The short circuit current at a short circuit at the battery terminals is: 4.7 kA.

The examples show that the internal resistance of the batteries is not very large. In subsequent calculations in this report a minimum internal resistance of 2 mΩ and a maximum resistance of 6 mΩ will be used for a 24 V DC source.

Battery inductance

The inductance of the source is important for short circuit calculations to determine the rise time of the fault current. Manufacturers do not give inductance values for their batteries. The inductance of a battery (L_c) is equal to the inductance (L_{cc}) of the cell circuit plus the inductance of the battery cells (L_{bc}). In 'Power systems analysis for direct current (DC) distribution systems' [34] the inductance is calculated for a certain battery. The result of these calculations is an inductance of about 30 μH for a battery with an internal resistance of 5 mΩ. So the time constant is $\frac{L}{R} = 6$ ms. This ratio will be used in the continuation of this report.

For battery systems with internal resistances of 2 and 6 mΩ, the inductance must be 12 and 36 μH respectively to obtain a $\frac{L}{R}$ of 6 ms. These values will be used in the short circuit calculations to represent a 24 V DC source.

The same calculations can be executed for the 120 V battery system. The 120 V system will need a capacity of 100 Ah for an energy reservoir of 12 kWh. The internal resistance and inductance for this system are:

$R_{i,min}$=10 mΩ, $R_{i,max}$=30 mΩ, $L_{i,min}$=60 μH, $L_{i,max}$=180 μH.

Appendix E: Calculation of grid impedances

The DC grid is modelled as shown in figure E.1. The resistance and inductance of the circuit depend on the length of the wires, on the cross-section of the wires and the lay-out of the system.

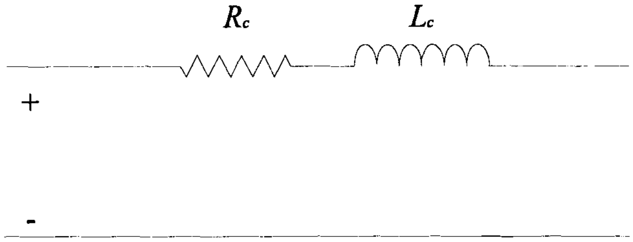


Figure E.1: Equivalent circuit for wires.

Circuit resistance

The resistance increases if temperature rises. To calculate the minimum short circuit current, the maximum tolerable conductor temperature of 70 °C is taken to calculate the resistance. The formula below is used to calculate the specific resistance for different temperatures.

$$\rho(T_2) = \rho(T_1) \cdot [1 + \alpha(T_2 - T_1)]$$

with:

- $r(T_2)$: resistance at temperature T_2;
- $r(T_1)$: resistance at initial temperature T_1;
- a: 0.00323 for copper conductors;
- T_1: initial temperature;
- T_2: desired temperature.

For copper conductors r(20 °C)=0.01724 Ω mm²/m. and r(70 °C)=0.020 Ω mm²/m.

Circuit inductance

To calculate the circuit inductance of the DC system, the formula for the self-inductance of two parallel conductors is used:

$$L = [0.05 + 0.2 \cdot \ln\frac{a}{r}] \cdot 10^{-6}$$

with:

- L: self-inductance in H/m;
- a: distance between conductors;
- r: radius of conductors.

The distance between the conductors is not constant through the whole installation. The minimum distance is defined by the thickness of the insulation. The maximum distance is determined by the diameter of the conduit carrying the wires. For the calculations it is assumed that a PVC conduit with a diameter of 19 mm is carrying the wires.

Table E.1 gives the inductance and resistance for 2.5, 4 and 6 mm^2 wires. The wires are carried by 19 mm PVC conduits. Table E.2 gives the inductance and resistance for wires which are carried in a copper duct of 19.8x22 mm, the copper duct is used as the return conductor.

Table E.1: Resistance and inductance values for different wire cross-sections

cross-sectio	r (mm)	a_{min} (mm)	a_{max} (mm)	R (Ω/m) 20 °C	R (Ω/m) 70 °C	L_{min} (μH/m)	L_{max} (μH/m)	L/R_{min} (ms)	L/R_{max} (ms)
2.5	0.89	3.3	15.7	0.0069	0.0080	0.31	0.62	38.8	89.9
4	1.13	3.9	15.1	0.0043	0.0050	0.30	0.57	60.0	132.6
6	1.38	4.4	14.6	0.0029	0.0033	0.28	0.52	96.6	179.3

If it is assumed that the wire is exactly in the middle of the copper duct, then the inductance for a wire in a copper duct can be calculated from the following equation:

$$L = 0.2 \cdot \ln(\frac{r_2}{r_1}) \cdot 10^{-6}$$

with:

- L: self-inductance in H/m;
- r_1: radius of inside conductor (mm);
- r_2: radius of outside conductor (mm).

