Eindhoven University of Technology

MASTER

Development of a voltage and frequency control strategy for an autonomous LV network with distributed generators

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2009

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Development of a Voltage and Frequency Control Strategy for an Autonomous LV Network with Distributed Generators

Master thesis report by M. Au-Yeung

The department of Electrical Engineering of the Eindhoven University of Technology disclaims any responsibility for the contents of this report.
Preface

After many months of struggling, debugging and solving problems I finally finished this graduation report. In addition a graduation paper is made and an conference paper from UPEC will be published. Before I go into detail about my graduation report, I want to focus on a side-story. Therefore I need to go back to september 2002, during this month I joined the electrical engineer introduction week where a lot of strangers are placed together. After few days of getting drunk, the strangers became during these years my classmates. I remembered the first year of my bachelor of electrical engineering as a hard time where lectures and projects occupied 40 hours a week. Housework was placed above these hours and creates 50 hours working weeks.

The remaining bachelor years I followed all the courses of electrical engineering and was very interested especially in energy topics. Therefore I selected the master with energy mini-courses where my interest grows for especially Intelligent Electricity Networks.

Next to my education, I was board member of the 'Wervingsdagen' (company fair TU/e) which gave me the opportunity to know how companies are operating. During this period I decided that I want do my internship in a company and in the field of Intelligent Electricity Networks. Therefore I (together with another classmate) walked into Johanna Myrzik's room and asked her for the possibilities. She supported us by giving us an opportunity to do our internship in Germany at the institute ISET located in Kassel which was a really nice experience. After my internship I walked again towards Johanna and asked her for possibilities to do my graduation in a company. Johanna gave me the opportunity to continue the work of Merel in Alliander and also introduces me to several supervisors, in the end a total of 4 supervisors are selected.

Greet Vanalme was one of my supervisors, she has been very supportive during my graduation period. She helped me to create a professional paper, graduation report and to present my work in a correct way. During my graduation, she gave me the opportunity to present my ideas in front of the Trein project. Therefore I would like to thank her for all the effort and time she spent on me.

As my graduation project is in cooperation with a company (Alliander (former Continuuon)) a supervisor from Alliander, Martijn Bongaerts was introduced to me. My first working day in Alliander have been a really nice experience, where Martijn showed me the nice landscape around the building and introduced me to many colleagues. It was really hard for me to remember all these people but thanks to a real Chinese (Cantonese kitchen) dinner where delicious chicken legs are introduced, I could remember some of the colleague names. I would like to thank Martijn for these nice experiences and also the support
during my graduation period.

At the start of my graduation, Merel suggested me to take an extra supervisor with a lot of technical knowledge. Therefore I asked Martijn for an extra supervisor, Jan Bozelie became my technical supervisor from Liandon providing me information about technical issues. I went to Jan for technical advice once or twice a month. Since Liandon is located at the other side of the Netherlands (fictional distance) mostly the trip is taking longer than the working time. However, the travel time is certainly not wasted because Jan provided me a lot of support for technical problems. In the end I would like to thank him for his support during my graduation period.

This has been a really nice graduation period, whereby I worked very hard and spent a lot of time. The hardest part of my graduation period is that during my simulations (each simulations takes a few hours simulation time) sometimes my notebook will crash. Fortunately, Martijn gave me the possibility to simulate my model in Alliander with a stronger computer. This provides me to work in parallel, writing report and doing simulations simultaneously. Besides my supervisors, I would like to thank Anton Ishenko for his support in showing me the DiGSILENT environment. Sjef Cobben and Sharmistha Bhattacharyya helped me to solve problems in DiGSILENT. I would like to thank Jasper Frunt for the support in Latex issues and Totis for helping me out in correcting my sentences in my paper. I would like to thank a friend who is also from electrical engineering Peter who helped me in correcting my English sentences.

From Alliander, I would like to thank Peter Sluijs, Harry van den Breen and Marcel Hooijmans for their support in my graduation. Hopefully I didn’t forget someone but in case I did I would like to thank everyone who supported me during my graduation.

This report is my final piece of work as my graduation is coming to an end. I would like to invite you to read my graduation report and additionally to read my graduation paper and shortly published UPEC paper.
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# List of Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Current in ampere</td>
<td>[A]</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
<td>[μF]</td>
</tr>
<tr>
<td>C-rate</td>
<td>Battery Hourly Rate charge/discharge</td>
<td></td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generator</td>
<td></td>
</tr>
<tr>
<td>E-demand</td>
<td>Electricity demand</td>
<td></td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Inductance</td>
<td>[H]</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Lithium-ion</td>
<td></td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage</td>
<td></td>
</tr>
<tr>
<td>MV</td>
<td>Medium Voltage</td>
<td></td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>Nickel Cadmium</td>
<td></td>
</tr>
<tr>
<td>μCHP</td>
<td>Micro Combined Heat and Power</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Active Power</td>
<td>[kW]</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
<td></td>
</tr>
<tr>
<td>PVGIS</td>
<td>Photovoltaic Information System</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>Reactive Power</td>
<td>[kvar]</td>
</tr>
<tr>
<td>R</td>
<td>Resistance</td>
<td>[Ω]</td>
</tr>
<tr>
<td>V</td>
<td>Voltage</td>
<td>[V]</td>
</tr>
<tr>
<td>X</td>
<td>Inductive reactance</td>
<td>[Ω]</td>
</tr>
</tbody>
</table>
List of Definitions

**Actuator**: A distributed generator or storage device with inverter interface whereby the power or voltage and frequency can be controlled.

**Autonomous operation or island state**: During disturbances (voltage drops, black out, faults, etc.) outside the microgrid, the generation and corresponding loads in the micro-grid can separate from the distribution system to isolate the loads from the disturbance (and thereby maintaining service even in situations of changing the loads) without harming the transmission grid's integrity. Maintaining service means satisfying the voltage and frequency requirements described in the Dutch grid code [55].

**Micro-grid**: A low voltage electrical grid where electrical loads and small generation systems (such as fuel cells, microturbines, wind generators, photovoltaic panels) together with storage devices (like flywheels and batteries) coexist through an embedded management and control system. This grid can operate in autonomous operation mode.
Summary

A novel control strategy to operate a low-voltage (LV) micro-grid in grid connected operation mode as well as autonomous operation mode is presented in this graduation report. The selected micro-grid is formed by small-scale single phase distributed generators such as Micro Combined Heat and Power (μCHP) and Photovoltaic (PV) systems close to the detached household. Active power produced by distributed generators is estimated using weather conditions (solar, temperature and wind) as described in [43].

The control strategy is based on inverter technology connected to a storage device. This control strategy is able to improve the voltage at the load during grid-connected operation mode. In case of autonomous operation mode the inverter takes over the responsibility from the upper-grid and creates the grid voltage and frequency. However, it is impossible to create permanently autonomous operation when the selected DG’s are only producing energy depending on the weather information because demand is more than produced power [43]. Therefore to establish permanently autonomous operation, μCHPs are enabled via a data communication system (in case of no heat demand) when the battery energy level is in critical state.

Additionally active and reactive power information is exchanged among multiple inverters using the communication system. This creates an equal distribution of active and reactive power in every part of the network.

In literature [35] it is shown that voltage and frequency can be controlled by active and reactive power. However the influence of active and reactive power on voltage and frequency depends on the inverter output impedance which is formed by resistance R and inductance X (embedding cable or/and series inductor or/and virtual resistive output impedance and low pass filter).

In case $R \gg X$ (resistive approach) decreases the influence of reactive power on the voltage compares to active power on voltage. In addition the influence of active power on the frequency decreases where the influence of reactive power on frequency increases. The relation will be denoted as resistive behavior while inductive behavior (HV overhead lines behavior) is used for networks where the $\frac{X}{R}$ ratio is very small.

In case $R \ll X$ (inductive approach), active power has more influence on the frequency compares to reactive power. But reactive power becomes more dominant to control the voltage compared to active power.

Stability analysis shows that resistive droop control approach is more robust
and damped compared to the inductive approach. Simulation results in DiGSI-
LENT Powerfactory verifies the stability analysis and confirms that resistive
droop is preferred in LV networks.

Therefore resistive droop control strategy is developed which injects active
power in case the measured inverter output voltage deviates from \(230V_{RMS}\)
(nominal voltage). During autonomous operation, when the measured frequency
deviates from 50 Hz(nominal frequency) reactive power is injected towards the
grid. In addition each phase voltage is separately controlled to create an unbal-
anced droop control strategy.

Simulation results for excess, shortage and average scenario’s show that the
voltage levels have been improved during all situations. E.g. excess scenario
in July results in voltages above the allowed voltage range but this is solved
by enabling the control strategy. Additionally the transformer loading has less
variations because of the control strategy.

Moreover simulation results in case of unbalanced loading show that the
novel control strategy can decreases the phase to phase voltage difference.

The control strategy is able to switch from grid-connected to autonomous
operation mode and power supply is guaranteed permanently due to the control-
able \(\mu\)CHPs. However, the transition from grid-connected towards autonomous
operation mode must be managed correctly otherwise oscillations will occur.

A choice is made between inductive and resistive droop, however in reality
the inverter output impedance is not fixed. This suggest to apply adaptive droop
control, calculating in real-time the output impedance to control the micro-grid
using resistive or inductive droop control. Another option is to use more robust
control algorithms such as LQGC (Linear Quadratic Gaussian Control) and
MPC (Modern Predictive Control)[7].

Furthermore, the developed communication system can be extended by send-
ing dynamic droop gain information. The droop gain information can be used
to reduce the electricity price (trader) or improving the voltage and frequency
(grid-operator).

Transients are out of the scope of this graduation project, in reality this can
play an important role in the control strategy. This indicates the need of further
research to extend this control strategy making it possible to solve transients.

At the end laboratory test are required to verify the simulation results.
Part I

Introduction and Background Information
Chapter 1

Introduction

In the future, a transition in the low voltage network might take place from the conventional design towards a micro-grid concept. The micro-grid is formed by small-scale single phase distributed generators such as Micro Combined Heat and Power (μCHP), Photovoltaic (PV) systems and storage devices (flywheels, batteries and energy capacitors) close to the loads (households and shopping centers). The shift towards small-scale generation close to the loads can increase the reliability, efficiency and voltage quality of the grid on the condition that the network is adequately managed and coordinated [8] ,[39]. The management and coordination of a micro-grid is complex because the energy production of the distributed generators mainly depends on the weather conditions (solar, temperature and wind) and is less predictable. Additionally, different stability problems can be caused by mismatching of supply and demand [35]. Moreover during disturbances (voltage drops, interruptions, faults etc.) inside or outside the micro-grid, the micro-grid must be able to operate in an autonomous operation mode, isolating the micro-grid from the upper-grid and comply with the standard as described in the Dutch grid code [47]. In case of autonomous operation mode sufficient storage capacity should be provided.

The main objective of this research is to create an efficient and reliable control strategy to operate a micro-grid connected to the grid or in autonomous operation mode.

This research fully concentrates on strategies based on inverter technology connected with a storage device.

Relevant side targets for the control strategy are:

1. The ability to maintain service under excess, shortage and average (demand) scenarios
2. The ability to react rapidly under fast energy production changing [11].
3. The ability to operate multiple inverters in parallel to manage and coordinate the micro-grid.

The research leads to a micro-grid simulation model based on an unbalanced droop controlled inverter including a communication interface between the inverters, implemented in DiGSILENT Powerfactory.
Chapter 1. Introduction

A correctly managed and coordinated micro-grid can decrease the loading in cables and transformers. As a consequence a decrease in investments in cables and transformers can be achieved. Additionally a micro-grid consisting of PV systems and μCHPs can reduce the transport losses [10] due to the close proximity of demand and supply. This results can possible decrease the CO₂ emission to help the Netherlands satisfying the Kyoto protocol [49].

The graduation report is divided in several parts and each part is divided in several sections. In the next section background information about control of voltage and frequency is explained. Part II describes in detail the simulated micro-grid including the corresponding generators and storage device. In part III the inverter control strategy is illustrated and the communication system with multiple inverters is described in part IV. The performance of the proposed control strategy and the effects on the low voltage (LV) network are presented using simulation results from D IgSILENT-PowerFactory in part V. Additionally section 9 describes the environmental impact as a consequence of the control strategy. Finally, part VI shows the conclusions and recommendations.
Chapter 2

Background Information

This section describes the reason behind the transition from conventional control strategies towards state of the art control strategies.

Figure 2.1: Power flow in conventional grid
Chapter 2. Background Information

2.1 Conventional Control Strategy

In figure 2.1 is illustrated the conventional grid whereby power flows from high voltage towards low voltage grid. The power flows in one direction, and the voltage and frequency is controlled by fully controllable synchronous generators at the HV grid [35]. When the produced active power is not equal with the demanded active power, the difference compensated by a change of kinetic energy at the rotating synchronous generators. This change results in a deviation from the nominal frequency. E.g generation is larger than demand at a given grid frequency, then the energy is stored in the rotating inertia of the grid connected generators, resulting in a slowly increasing frequency. A change of voltage is a result of an unbalance in reactive power supply and demand.

The conventional grid controls the voltage and frequency between the allowed range [47] using the synchronous generators. The control is divided in three parts primary control, secondary control and tertiary control [35]. Primary control (based on droop control) is used to establish equal demand and supply at a system frequency close to 50 Hz. Secondary control restores the frequency towards 50 Hz and tertiary control ensures that the active power is dispatched in the most economic way.

Whenever the share of DGs increases at the low voltage network, it is not advisable/possible that the grid connected generators guarantees the balancing of the power flow. Therefore new control strategies should be applied to guarantee the voltage and frequency stability [36].

2.2 State of the Art Control Strategies

The possible increase of DGs in the low voltage network [36] will result that the power does not flow only in one direction as shown in figure 2.2.

The transition of power flow from unidirectional towards bidirectional can cause for example voltage problems in the LV grid [32]. The conventional control strategy does not take into account this transition change and can not manage correctly the increase of power flow in the LV grid. To overcome these problems, researchers are trying to find new control strategies to control the voltage correctly in the LV grid.

State of the art control strategies are able to continuously supply energy to the load in case of problems in/out side of one part of the LV grid. Researchers are using micro grid [36] as reference network to analyze the LV grid during grid-connected mode as well as autonomous operation mode.

In a micro grid, it will not be common to find fully controllable synchronous generators, which are normally responsible for voltage and frequency control. Most DGs are not suitable for direct connection to the electrical network due to the characteristics of the energy produced. Consequently, power electronic interfaces (DC/AC) are required for the storage devices and photovoltaic system to connect with the grid. The power electronic interface like inverters plays a important role for the voltage and frequency control in a micro-grid.

Several control strategies for inverters can be applied, in this case two control strategies from literature are analyzed whereby one is based on controlling the DGs and storage devices centrally and the other one managed the grid using a decentralized method.
2.2 State of the Art Control Strategies

Figure 2.2: Power flow in future networks

Figure 2.3 shows an overview of the central controlled micro grid containing loads, controllers, inverters and DGs. The strategy which controls the DGs and storage devices centralized use a micro grid central controller (MGCC) installed at the MV/LV transformer as top of the hierarchical control system [39]. At a second hierarchical control level, controllers located at loads (LC) or at groups of loads and controllers located at DGs (MC) exchange information with the central controller, that manage the control of the micro grid by providing set...
points to the load controllers and DGs controller.

The information exchange contains set points such as active and reactive power for controllers at loads, at DGs and at storage devices. In addition information requests sent by the micro grid central controller about active and reactive powers, voltage levels and messages to control the micro grid switches.

The second control strategy is based on distributed control of DGs and storage devices whereby information is exchanged only between the different DGs and storage devices [19]. In this case the MGCC is not required anymore.

Both strategies use an inverter who can control the voltage and frequency. However one is totally distributed controlling the storage devices and DGs and the other one is centrally controlling the DGs and storage devices. Information exchanged with the network operator is the status, currently exchanged power to/from the grid. An overview of advantages and disadvantages about the central and the distributed control of distributed DGs and storage devices are shown in table 2.1 and table 2.2.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well ordered global overview micro grid</td>
<td>Risk of global problems in case of software problems</td>
</tr>
<tr>
<td>Only short digital communication lines</td>
<td>Requires a lot of digital communication lines</td>
</tr>
<tr>
<td>Only requires to maintain the central system</td>
<td>Requires qualified people to control central system</td>
</tr>
<tr>
<td>Globally overview of control</td>
<td>Complex system to regulate all DGs</td>
</tr>
<tr>
<td>Require a special protocol to transfer</td>
<td></td>
</tr>
<tr>
<td>Easy target for terrorist to attempt</td>
<td></td>
</tr>
<tr>
<td>Requires special security measures for the location</td>
<td></td>
</tr>
<tr>
<td>Privacy problems considering the information exchange</td>
<td></td>
</tr>
<tr>
<td>Complexity increase by increase of units</td>
<td></td>
</tr>
<tr>
<td>Price consideration for development of central system and communication protocol</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Overview advantages/disadvantages central controlled micro grid using distributed actuators

The overview shows that the central system has some important disadvantages compared to advantages.

E.g. when there is a disturbance in the central system it will cause a malfunction in the central system which can lead to large problems. The requirement to use new digital communication lines to communicate with the central server can be discarded by exchanging information using the existing internet infrastructure such as ADSL, cable and optical fiber communication systems.

The complexity increases by extending the amount of units yielding an adaptive algorithm to allocate and add new units in the centrally controlled micro-
### 2.2 State of the Art Control Strategies

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less people required to maintain distributed system</td>
<td>Maintaining households requires reparation at home</td>
</tr>
<tr>
<td>Software problems are only local problems causing only loss of one resource</td>
<td>More measurement points required</td>
</tr>
<tr>
<td>Adding units will not increase complexity</td>
<td>Inverter control strategy complexity increases</td>
</tr>
<tr>
<td>Difficult target for terrorist</td>
<td>Price considerations inverter</td>
</tr>
<tr>
<td>Only requires unidirectional information exchange towards grid operator</td>
<td>Less control and overview total micro grid</td>
</tr>
</tbody>
</table>

Table 2.2: Overview advantages/disadvantages distributed controlled micro grid using distributed actuators

Distributed control system is more preferred considering the function to 'plug and play' without increasing the complexity. Also the communication protocol is more simple compared to the central control system where all the information is aggregated.

In paper [19] a distributed control based on technical and cost constraints is presented and an micro grid internet communication protocol is shown in paper [51].

State of the art control strategies show two directions, one which controls the micro-grid using a central controller which is located at the MV/LV transformer. Another direction is based on multi-agent which leads to decentralized decisions, each unit determines his own actions.
Part II

Defining the Micro-Grid
Chapter 3

Proposed LV Network

This section presents a representative Dutch LV network which operates as reference network for simulations. The performance and robustness of the control strategy should be tested using this reference network. Section 3.1 describes the urban area Meekspolder which is the starting point of the reference network. The urban area Meekspolder is reduced to a smaller LV network which is more suitable for research purposes in section 3.2.

3.1 Micro-grid Meekspolder

The main focus is to develop a voltage and frequency control strategy for the LV micro-grid. Therefore an appropriate LV network, a network which satisfies all requirements for a real LV network should be used as reference network. As starting point a typical Dutch modern urban area called 'Meekspolder' is analyzed as shown in figure 3.1.

This area entails:

- 184 households, 5 different types

![Figure 3.1: Electrical grid structure 'Meekspolder' [23]](image-url)
• Three apartment buildings
• One big school
• Shopping center
• 8 m² roof surface on the southern side of each household
• 1000 m² roof surface on the southern side of the utilities

where the low voltage grid settings:
• Radial structure
• 95 mm² Al cables
• 630 kVA MV/LV transformer
• Average of 40 households on one descending cable
• Maximum feeder length 500 m
• Utilities on separate cable.

This network entails every aspect of an urban area but it is more understand-able to analyze the control strategy using a reduced network. However, reducing the network must not lead into a unreliable simulation network. Most important aspect is to verify that the control strategy will work for the reduced network as well for the Meekspolder. In the following section a reduced LV network is developed by reducing the Meekspolder using worst case scenarios.