Table E.2: Resistance and inductance values for wires in copper duct.

	r_1	r_2	R (Ω/m) 20 °C	R (Ω/m) 70 °C	L (μH/m)	L/R_{min} (ms)	L/R_{max} (ms)
2.5 mm^2	0.89	11	0.0069	0.0080	0.50	56.4	65.4
4 mm^2	1.13	11	0.0043	0.0050	0.46	78.4	91.1
6 mm^2	1.38	11	0.0029	0.0033	0.42	100.7	115.1
Copper duct 19.8x22 mm			0.00075	0.00087			

Appendix F: AC protection devices for DC systems (Merlin Gerin)

DC netwerken

keuze van de installatie-automaat

technische gegevens

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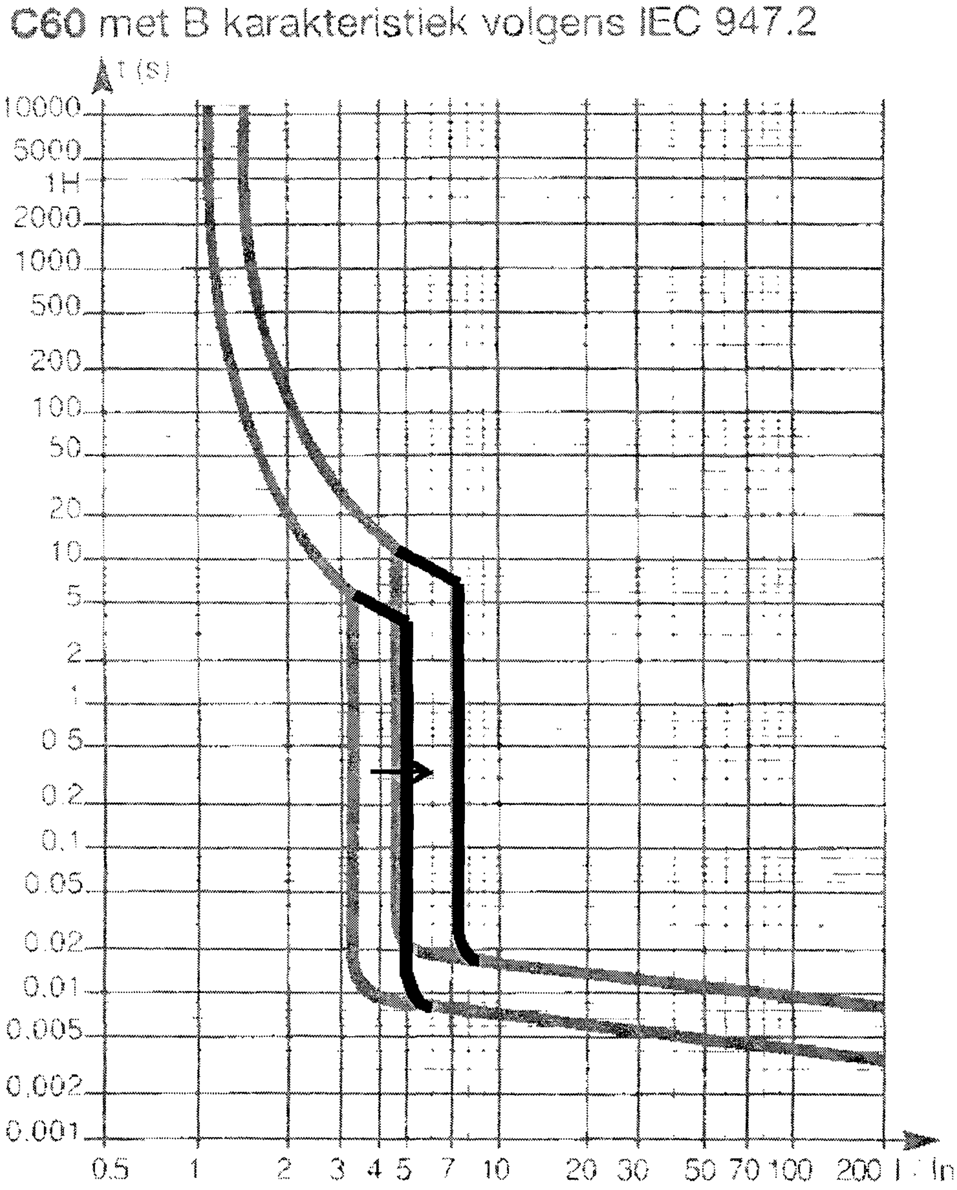
keuze van de installatie-automaat in DC netwerken
De keuze van het type installatie-automaat dat gebruikt kan worden in een DC netwerk is afhankelijk van de volgende criteria:

- de nominale stroom van de aangesloten apparatuur
- de voeding (ongeaard, één geaarde pool of middenaarding)
- de nominale spanning voor het bepalen van het aantal polen dat aan de uitschakeling moet deelnemen
- de maximaal optredende kortsluitstroom voor het bepalen van het kortsluitafschakelvermogen van de installatie-automaat

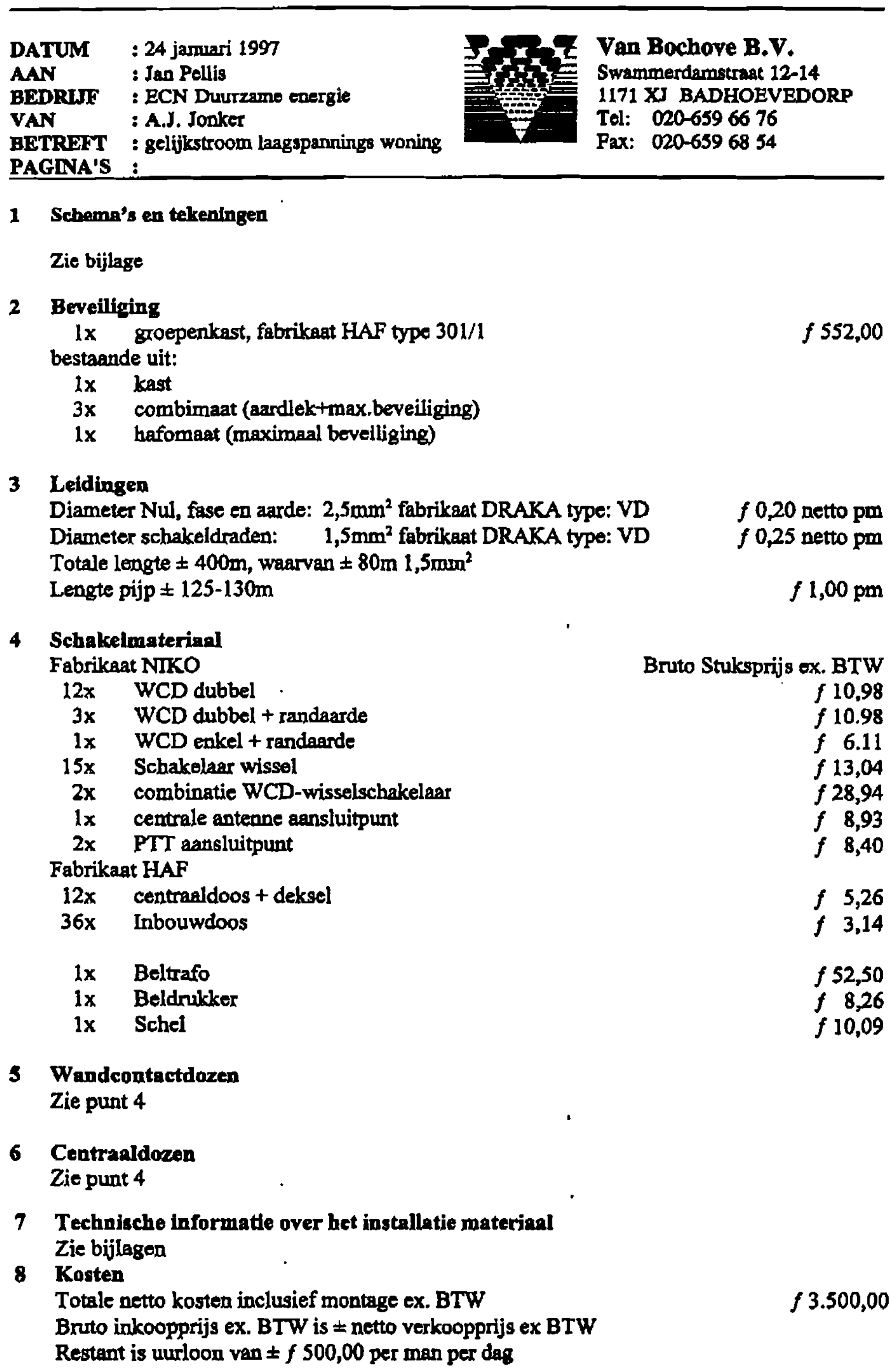
type automaat	In (A)	kortsluitafschakelvermogen (Icu in kA, L/R 0,015 s) (tussen haakjes het aantal polen dat aan de uitschakeling moet deelnemen)					overbelastings-beveiliging	coëfficient voor kortsluitbeveiliging
		24/48 V	**125 V**		**250 V**	**500 V**		
C32HDC*	1 tot 40	20(1P)	10(1P)	20(2P)	10(2P)		speciaal DC	speciaal DC
DPNa		15(1P+N)					gelijk aan AC	1,5
DPN N		15(1P+N)					gelijk aan AC	1,5 example: next page
C60a	6 tot 40	10(1P)	10(2P)	20(3P)	25(4P)		gelijk aan AC	1,38
C60N	6 tot 63	15(1P)	20(2P)	30(3P)	40(3P)		gelijk aan AC	1,38
C60H	1 tot 63	20(1P)	25(2P)	40(3P)	50(3P)		gelijk aan AC	1,38
C60L	1 tot 63	25(1P)	30(2P)	50(3P)	60(4P)		gelijk aan AC	1,38
NC100H	10 tot 100	20(1P)	30(2P)	40(3P)	20(4P)		gelijk aan AC	1,42
NC100L	10 tot 63				25(1P)	25(3P)	gelijk aan AC	1,42
NC100LS	10 tot 63				36(1P)	36(3P)	gelijk aan AC	1,42
NC100LH	10 tot 63				50(1P)	50(3P)	gelijk aan AC	1,42
NS100N	TMD16D	50(1P)	50(1P)		50(1P)	50(2P)	gelijk aan AC	gelijk aan AC
NS100H	TMD25D	85(1P)	85(1P)		85(1P)	85(2P)		
NS100L	TMD40D	100(1P)	100(1P)		100(1P)	100(2P)		
NS160N	TMD63D	50(1P)	50(1P)		50(1P)	50(2P)		
NS160H	TMD80D	85(1P)	85(1P)		85(1P)	85(2P)		
NS160L	TMD100D	100(1P)	100(1P)		100(1P)	100(2P)		
NS250N	TMD125D	50(1P)	50(1P)		50(1P)	50(2P)		
NS250H	TMD160D	85(1P)	85(1P)		85(1P)	85(2P)		
NS250L	TMD200D	100(1P)	100(1P)		100(1P)	100(2P)		
	TMD250D							