3.2 Reduced Micro-Grid

The proposed reduced micro-grid system consist of a combination of 3 storage devices including inverter front-end and 360 households with PV systems, μCHP systems as shown in fig. 3.2. The micro-grid can be connected to or disconnected from the upper-grid and transformer (10 kV/400 V, 630 kVA) by operating a breaker.

The houses are equally distributed among the 3 phases of 3 feeders (Al, 95mm², worst case scenario(maximum feeder length Meekspolder): lengths of 400m, 450m and 500m). To simplify the simulations, the 40 houses connected to the same phase of a feeder are aggregated to 1 load and 1 generator (simulated as 1 negative load representing 40 μCHPs and 40 PV systems).

Loads (power demand of detached households), μCHPs (1 kW_e, 4 kW_th) and PV systems (1 kW_{peak}) are modeled based on load and generator power profiles from weather records (wind, solar and temperature data sets) acquired from [43]. The main reason to simulate detached households is the higher demand of heat leading to a higher electricity production and therefore to possible excess scenarios.

The analysis is performed for the year 2020 considering an electrical power demand increase by 1.5% per year compared to the information provided by [43]. The voltage and frequency stability is guaranteed by the storage system and inverter during grid-connected operation mode as well as autonomous operation.
3.2 Reduced Micro-Grid

Figure 3.2: Micro-grid system description

mode. The storage systems are placed on each feeder (at distances of 630 m, 680 m and 730 m from the transformer to create a worst case scenario). Lithium-ion battery storage is chosen because of the high performance and high energy density (210 W h/dm$^3$) as described in [34]. From practical point of view (use of public area) and to enable autonomous operation mode for a specified time period, a maximum storage size of 6300 kWh (size of a sea-container) is chosen. In section 5, several storage device options and storage sizes are considered.
Chapter 4

Distributed Generators

This section explains the working principles of the used DGs in the autonomous LV micro-grid. A combination of $\mu$CHP and PV is chosen because of the complementary weather depending behavior of both generators. First of all electricity production from $\mu$CHP depends on the heat demand and photovoltaic produces electricity depending on the amount of solar radiation. During winter the temperature and solar radiation is low causing a low PV electrical power output and high $\mu$CHP electrical power output. While in summer the temperature and solar radiation is high, resulting in a high PV electrical power output and a low $\mu$CHP output. The combination of both DGs enhance the possibility to match supply and demand during the whole year. Section 4.1 describes the $\mu$CHP and section 4.2 illustrates the PV system.

4.1 $\mu$CHP

$\mu$CHP is the simultaneous production of heat and power in the home. Essentially, the $\mu$CHP replaces the conventional boiler in a central heating system, and comprises a small gas engine which drives an electrical generator. The waste heat from the engine is used for heating and the electricity is either used in house or exported to the network to be consumed by neighbors [27].

Currently, there are several parties developing different types of $\mu$CHPs [41]. In this report, a choice is made to use the Microgen as reference for the $\mu$CHP (Highest market potential in the Netherlands). The further developed and tested Microgen proves to be suitable to supply detached households with heat and electricity [43], [6], [48].

The Microgen Stirling engine, a $\mu$CHP formed around a free piston Stirling engine to produce simultaneously heat and electricity is shown in figure 4.1. Additionally, figure 4.2 shows the working principle of the built in beta type Stirling engine.

The working principle is described already in [43] and enumerated below.

1. Gas is burned in the gas burner.

2. The hot gas is entering the acceptor and exchanges the heat with the cold water from the central heating system.

3. Due to the temperature difference, the gas pressure increases.
Chapter 4. Distributed Generators

4. Conversely, lowering the temperature of the gas using the rejector leads to a corresponding decrease in gas pressure.

5. The displacer moves from one side to the other side and vice versa due to the change in gas pressure.

6. The displacer motion causes a pressure wave upon the face of the piston.

7. The piston is attached to a ring of magnets which will swing through the coil of wire within the linear alternator.

8. This creates a magnetic field and as a consequence the alternator produces an AC current.

The swing through the coil is balanced at 50 Hz resulting in a 50 Hz AC current output.

The Remeha Microgen has an overall efficiency of 110 % which is 30 % electrical efficiency and 80 % thermal efficiency [22]. The total efficiency is
4.2 Photovoltaic System

above 100% due to the added condenser in the Microgen. The condenser make use of the outside temperature to enlarge the temperature difference leading to a higher efficiency. Microgen produces around 1 kW electrical power and 4 kW thermal power which is sufficient to supply the detached household demand [43]. Moreover, an additional heater of 20 kWth is embedded in the Microgen to provide warm water, therefore an extra boiler is not required.

Figure 4.3 shows the measured start-up cycle of the Microgen. After turning on the Microgen, it takes 2 minutes for the generator to supply electricity to the grid. After that, the power output raises slowly to full capacity. The 15-minute-mean electricity supply of a start-up delivers 71% of the nominal 15-minute-mean electricity supply, corresponding to an average electricity yield of 0.18 kWh in 15 minutes and a continuous average power output of 0.72 kW after start-up. When the Microgen is deactivated, it takes 3.5 minutes before the generator completely stops delivering power. In the 15 minutes after the μCHP is deactivated the μCHP electricity supply is 12% of the nominal electricity supply, corresponding to an average electricity yield of 0.03 kWh in 15 minutes and a continuous power output of 0.12 kW after the μCHP is turned down. Concluding, the μCHP power profile starts with 0.72 kW for the first 15 minutes and remains 1 kW until the μCHP is switched off. The power profile finishes off with 0.12 kW along the 15 minutes after the μCHP has been turned off [44].

Figure 4.3: Measured start and stop cycle for a Microgen (y-axis: Output power(Wₑ), x-axis: Time(minutes)) [6]

4.2 Photovoltaic System

Photovoltaic is related to the field of energy applications using solar cells by converting sunlight directly into electricity. The electrical power output depends on the solar radiation and outside temperature.

The power output of the Philips crystalline solar cell (PSM 125) is taken as an example in this research, which delivers 125 W_{peak} per panel with a surface of 1 m². The reactive power output is mainly formed by the inverter capacitance. Electronic converters have a power factor of 0.95 or higher. The optimum inclination angle in a Dutch case is 36° and south-oriented. The monthly and yearly potential electricity generation E (kWh) of a crystalline PV configuration with defined module-inclination and orientation can be calculated with the following formula: \[ E = n \times P_k \times r_p \times H_{h,i} \] Where n is the number of days in a month or year, \( P_k \) (kW_{peak}) is the peak power installed, \( r_p \) is the system performance ratio (typical value for roof mounted system with modules...
from mono- or polycrystalline silicon is 0.75) and $H_{b,i}$ is the monthly or yearly average of daily global irradiation on the horizontal or inclined surface. Further aspects that influence PV yield are:

1. Estimated losses due to temperature: 7.0% (using local ambient temperature)
2. Estimated loss due to angular reflectance effects: 3.0%
3. Other losses (cables, inverter etc.): 14.0%

Above values are estimated by the Photovoltaic Information System (PVGIS), a research, demonstration and policy support instrument of the European Commission [43].
Chapter 5

Storage Devices

In this section a comparison is made between different storage methods. Additionally, arguments are provided for the selected storage size and position of the storage device in the reduced micro-grid.

The reduced micro-grid situation requires storage to ensure among other things such as load leveling, load dispatch and production dispatch. This implies storing up energy during off-peak hours (low energy cost) and the use of stored energy during peak hours (high energy cost). The use of storage in the reduced micro-grid can be accomplished using one big storage device, few medium storage devices or small storage devices in each house. The choice whether to choose for a big, small or medium storage device depends on the voltage and frequency control approach.

Consider a few medium size storage devices (possible size in public area) which are placed at the end of the feeder supplying 120 households. The distance between storage device and transformer is chosen quite large to realize a worst case scenario. In case the control strategy can operate under these circumstances, it certainly can handle distances closer to the transformer. Note that in reality, a network operator will consider earlier to place the storage devices closer to the transformer because of the space around the transformer house. To verify the control strategy a bad case scenario is analyzed to guarantee that the control strategy not only function correctly in the reduced LV network but can also function correctly in the urban area Meekspolder.

Another important aspect is to determine an optimum battery storage size considering several aspects such as autonomous operation, price consideration and statistical information about the duration of an outage which demands a certain storage size.

Consider the duration of a normal outage which is in the Netherlands around 85 minutes average [14]. This suggest to have a maximum storage size which can handle at least 85 minutes of autonomous operation. However, this assumption is only valid when the upper-grid will be connected to the micro-grid after a certain time.

The main objective of this research is to create a micro-grid which operates in autonomous operation mode for a long period. This means that the micro-grid must satisfy the voltage and frequency regulations during this period as described in [47]. This criteria requires to place as large as possible storage
device in the micro-grid, leading to a maximum volume for the storage device\(^1\).

A sea container has a volume of 30 m\(^3\), this is a realistic maximum volume for placement in an urban area. During the simulations a storage device with a volume of 30 m\(^3\) is chosen as reference size.

The storage technology can be compared using criteria enumerated below [26] and a short summary is shown in figure 5.1

<table>
<thead>
<tr>
<th></th>
<th>Storage capacity</th>
<th>Available power</th>
<th>Power transmission rate</th>
<th>Discharge time</th>
<th>Efficiency</th>
<th>Durability</th>
<th>Autonomy</th>
<th>Costs</th>
<th>Feasibility and adaptation to the generating</th>
<th>Self discharge</th>
<th>Mass and volume densities of energy</th>
<th>Monitoring and control capabilities</th>
<th>Operational constraints</th>
<th>Reliability</th>
<th>Environmental aspect</th>
</tr>
</thead>
</table>

The classification in power ratings and discharge time at rated power is shown in figure 5.2. Power demand for a separate household, school, apartment buildings or shopping center is estimated between 1kW and 60kW. Applying the power demand constraint on figure 5.2 a selection of storage techniques can be composed consisting of Lithium ion accumulators (Li-ion), lead acid battery, long duration flywheels, high energy capacitors, high power flywheels and high power super capacitors.\(^2\).

Currently, lead acid batteries are relatively the most inexpensive storage technique as shown in figure 5.3 [42]. But they are not necessarily the least expensive option for energy management, due to their relatively low durability. In contrast with lead acid batteries have electrochemical capacitors, Li-ion and flywheels a longer durability without losing efficiency.

Moreover, the urban area realization is aimed for 2020 whereby the prices for Li-ion, high power energy capacitors and high power flywheels will probably reduce to an acceptable value [34].

Besides those aspects, it is also important to have an insight about the mass and volume densities for the different storage techniques. Despite the fact that the storage is placed stationary, the space around a feeder can possibly be limited. In this case Li-ion is preferred to operate in the urban area Meekspolder.

\(^1\)The excess periods should be stored in the storage device and used in a later stage. The selected DGs (\(\mu\)CHPs and PV systems) in the reduced micro-grid will always result in a shortage according to the yearly electricity production and demand [44]. This shortage will be larger when the excess periods are not stored, then the shortage need to be repaired by e.g. controllable \(\mu\)CHPs (autonomous operation) which has an electrical efficiency of 15\% (heat demand is zero). More information about the electricity demand and production and the time this storage device can run in autonomous operation is explained in section 9.

\(^2\)The storage technology nickel cadmium (Ni-Cd) is not considered due to the extreme toxicity of cadmium.
Figure 5.1: Summary storage techniques [43]

Figure 5.2: Compare storage techniques by power [26]

An overview for the weight energy density with the volume energy density is shown in figure 5.4.
Figure 5.3: Compare storage techniques by cost [26]

Figure 5.4: Compare storage techniques by mass and volume densities of stored energy [26]

Additionally, state of the art technology (year 2009) of commercial products shows that the discharge rate of Li-ion cell is fast enough to solve excess and shortage problems within the required time period (seconds)\(^3\). The discharge rate depends on the size of the storage size, e.g. when the C-Rate is 1 for a 100 kWh storage a continuously discharge of 100 kW for one hour is achieved. In case the C-Rate is 2, this results in a continuously discharge of 200kW for a half hour under the same circumstances. However there is a trade-off between the discharge rate and nominal capacity as shown in figure 5.5. State of the

\(^3\)http://www.al23systems.com/technology/power
art Li-ion cell shows that nominal capacity is barely reduced until a C-Rate of 35, in this case the Li-ion cell can maximum discharge 3500 kW in 1.7 minutes which is equal to \(34 \frac{kW}{s}\).

![Power High Retained Capacity](image)

Figure 5.5: Discharge rate for a state of the art Li-ion cell

Also power quality problems can be solved by Li-ion however this is not recommended because a high discharge rate reduces considerable the battery effective capacity. Super capacitors or flywheels are recommended for power quality problems [26].

As described before a storage size of 30 m\(^3\) is considered as storage volume which is in case of Li-ion equal to 6300 kWh or for each detached household is 52.5 kWh (Yearly E-demand (2020) household = 4600 kWh) storage reserved.

The trend towards Li-ion as main storage technology is clearly visible. Several examples using Li-ion as storage technology are already in the market such as laptop battery, phone battery, digital photo-camera and one of the most promising increase of Li-ion usage is the introduction electrical cars [30]. The electrical cars are normally embedded with a storage size between 20-53 kWh depending on the type of the car. E.g. an Mitsubishi i-MiEV (family car) is embedded with a storage of 20 kWh ⁴ while a Tesla Roadster (sports car) is embedded with a storage size of 53 kWh ⁵.

The penetration of electrical cars results also in an increase of storage in the LV network. This results in a possible decrease of investments in new battery storage systems to enable efficiently autonomous operation.

Summarizing, in the year 2020 Li-ion is preferred to operate as storage technology to solve shortage and excess periods and super capacitors or flywheels are recommended for power quality problems.

⁵[http://www.teslamotors.com/blog4/?p=59]
Part III

Inverter Control Strategy
Chapter 6

Voltage and Frequency Control Based on Inverter Technology

The stability in a micro-grid concerning frequency and voltage control can be controlled by inverters [4],[7],[32],[39].

In section 6.1 the PWM inverter is described followed by the classification of the inverter functionality; enabling the possibility to operate the urban area 'Meekspolder' in autonomous operation mode or grid connected operation mode. Section 6.3 describes the LV relations between active or reactive power against voltage or frequency. Two main inverter control topologies are introduced in section 6.4 where one topology is selected to deploy the voltage and frequency control. Subsequently, in section 6.5 stability analysis are performed to design a proper controller.

In the appendices, detail about the implementation in DiGSILENT and the design of some subsystems are described. Firstly appendix B explains the design of a proper current control and a method to retrieve the single phase dq transformation. Finally in appendix D every part of the DiGSILENT implementation is described.

6.1 Basics of PWM Inverter

Pulse width modulated (PWM) inverter converts a direct current (DC) into an alternating current (AC) or AC to DC, a common PWM inverter circuit is shown in figure 6.1.

These inverters can control the magnitude and frequency of the output voltage by applying pulse width modulation to change the duty ratio of the switches [46]. In order to create an alternating current a sinusoidal control signal with a desired frequency is compared with the triangular waveform. Based on the magnitude comparison, switches $T_{a+}$ or $T_{a-}$, $T_{b+}$ or $T_{b-}$, $T_{c+}$ or $T_{c-}$ are switched on. The frequency of the triangular waveform establishes the inverter switching frequency and is kept constant along with its amplitude.

A simple schematic for the PWM inverter together with the control is shown
in figure 6.2 where at the DC side a storage device is connected and the grid is connected with the AC side. The control part creates a sinusoidal control signal with a desired frequency based on the current and voltage measurement. The measurements are directly taken from the converter (point:1) or after the transmission cables (point:2). From stability criteria it is more robust to take it from point 2 [15], however this requires a data communication system to forward the measurement values from the end of the cable back to the control. Additionally it increases the system to rely on the data communication system, therefore this graduation report proposed to control the system using measurement values from point 1 (directly after the LPF). The design and implementation for the control system is discussed in the following sections.
6.2 Classification of Inverter Functionality

Inverters interconnected in parallel to the grid can be classified in feeding, supporting and forming the grid by their electrical behavior and contribution to the grid [7].

Grid-feeding inverters are designed to feed a certain amount of power defined by the maximum power adaptation. The grid feeding-inverter can be modeled as current source and can only be applied to an existing grid.

Contrarily, the grid-forming inverter can realize a stand-alone system by controlling the grid frequency and the grid voltage by balancing the active and reactive power demand and supply. This type of inverters can be characterized
as a voltage source and because of large circulating reactive power in case of
parallel connected, they are not allowed to be connected in parallel with other
grid-forming inverters. The large circulating reactive power is caused by voltage,
phase or frequency measurement errors, which caused the inverters to obstruct
each other to control towards the specified voltage and frequency. In this case
a master and slave combination has to be created in order to prevent large
circulation of reactive power.

The grid-supporting inverter can control the grid voltage and frequency with­
out causing circulating reactive power. The inverter supports the grid in power
balance by adjusting the supply of active and reactive power.

The aim for the graduation topic is to realize a micro-grid which can operate
connected to the grid and as isolated island.

### 6.3 Control Relations in Low Voltage Grids

The relationships of voltage and frequency control depends on the output impedance
which is formed by e.g. the connected underground LV cable. An comparison of
different kind of transport cables/lines is shown in table 6.1. This comparison
shows that high voltage lines are mainly inductive and low voltage cables are
predominantly resistive. The medium voltage line has mixed parameters, the
simulation made for the urban area 'Meekspolder' consist of low voltage cables.

<table>
<thead>
<tr>
<th>Cable and overhead line</th>
<th>Resistance ([\Omega_{/\text{km}}])</th>
<th>Inductive reactance ([\Omega_{/\text{km}}])</th>
<th>Capacitive reactance ([\Omega_{/\text{km}}])</th>
<th>Maximum current rating ([\text{A}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV line</td>
<td>0.047</td>
<td>0.1382301</td>
<td>0.16</td>
<td>664</td>
</tr>
<tr>
<td>MV line</td>
<td>0.161</td>
<td>0.190</td>
<td>0.2</td>
<td>396</td>
</tr>
<tr>
<td>LV cable</td>
<td>0.32</td>
<td>0.082</td>
<td>0.66</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 6.1: Overview of different line and cable parameters [1]

The control dependency can be described by means of the power transfer
through an impedance as depicted in figure 6.3. \(U_a\) and \(U_b\) are respectively input
and output voltages with a specific power angle. For simplicity the power angle
for \(U_a\) is fixed at 0 degree. The angle \(\phi\) between the current and voltage \(U_a\) is
the power factor angle at point a. The cable inductive reactance, resistance R
and a possible additional inductive term are united in the impedance \(Z\) with a
specific angle \(\theta\) \((Z=R+jX, R=Z\cos(\theta), X=Z\sin(\theta))\). Cable capacitances are
ignored due to the high impedance which results in a negligible influence in the
voltage.

\[
\begin{align*}
  \begin{array}{cc}
    a & \quad I \angle \phi \\
    S_a & \quad U_a \angle 0 \\
    & \quad Z \angle \theta \\
    & \quad U_b \angle -\delta \\
  \end{array}
\end{align*}
\]

Figure 6.3: Power flow through a LV cable
6.3 Control Relations in Low Voltage Grids

The model will be analyzed for sinusoidal steady state using complex phasors. The complex analysis are valid for single phase and balanced three phase systems[7], [46]. Starting from the left side of figure 6.3, the complex power flowing through point a can be defined as:

\[ S_a = P + jQ = U_a^* I^* = U_a \left( \frac{U_a^*}{Z} \right)^* = U_a \left( \frac{U_a - U_b e^{j\delta}}{Ze^{-j\theta}} \right) \]  

(6.1)

Editing these equations by mathematical operations as described in appendix A.1 results in:

\[ U_a - U_b \cos(\delta) = \frac{RP + QX}{U_a} \]  

(6.2)

\[ U_b \sin(\delta) = \frac{XP - RQ}{U_a} \]  

(6.3)

Observe from equation 6.2 and 6.3 that active and reactive power are coupled with voltage and phase angle \( \delta \).

The coupling intensity depends on the cable R and X ratio. For higher \( \frac{R}{X} \) ratio is the influence of reactive power on the voltage lesser compares to active power on voltage. Additionally, the influence of active power on the power angle \( \delta \) decreases where the influence of reactive power on the power angle increases.