* de C32HDC is een gepolariseerde installatie-automaat uitgevoerd met een permanent magneet om een goede en snelle afschakeling van de stroom te realiseren. Zorg dus altijd voor de juiste aansluiting van de + en - pool zoals aangegeven op de installatie-automaat.



Conversion of AC trip curve to DC curve.

Appendix G: Price of electrical installation of single family dwelling



DATUM : 24 januari 1997
AAN : Jan Pellis
BEDRIJF : ECN Duurzame energie
VAN : A.J. Jonker
BETREFT : gelijkstroom laagspannings woning
PAGINA'S :

Van Bochove B.V.
Swammerdamstraat 12-14
1171 XJ BADHOEVEDORP
Tel: 020-659 66 76
Fax: 020-659 68 54

1 **Schema's en tekeningen**

Zie bijlage

2 **Beveiliging**

1x	groepenkast, fabrikaat HAF type 301/1	*f* 552,00

bestaande uit:
- 1x kast
- 3x combimaat (aardlek+max.beveiliging)
- 1x hafomaat (maximaal beveiliging)

3 **Leidingen**

Diameter Nul, fase en aarde: 2,5mm² fabrikaat DRAKA type: VD	*f* 0,20 netto pm
Diameter schakeldraden: 1,5mm² fabrikaat DRAKA type: VD	*f* 0,25 netto pm
Totale lengte ± 400m, waarvan ± 80m 1,5mm²	
Lengte pijp ± 125-130m	*f* 1,00 pm

4 **Schakelmateriaal**

		Bruto Stuksprijs ex. BTW
Fabrikaat NIKO		
12x	WCD dubbel	*f* 10,98
3x	WCD dubbel + randaarde	*f* 10.98
1x	WCD enkel + randaarde	*f* 6.11
15x	Schakelaar wissel	*f* 13,04
2x	combinatie WCD-wisselschakelaar	*f* 28,94
1x	centrale antenne aansluitpunt	*f* 8,93
2x	PTT aansluitpunt	*f* 8,40
Fabrikaat HAF		
12x	centraaldoos + deksel	*f* 5,26
36x	Inbouwdoos	*f* 3,14
1x	Beltrafo	*f* 52,50
1x	Beldrukker	*f* 8,26
1x	Schel	*f* 10,09

5 **Wandcontactdozen**
Zie punt 4

6 **Centraaldozen**
Zie punt 4

7 **Technische informatie over het installatie materiaal**
Zie bijlagen

8 **Kosten**

Totale netto kosten inclusief montage ex. BTW *f* 3.500,00
Bruto inkoopprijs ex. BTW is ± netto verkoopprijs ex BTW
Restant is uurloon van ± *f* 500,00 per man per dag