In networks where \( \frac{R}{X} \) ratio is lower, the relations becomes reversed which means that active power influenced more the power angle \( \delta \) compares to reactive power. But reactive power becomes more dominant to control the voltage compares to active power.

In low voltage networks are mainly resistive cables placed leading to the relation \( R > > X \). Analyzing the behavior in case of a small power angle \( \delta \); \( \sin(\delta) = \delta \) and \( \cos(\delta) = 1 \) yields

\[ U_a - U_b \cos(\delta) \approx U_a - U_b \approx \frac{RP}{U_a} \]  

(6.4)

\[ U_b \sin(\delta) \approx U_b \delta \approx -\frac{RQ}{U_a} \]  

(6.5)

or described as:

\[ P = \frac{U_a^2}{R} - \frac{U_a U_b \cos(\delta)}{R} \]  

(6.6)

\[ Q = -\frac{U_a U_b \sin(\delta)}{R} \]  

(6.7)

A phase shift \( \delta \) between two voltage sources can be controlled by reactive power transmission according to equation 6.5. The stability boundary for the power angle \( \delta \) is located between -90 deg and 90 deg due to the nearly linear behavior (angle changes are coupled with a linear change in reactive power) as shown in figure 6.4. In practically applications, power angle \( \delta \) is normally small resulting in the relations 6.4 and 6.5.
Chapter 6. Voltage and Frequency Control Based on Inverter Technology

Active power transmission depends on the voltage difference $U_a$ and $U_b$. This forms two decoupled dependencies of active power to voltage and reactive power to phase shift; this relationship is hereinafter called resistive droop.\(^1\)

A graphical representation of the active and reactive power in polar coordinates for resistive output impedance is shown in figure 6.5.

Figure 6.5 is explained using two examples. In these two examples a change of input voltage is illustrated as well as an adjustment of phase angle $\delta$. The two examples are summarized in table 6.2.

<table>
<thead>
<tr>
<th>Example</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Voltage step: $U_1 \rightarrow U_2$</td>
<td>$P$ and $Q$?</td>
</tr>
<tr>
<td>Case 2</td>
<td>Phase angle step: $\delta_1 \rightarrow \delta_2$</td>
<td>$P$ and $Q$?</td>
</tr>
</tbody>
</table>

Table 6.2: Summary $P$ and $Q$ changes excited by different voltages or power angles $\delta$

Starting with the first example, from operation point $S_1$, an increase of voltage $U_m$ from $U_1$ to $U_2$ leads to a higher apparent power operation point $S_2$. This causes a small change (increase) of reactive power and a larger change of (increase) active power as depicted in figure 6.5.

Furthermore a transition from operating point $S_2$ to $S_3$, caused by an increase of power angle from $\delta_1$ to $\delta_2$, tends to significantly increase the reactive power and create a small change of active power towards a lower output power value. These relations can also be considered in the other way around, analyzing the influence of changing active and reactive power on the voltage and power angle $\delta$.

Nevertheless are most paper publications based on inductive droop control,

\(^1\)Droop approaches are named differently in several papers. In [2] it is denoted as conventional and opposite droop. In this paper inductive and resistive droop control is consistently used as it is more clear to name the approaches according to the output impedance at the power injection point (impedance of virtual resistive output impedance, LV cables and inverter low pass filter).
6.3 Control Relations in Low Voltage Grids

Figure 6.5: Polar plot for $P$ and $Q$ with different voltages and power angles for resistive output impedance

controlling phase shift with active power and voltage with reactive power under the same low voltage cable parameters [2], [9], [20], [31], [54]. Inductive droop control can only be applied when $X >> R$ yielding for a small power angle $\delta$:

$$U_a - U_b \cos(\delta) \approx U_a - U_b \approx \frac{QX}{U_a} \tag{6.8}$$

$$U_b \sin(\delta) \approx U_b \delta \approx \frac{XP}{U_a} \tag{6.9}$$

The two examples (see table 6.2) are also shown in a polar representation (only valid for inductive output impedance) as shown in figure 6.6.

For the situation of inductive output impedance an increase of voltage $U_1$ to $U_2$ leads to e.g. increasing reactive power and a small increase in active power. Additionally a reasonable increase of active power is achieved by increasing the power angle which also causes a small decrease in reactive power.

The change of phase angle $\delta$ is related to the frequency deviation $df$ according to (6.10) (Laplace domain)

$$\frac{d\delta}{df} = \frac{2\pi}{s} \tag{6.10}$$

A comparison of controlling voltage and frequency by resistive or inductive approach regarding technical possibilities is shown in Table 6.3 [20].

Both strategies have advantages and disadvantages.

The first advantage for the inductive droop approach is that it can enable active power dispatch because frequency is a global parameter. Since voltage can only be influenced locally the resistive droop approach is not applicable for active power dispatch.
Moreover, the inductive approach is compatible with the high voltage level while this is not the case for the resistive approach. Finally, synchronous generators are also using the inductive droop approach, which makes it a well known approach.

In case of resistive droop, voltage can be controlled directly by injecting active power which is impossible for the inductive droop approach.

In addition, the impedance in LV networks is predominantly resistive ($R \gg X$). Applying inductive droop control in LV grid requires the addition of a series inductor (at the inverter output filter or in front of the load) or assuming a large inductive value at the output of the filter to increase the $\frac{X}{R}$ ratio. However, assuming a large inductive value at the output filter is not always true as it also depends on the control strategy. E.g. in [24] is an inverter design with resistive virtual output impedance proposed.

Furthermore, the inductive coupling can cause problems for the voltage stability of the system. This occurs due to a possible decrease of resonance frequency towards the grid frequency [21], [24], [37].

Both approaches are able to control voltage and frequency. An investigation is performed for the resistive and inductive droop approach to determine which implementation is more preferable to create a micro-grid. In section 6.5 stability analysis will be performed for both strategies.
6.4 Control of Grid Supporting Inverters

<table>
<thead>
<tr>
<th>Active power dispatch</th>
<th>Inductive droop</th>
<th>Resistive droop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+ (yes)</td>
<td>- (no)</td>
</tr>
<tr>
<td>Compatible with HV level</td>
<td>+ (yes)</td>
<td>- (no)</td>
</tr>
<tr>
<td>Compatible with synchronous generators</td>
<td>+ (yes)</td>
<td>- (no)</td>
</tr>
<tr>
<td>Direct voltage control</td>
<td>- (no)</td>
<td>+ (yes)</td>
</tr>
<tr>
<td>Series inductor</td>
<td>- (yes)</td>
<td>++ (no)</td>
</tr>
<tr>
<td>Stability</td>
<td>- (yes)</td>
<td>++ (no)</td>
</tr>
</tbody>
</table>

Table 6.3: Comparison resistive and inductive droop relations (+=Positive and -=Negative)

6.4 Control of Grid Supporting Inverters

In this section two main control structures for the inverter are compared and one of them is used as main frame for the control of grid supporting inverters. The droop relations as depicted in section 6.3 should be used to create droop controlled inverters or grid-supporting inverters. Both control structures are formed with inductive and resistive droop relations as described in [2], [7], [39].

The first control structure use droop relations which relates frequency or voltage in function of active and reactive power as depicted in equations 6.11 and 6.12.

\[
egin{align*}
    f &= f_0 - k_{fi}(P - P_0) \\
    U &= U_0 - k_{ui}(Q - Q_0) \\
    f &= f_0 + k_{fr}(Q - Q_0) \\
    U &= U_0 - k_{ur}(P - P_0)
\end{align*}
\]  

(6.11)  

(6.12)

whereby the frequency \( f \) and amplitude voltage \( U \) of the inverter output are controlled by the inductive \( (k_{fi}, k_{ui}) \) or resistive \( (k_{fr}, k_{ur}) \) droop gains as a function of active and reactive power. The voltage and frequency set-points are denoted by \( f_0 \) and \( U_0 \) and fixed at 50 Hz and 230 V\text{RMS} [47]. Active and reactive power set-points are denoted by \( P_0 \) and \( Q_0 \). The storage device should only operate when there is active and reactive power demand resulting in zero active and reactive power set-points.

Consider figure 6.7; the functional block on the right side 'inverter input/output' is connected on one side to the upper grid, and on the other side to the droop control. The DC/AC inverter is connected to a user defined energy supply; for the 'Meekspolder' situation a storage device is connected. an output filter is connected on the other side of the inverter preventing harmonics towards the grid. The three phase output current and voltage \( I_{abc} \) and \( U_{abc} \) or single phase currents and voltages are the measurement values to control the inverter.

To be able to control active and reactive power separately, the three phase current or voltage is transformed using Park and Clarke transformation into a rotational dq frame [29]. For unbalanced single phase transformation; other methods are applied to transform it towards a \( d,q \) frame as described in [5], [7], [45].
Figure 6.7: Inverter droop control scheme

The subsystems 'calculate and decouple P and Q' and 'droop control' are used to determine the phase angle, reference currents and voltages which can establish the required grid voltage and frequency range according to the DTe [47]. The reference currents and voltages are forced to be the output of the inverter using the voltage and current control.

To determine the phase angle output for the inverters, the frequency \( f \) is converted using the block 'phase(f)'.

At the end the output voltages and phases are transformed back to the three phase system using the block 'dq \rightarrow ABC'.

Another control structure is based on frequency and voltage control as shown in figure 6.8.

Figure 6.8: Inverter inverse droop control scheme

Depending on the inverse droop equations as depicted in 6.13 and 6.14 a reference active and reactive power is determined.

\[
P = P_0 - k_{pi}(f - f_0) \tag{6.13}
\]

\[
Q = Q_0 - k_{qi}(U - U_0)
\]
6.5 Stability Analysis for Droop Controlled Inverters

\[ P = P_0 - k_{pr}(U - U_0) \]
\[ Q = Q_0 - k_{qr}(f - f_0) \]  

(6.14)

Additionally, to the control structure a dead band (\(D_{tb}\) and \(D_{vb}\)) around the nominal voltage and frequency is implemented. The dead band prevents control during each small voltage and frequency deviation which can cause oscillations in the system.

Besides the stability issue, a dead band is placed to prevent the transformer tap changer switching continuously around nominal voltage.

The phase locked loop, PLL is used to determine the frequency and phase for the Park transformation. Additionally it ensures that the reactive voltage \(U_q\) is zero so that \(U_d\) is the amplitude of the voltage. The reference currents values are calculated using the reference active and reactive power divided by the voltage \(U_d\). The current control forced the inverter to inject these reference active and reactive current towards the grid.

Both systems leads to the same steady state behavior but there are some differences regarding to stable operation, this will be explained in the following context.

In control systems; it is common that increasing the proportional droop gains leads to instability, this is valid for both schemes [50].

However the control structure shown in figure 6.7 is tightly controlling the voltage and frequency using small droop gains, the inverse droop control structure is controlling the active and reactive power using small droop gains [7]. It is not possible for the first control structure to take the limited power of the generator into account, because this will lead to an infinite droop gain making the voltage and frequency undefined.

Additionally in the inverse droop control scheme it’s easy to implement a dead zone around the voltage and frequency set points. This is very desirable due to the allowed range of voltage and frequency where control is not needed.

Certainly there are also drawbacks by using the control strategy in figure 6.8; the frequency estimation using PLL should be accurate enough to enable the droop control.

The second control structure has more benefits than the first control structure. The second control structure is applied for the urban area 'Meekspolder' with comparison between resistive and inductive droop control. In the stability analysis, the first control structure is used to show the initial droop gains in case of autonomous operation.

6.5 Stability Analysis for Droop Controlled Inverters

In control theory it is important to define precisely the object that need to be controlled, the so called plant. The plant for a grid supporting inverter contains the network dynamics such as the low voltage cable impedance (inductance and resistivity) and an possible additional output filter inductance (depends on control strategy, in [25] is an adaptive virtual resistive output impedance proposed which removes the inductive behavior).

To make the dynamic analysis of the network more comprehensive, a dynamic phasor model as shown in [8], [13] is developed. The traditional phasor
representation of sinusoidal signals is limited by the quasistationary assumption on the speeds of the phasor states [3]. The conversion method as described in [58] is applied on the three phase signal and has no restrictions on the speed.

Additionally stability analysis for the droop gains are performed on the defined plant.

### 6.5.1 Defining the network dynamics

Consider a balanced three phase system \( \overline{e}'(t) \)

\[
\overline{e}'(t) = \begin{bmatrix}
e_a(t) = \sqrt{2}E(t)\cos(\omega t + \delta(t)) \\
e_b(t) = \sqrt{2}E(t)\cos(\omega t + \delta(t) + \frac{2\pi}{3}) \\
e_c(t) = \sqrt{2}E(t)\cos(\omega t + \delta(t) + \frac{4\pi}{3})
\end{bmatrix}
\]  

(6.15)

The three phase signal will be transformed into a rotational d,q frame using the Clarke and Park transformation [29]. Firstly the Clarke transformation is applied to remove the AC signal by transforming the three phase signal into the x,y axis or better known as the \( \alpha \) and \( \beta \) axis:

\[
\begin{bmatrix} E_x \\ E_y \\ E_0 \end{bmatrix} = \sqrt{2} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}
\]

(6.16)

Eventually the \( E_\alpha \) and \( E_\beta \) are transformed towards the rotational d,q-frame using the park transformation

\[
\begin{bmatrix} E_d \\ E_q \end{bmatrix} = \begin{bmatrix} \cos(\phi) & \sin(\phi) \\ -\sin(\phi) & \cos(\phi) \end{bmatrix} \begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix}
\]

(6.17)

This means that the three phase balanced system is described in the dynamic phasor representation by

\[
\mathcal{P}(e(t)) = \dot{E}(t) = E_d + jE_q = E(t)\cos(\delta(t)) + jE(t)\sin(\delta(t))
\]

(6.18)

A special property is created via the park and clarke transformation, this property is described in [58].

\[
\frac{\partial}{\partial t} \overline{e}'(t) = j\omega \overline{E}(t) + \frac{\partial}{\partial t} \overline{E}(t)
\]

(6.19)

where \( \overline{e}'(t) \) is a time-varying phase signal and \( \overline{E}(t) \) is the phasor representation.

Normally for the approximation of the model of the electrical impedance, the time-derivative on the right hand side of equation 6.19 is assumed to be insignificant and ignored [7]. Considering systems with fast-acting inverters, the time-derivative can't be neglected.

The plant is composed using the electrical model whereby power flow through a output impedance. The dynamic phasor transfer functions as a function of the power angle \( \delta \) and the voltage \( U \) are calculated using the electrical model depicted in figure 6.10.

Assume cable and possible series inductor denoted by \( Z \), where the voltage across the impedance is described by:

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6.5 Stability Analysis for Droop Controlled Inverters

\[ \mathbf{E}_{dq} = \mathbf{E}_{a,b} = \mathbf{E}(t) \]

\[ \mathbf{E}_{\alpha,\beta} \]

Figure 6.9: Phasor diagram of the Park and Clarke transformation

By using a special feature of the time varying phasor representation as described in equation (6.19):

\[ \mathbf{U}_a - \mathbf{U}_b = R \mathbf{i} + L \frac{\partial}{\partial t} \mathbf{i} \quad (6.20) \]

and reordering and transforming equation (6.21) into Laplace domain (as described in A.2) yields:

\[ \mathbf{U}_a - \mathbf{U}_b = RI(t) + j \omega LI(t) + L \frac{\partial}{\partial t} I(t) \quad (6.21) \]
Chapter 6. Voltage and Frequency Control Based on Inverter Technology

\[ P_a = \frac{3U_a^2 - 3U_aU_b \cos(\delta)(L_s + R) - 3U_aU_b\omega L \sin(\delta)}{(R + L_s)^2 + (\omega L)^2} \] (6.22)

\[ Q_a = \frac{3U_aU_b \sin(\delta)(L_s + R) - 3U_aU_b\omega L \cos(\delta) + 3U_a^2\omega L}{(R + L_s)^2 + (\omega L)^2} \] (6.23)

In order to linearize (6.22) and (6.23), (6.24) and (6.25) are used.

\[ dP = \frac{\partial P}{\partial U_b} dU_b + \frac{\partial P}{\partial \delta} d\delta \] (6.24)

\[ dQ = \frac{\partial Q}{\partial U_b} dU_b + \frac{\partial Q}{\partial \delta} d\delta \] (6.25)

The two parts can be classified as one that belongs to the resistive output impedance and the other one for the inductive output impedance. In case of resistive output impedance is \( \frac{\partial P}{\partial \delta} = 0 \) and \( \frac{\partial Q}{\partial U_b} = 0 \) as described in section (6.3).

There is a small difference between the voltage \( U_a \) and \( U_b \), \( U_aU_b \approx U_a^2 \).

Additionally consider also a small angle \( \delta \) which means \( \cos(\delta) = 1 \), \( \sin(\delta) \approx 0 \) yielding:

\[ dP_r = \frac{-3U_a(R + L_s)}{(R + L_s)^2 + (\omega L)^2} \] (6.26)

\[ dQ_r = \frac{3U_a^2(R + L_s)}{(R + L_s)^2 + (\omega L)^2} \] (6.27)

While for inductive droop control \( \frac{\partial P}{\partial U_b} = 0 \) and \( \frac{\partial Q}{\partial \delta} = 0 \) and the dynamic model for inductive droop control becomes

\[ dP_i = \frac{-3U_a\omega L}{(R + L_s)^2 + (\omega L)^2} \] (6.28)

\[ dQ_i = \frac{-3\omega L U_a}{(R + L_s)^2 + (\omega L)^2} \] (6.29)

The open loop plant poles in case of resistive output impedance are calculated using 6.26 and 6.27:

\[ s^2 + \frac{2R}{L} + \left( \frac{R^2}{L^2} + \omega^2 \right) = 0 \] (6.30)

\[ s = \frac{-2R}{L} \pm \sqrt{\left( \frac{2R}{L} \right)^2 - 4\left( \frac{R^2}{L^2} + \omega^2 \right)} \]

\[ \frac{2}{2} = \frac{-R}{L} \pm j\omega \]

and the zero(s) are:

\[ s = \frac{-R}{L} \] (6.31)
6.5 Stability Analysis for Droop Controlled Inverters

while for inductive output impedance, the poles are equal as defined in 6.30 and there are no zeros.

Equations (6.26), (6.27), (6.28) and (6.29) assumed the droop control model without an output filter. In the real situation a filter is connected to the inverter output preventing harmonics towards the grid, therefore the droop control is analyzed together with a first order low pass filter (LPF) described in equation 6.32 (Laplace LPF).

\[ \frac{1}{sT_c + 1} \]  

(6.32)

Using relation (6.10) and (6.26)-(6.29), the open loop system (plant) for inductive output impedance can be described by:

\[
\frac{dP_i}{df} = \frac{2\pi \omega_c}{s + \omega_c} \frac{-3U_a^2\omega L}{s + \omega_c (R + Ls)^2 + (\omega L)^2} \tag{6.33}
\]

\[
\frac{dQ_i}{df} = \frac{\omega_c}{s + \omega_c} \frac{-3\omega L U_a}{s + \omega_c (R + Ls)^2 + (\omega L)^2} \tag{6.34}
\]

while for resistive output impedance

\[
\frac{dP_r}{dU_b} = \frac{\omega_c}{s + \omega_c} \frac{-3U_a(R + Ls)}{s + \omega_c (R + Ls)^2 + (\omega L)^2} \tag{6.35}
\]

\[
\frac{dQ_r}{df} = \frac{2\pi \omega_c}{s + \omega_c} \frac{3U_a^2(R + Ls)}{s + \omega_c (R + Ls)^2 + (\omega L)^2} \tag{6.36}
\]

At the end, the closed loop poles and zeros (for P, Q, resistive and inductive cases) are described in 6.38 and 6.39 using 6.13, 6.14, 6.33-6.36 and 6.37:

\[
\frac{kH(s)}{1 + kH(s)} \tag{6.37}
\]

whereby the droop gain and the Laplace open loop system is described by respectively k and H(s).

\[
Pole_f = s^4L^2 + s^3(2RL + \omega_c L^2) + s^2(R^2 + 2RL\omega_c - 3k\omega_c U_a L) + s(\omega_c (\omega L)^2 + \omega_c R^2 - 3k\omega_c U_a R) \\
\]

\[
Pole_U = s^3L^2 + s^2(2RL + \omega_c L^2) + s(R^2 + 2RL\omega_c - 3k\omega_c U_a L) + \omega_c \omega L^2 + \omega_c R^2 - 3k\omega_c U_a R \tag{6.38}
\]

\[
Zero_{res} = -3k\omega_c U_a(R + Ls) \\
Zero_{ind} = -3k\omega_c U_a^2L \tag{6.39}
\]

6.5.2 Stability Analysis Using Root Locus

As already mentioned in the overview scheme of section 6.4, to determine the correct reference currents requires to analyze and design a control for the defined plant in section 6.5.1. An approach to analyze the stability of the droop gains is to analyze the closed loop transfer functions using root locus.
Chapter 6. Voltage and Frequency Control Based on Inverter Technology

Closed loop System Voltage and Frequency Control

Figure 6.11: Closed loop voltage and frequency control system

The closed loop transfer functions is illustrated in figure 6.11 and the closed loop poles and zeros are described in the last section. Following from the inverse droop equations 6.13 and 6.14, a difference between the nominal frequency and actual frequency or frequency deviation enables the inverter droop control. Subsequently the inverter injects/consumes active/reactive power in the grid (plant).

The conversion from frequency deviation for the inverter 'fstep' to phase angle $\Delta \delta$ is in Laplace domain described by equation 6.10.

In reaction of the frequency deviation or a phase $\Delta \delta$ step the control loop adjust the active or reactive power output [24], [54].

While for the control of voltage a similar approach is applied, the control system injects/consumes active or reactive power as reaction of a voltage step.

For frequency and voltage control is the amount of injected active and reactive power related to the inverse droop gains (in figure 6.11 denoted as C) as described in (6.13) and (6.14).

Root-locus Droop Control Design

As described in section 6.3, is the inverter output impedance build up from a LV cable impedance ($Z$), a possible series inductor ($Z_1=\omega L_1$) or virtual output impedance (resistive) [25]. The inverter output impedance is denoted in equations (6.33)- (6.36) as $R$ and $X=\omega L$.

The inverter output impedance must be mainly inductive in case the inductive droop control approach is applied (as explained in section 6.3). This requirement can only be fulfilled when there is a large inductor at the output filter [31], because the cables are mainly resistive ($\frac{R}{X}=4$). However assuming a large inductance at the output filter is not always valid, since the output impedance also depends on the control strategy [24]. Therefore an additional series inductor is proposed to increase the $\frac{R}{X}$ ratio towards factor 10. The stability analysis for inductive output impedance are performed assuming a $\frac{R}{X}=10$ ratio created by the inverter output inductance and an additional series inductor.
6.5 Stability Analysis for Droop Controlled Inverters

While the inverter output impedance must be resistive in case of resistive droop approach. This requirement is valid for the LV cables which are mainly resistive. However the inductor at the output filter is not resistive, to overcome this issue a virtual output impedance as described in [25] is proposed. Applying the adaptive virtual output impedance a resistive behavior at the output of the inverter can be achieved. The stability analysis are performed for \( \frac{f_e}{f} = 4 \) ratio assuming that the adaptive virtual output impedance has removed the inverter output filter inductive behavior.

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Nominal Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable impedance [fig. 6.10]</td>
<td>( Z )</td>
<td>0.16+j0.041</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>Series inductor [fig. 6.10]</td>
<td>( Z_1 )</td>
<td>1.559</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>LPF cut-off frequency [eq. 6.35]</td>
<td>( \omega_c )</td>
<td>10</td>
<td>( \frac{rad}{s} )</td>
</tr>
<tr>
<td>Nominal Frequency [47]</td>
<td>( f_c )</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Nominal Angular Frequency [47]</td>
<td>( \omega )</td>
<td>100( \pi )</td>
<td>( \frac{rad}{s} )</td>
</tr>
<tr>
<td>Nominal Amplitude [47]</td>
<td>( U_a )</td>
<td>230</td>
<td>( V_{RMS} )</td>
</tr>
</tbody>
</table>

The root-locus for the inductive and resistive dynamic models are depicted in figure 6.12 and 6.13 using the parameters enumerated in table 6.4. The allowed droop gain range to control voltage and frequency is also listed in the root-locus plots. ² A sharper LPF can improve the range of possible droop gains but will decrease the settling time of the control.

Figure 6.12a shows the influence of active power on voltage by increasing the droop gains. The overshoot will increases due to the poles which are moving more towards the imaginary axis. However the system is still stable because the poles are still located in the left half plane. The influence of reactive power on frequency is shown in figure 6.12b where an increase in droop gain tend to move the poles towards the right half plane causing an unstable system.

In case of inductive droop, increasing the droop gain tends to move the closed loop poles to the right half plane causing an unstable system. This applies for the active power to frequency droop as well as the influence of reactive power on voltage.

Considering the stability, resistive droop control is more damped and more stable than inductive droop control.

E.g. the step responses for resistive and inductive droop control are shown in figure 6.14 and figure 6.15. The step responses in case of resistive output impedance is more damped compared to inductive approach (figure 6.14a vs figure 6.15b)

From the stability analysis, it can be concluded that resistive droop control is preferred above the inductive droop control.

²Inverse droop gain relations are used to show the critical droop gain range in case of autonomous operation
Chapter 6. Voltage and Frequency Control Based on Inverter Technology

Figure 6.12: Root-locus plots resistive droop control

(a) $P \rightarrow U$, $0 < k_{ur} < 0.018 \frac{V}{W}$

(b) $Q \rightarrow f$, $0 < k_{qr} < 0.000015 \frac{Hz}{V}$
6.5 Stability Analysis for Droop Controlled Inverters

Figure 6.13: Root-locus plots inductive droop control
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Figure 6.14: Root-locus plots resistive droop control
6.5 Stability Analysis for Droop Controlled Inverters

Figure 6.15: Root-locus plots inductive droop control
Part IV

Multiple Inverter Control Strategy
Chapter 7

Communication System inside the Micro-Grid

In the last chapters a control strategy is proposed to control voltage and frequency using a single inverter. In this section, communication lines are used to prevent battery storage system to become empty. In case the micro-grid operates in autonomous operation, this feature will prevent the micro-grid violating the voltage and frequency regulations [47]. Moreover an additional feature to improve the inverter active and reactive power distribution using a communication system is proposed. The implementation of the communication system in DiGSILENT is illustrated in appendix D.

7.1 Battery Storage System

The battery storage system can be explained by the flow diagram shown in figure 7.1. In normal situations the storage system recharges during voltage above the nominal value. During critical shortage periods, it can happen that
the battery is not sufficient charged by the DGs, therefore an emergency case enables the possibility of recharging the battery. The emergency case activates when the remaining battery energy is lower than 5/3 even when the other battery storage systems are fully charged. The battery storage system sends an activation request to turn on a certain amount (x1) of μCHPs using a data communication link. Each battery storage system can only turn on the μCHPs located at its feeder, e.g. the battery storage system with inverter 1 can only enable the μCHPs connected to household cable 1 as depicted in figure 3.2.

As a consequence extra electricity is produced by the μCHPs. Between 1.25%–0.001% another amount (x2) of μCHPs are turned on to solve the mismatch in supply and demand. When the battery is recharged above 10%, the battery storage system restores the μCHPs heat demand operation.

In the very unlikely situation when the remaining energy is lower than 0.001% the storage system automatically shuts down. Normally, it should be sufficient to supply 40 households with 40 μCHPs. When the remaining energy keeps dropping, this can be caused by a problem inside/outside the micro-grid. In case the battery storage system is fully charged, the storage system is disabled to prevent it from consuming power.

Besides satisfying the electricity demand the excess heat is stored in a storage vessel as described in [43].

### 7.2 Active and Reactive Power Dispatch

The second feature uses the data communication system to optimize the active and reactive power distribution as shown in figure 7.2. The battery storage system continuously receives active and reactive power average values from the connected neighbor battery storage system using the data communication link (comlink). After receiving the average values $P_{comav}$ and $Q_{comav}$, the droop control recalculates the active and reactive power reference values $P_{ref}$ and $Q_{ref}$ as described with (7.1) and (7.2).
7.2 Active and Reactive Power Dispatch

\[ P_{ref} = \frac{P_{ownref} + P_{comav}}{2} \]  \hspace{1cm} (7.1)

\[ Q_{ref} = \frac{Q_{ownref} + Q_{comav}}{2} \]  \hspace{1cm} (7.2)

\( P_{ownref} \) and \( Q_{ownref} \) are the calculated active and reactive power reference values according to the local voltage and frequency measurement without the communication system.
Part V

Analyzing the Simulation Results
Chapter 8

Simulation Results

In this section the performance of resistive and inductive droop is illustrated. In addition simulation results for average, shortage and excess scenarios are described. The scenarios are illustrated in detail in appendix C.

Section 8.3 shows the performance of the control strategy during unbalanced loading. Finally, simulation for an autonomous network and the performance of the communication system is described in section 8.4.

8.1 Control Strategy Performance

Figure 8.1: Resistive droop control $k_p = 4.5 \frac{\text{V}}{\text{W}}$
Chapter 8. Simulation Results

The control strategy performance is verified for inductive and resistive droop control using the micro-grid described in section 3.2. E.g. at July, due to the high temperature the $\mu$CHP is not producing any electricity and the active power production is fully supported by the PV system. Suddenly, a large cloud appears above the solar systems causing a fast decrease in active power production as shown in figure 8.1 and 8.2. As a consequence of the sudden decrease in active power, the voltage level collapsed towards $210\text{V}$ as shown in figure 8.4a.

8.1.1 Inductive Droop Control

The inductive droop control strategy is tested using the load profile from the previous example. Figure 8.1 shows the reactive power produced by the battery storage system.

Under influence of a change in voltage, capacitive (-) or inductive (+) reactive power is injected into the network. Due to the injected reactive power a decrease in voltage deviations is expected. However, as mentioned in the stability analysis and shown in 6.13, by increasing the inductive droop gain a large overshoot can occur.

The droop gain is limited to $4.5\frac{kW}{V}$ to guarantee maximum power injected/consumed by the inverter (per phase $8\text{V}$ deviation refers to $36\text{kW}$), to decrease the overshoot and steady state error. This overshoot is clearly visible in the voltage profile as illustrated in figure 8.3a. Furthermore, figure 8.3b shows that the transformer loading has barely decreased. These results verify that inductive droop control has a large overshoot in case of fast changes.
8.1 Control Strategy Performance

Figure 8.3: Inductive droop control: Reaction speed during fast changing weather circumstances

8.1.2 Resistive Droop Control

In case resistive droop control is applied on the previous example, active power is injected to correct the voltage deviations as illustrated in figure 8.1.

Due to the active power injection, the voltage has visibly improved in every part of the network and figure 8.4a shows that the single phase voltage is almost...
Chapter 8. Simulation Results

Figure 8.4: Resistive droop control: reaction speed during fast changing weather circumstances

(a) Single phase voltage at the load (NC=Nocontrol, C=Control)

(b) Transformer loading

equal at each part of the network due to the droop control.

Additionally, the transformer loading significantly decreases as shown in figure 8.4b. This shows that resistive droop control should be applied into a low voltage network to prevent system instabilities.

The remaining simulation results are according to the resistive droop control
8.2 Balanced Loading

8.2 Balanced Loading

In this section simulation results for a week based on 15-minute-mean load and generator profiles during excess, shortage and average scenarios are illustrated [43]. The simulations results are illustrated using a box plot diagram which is divided into 6 vertical levels as described in table 8.1 [56]. The initial storage energy is listed below.

1. Battery energy (average): 50%
2. Battery energy (excess): 0%
3. Battery energy (shortage): 100%

<table>
<thead>
<tr>
<th>Level</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The upper adjacent value</td>
<td>Maximum percentile at 99.65%</td>
</tr>
<tr>
<td>2</td>
<td>The upper whisker</td>
<td>Top of the box</td>
</tr>
<tr>
<td>3</td>
<td>The box</td>
<td>The tops and bottoms are the 25th and 75th percentiles of the samples</td>
</tr>
<tr>
<td>4</td>
<td>The median</td>
<td>Separating the higher half of a sample from the lower half</td>
</tr>
<tr>
<td>5</td>
<td>The lower whisker</td>
<td>Tail of the box</td>
</tr>
<tr>
<td>6</td>
<td>The lower adjacent value</td>
<td>Minimum percentile at 0.35%</td>
</tr>
</tbody>
</table>

Table 8.1: Levels in statistical box plot

8.2.1 Voltage Levels

Figure 8.5 shows that due to the DG's penetration, the voltage level does not always comply with the standard as described in [47]. Especially, for the shortage scenario in January, excess scenario in July, average and shortage scenario in October. However, when the control strategy is enabled a clear improvement in voltage level is shown. The control strategy enables that shortage and excess periods are solved by injecting or consuming active power. Due to the control strategy, the allowed voltage range is not violated.

8.2.2 Transformer Loading

The control strategy significantly decreases current flowing through the transformer as shown in figure 8.6. E.g. the transformer loading during excess scenarios in April is around 75%. When the control strategy is enabled, the transformer loading decreases with 20%.
Chapter 8. Simulation Results

8.3 Unbalanced Loading

This section shows an example that the control strategy can improve the voltage level even in an unbalanced network. The unbalanced network is caused by differences in electricity demand in each phase. In figure 8.7a the simulated unbalanced load profile is shown. In case the storage device is not enabled
and only the upper-grid is supporting the network an unbalanced voltage is clearly visible as shown in Figure 8.7b. When the unbalanced droop control is activated a visible improvement in the voltage profile is shown. The single phase voltages are closer to each other compared to the one without control (voltage difference phase to phase from dx1 to dx). This example shows that the control
can improve an unbalanced network in a more equal distributed voltage at each phase.

Figure 8.7: Improving the voltages at the load in an unbalanced network
This section shows the micro-grid changing from grid-connected to autonomous operation mode. Consider an example without active power production from DG’s and only the storage devices inject active and reactive power into the grid. The active and reactive power demand and supply from the households and storage devices are shown in figure 8.8.

![Active and reactive power injection and consumption](image)

**Figure 8.8:** Active and reactive power injection and consumption (vac=voltage source, iac=current source (see D.3))

On the left side of figure 8.9, the micro-grid disconnects from the upper-grid. The disconnection causes at the beginning an activation phenomenon for the voltage and frequency as shown in figure 8.10.

Around this period the voltage and frequency will violate the Dutch grid code for a short period, however this activation phenomenon can be limited by limiting the active and reactive power demand from the load. The problems concerning transients between switching from grid-connected operation mode towards autonomous operation mode is out of the scope of this graduation project. Information concerning switching from one mode to the other mode and vice versa is described in [40].

The frequency follows the reactive power demand (Qload) as depicted in figure 8.8 and described in D.3. The droop gain to create grid frequency and grid voltage is limited by the stability of the system (see section 6.5.2) yielding a maximum value of \( k_{fr} = 0.000005 \frac{Hz}{V^2} \) and \( k_{ur} = 0.2 \frac{V}{W} \). During the simulation in DiG_SILENT, it is shown that the overshoot is quite large for the frequency droop gain therefore a lower droop gain value of 0.000005 \( \frac{Hz}{V^2} \) is selected.

A second example illustrates the battery energy management system using the same demand.
During autonomous operation, it is certainly possible that the storage system becomes empty. Therefore to guarantee that the demand is supplied a control signal is sent towards the μCHPs. E.g. the remaining battery storage system energy becomes lower then 5% at \( t=850 \) s, resulting in activation of the μCHPs as depicted in figure 8.11.
8.5 Battery Utilization

This section describes the excess and shortage of the battery storage system during average scenarios. Concretely, how often is the battery storage system empty, when is the battery storage system full. The analysis follows from yearly
Chapter 8. Simulation Results

Figure 8.11: Communication system activates μCHPs

Demand and supply information additionally considering the excess and shortage periods for the battery storage system including control.

Consider an average scenario for one detached household, one PV system and one μCHP. The reserved storage size is 52.5 kWh and the total electrical demand is equal to 4600 kWh (year 2020). The μCHP produces around 3000 kWh [41] per year and the PV systems produces 865 kWh (inclination angle of 36° and southern orientation) as described in PVGIS. First of all during one year there is always a shortage of 735 kWh which is supplied by the controllable μCHPs. The excess periods are estimated using the simulation results. The battery storage system consumes active power only when the output voltage is above the nominal dead band value.

The storage device usage for one year can be estimated using the simulation results information for 4 seasons and 7 days. However to calculate correctly the battery utilization for one year, the excess energy for each season will be multiplied by roughly 13 (1 year = 365 days, therefore 1 season = 91.25 days). In the analysis excess periods are extreme during April (3 months) 307 kWh followed by January (3 months calculation) with 45.3 kWh. For the month July (3 months) 12.6 kWh and 7.7 kWh for October (3 months). Summing the total excess energy for one household during one year is equal to 372.6 kWh.

From simulation of average scenarios of 7 days, the battery storage device

8.5 Battery Utilization

is never full however excess will certainly occur during April, May and June after roughly \( \frac{32.5}{\sqrt{12}} \approx 16 \) days. This means that the storage can not store these excess periods. Certainly some other solutions are possible such as discharging the battery storage systems preventing over voltage happening.
Chapter 9

Discussion

This research has developed a control strategy for the micro-grid in order to fulfill the technical requirements. However the question remains what the developed control strategy using storage devices improves in terms of environmental impact. In this section a comparison for $\text{CO}_2$ emission is described using a combination of $\mu$CHPs and PV systems where the temporary excess and shortage is solved by only the steam and gas electricity generator (STEG) (case 1) or in combination with the battery storage system including control strategy (case 2). An approach to calculate the $\text{CO}_2$ emission for the two scenarios is shown in fig. 9.1.

![Diagram of CO2 emission calculation](image)

Figure 9.1: Yearly $\text{CO}_2$ emission with/without control strategy
Chapter 9. Discussion

The yearly energy production from one μCHP and solar cell is estimated at 3000 kWh [28] and 865 kWh (inclination angle of 36° and southern orientation) as described in PVGIS. 1 Additionally, the yearly energy demand for a detached household is equal to 4600 kWh (in the year 2020) [57] leading to a yearly shortage of 4600-3000-865=735kWh which is solved by the STEG in both scenarios.

The energy directly from the μCHP and solar cell which is directly consumed by the household is denoted as a1 and b1. Energy stored from excess periods in the storage device is denoted as a2 and b2 and summed up to become x (case 2). The battery storage system is only activated when the voltage deviates from the nominal voltage and the voltage dead band $D_v$. According to average scenarios simulations is the total battery storage system energy consumption (excess) equal to 372.6 kWh per year.

The electrical efficiency for the battery storage systems is according to [34] 84.6%. Therefore in case 2 only 0.846x is forwarded to the load and the remaining energy 0.154x is produced by the STEG. For case 1, the x amount of energy is delivered by the STEG which is equal to 372.6 kWh.

Moreover, the CO2 emission (excluding manufacturing process) for μCHP and STEG are 0.22 kWh and 0.385 kWh [22] assuming 0 CO2 emission for PV systems.

The yearly CO2 emission for scenario 1 is equal to (3000)(0.22)+(735+372.6)(0.385) $\approx$ 1112.54 kg CO2 and in case of scenario 2 is the CO2 emission (3000)(0.22)+(735+372.6(1-0.846)(0.385)) $\approx$ 969.05 kg.

At the end a significantly CO2 reduction of nearly 11 % is achieved by solving temporary excess and shortage using the storage device instead of STEG.

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Part VI

Conclusions and Recommendations
Chapter 10

Conclusions

The main objective of this research is to create a safe, efficient and reliable control strategy to operate a micro-grid connected to the grid or in autonomous operation mode. The micro-grid is formed by small-scale single phase distributed generators such as (controllable) μCHPs, PV systems close to the loads (households and shopping centers). The control strategy is developed around a battery storage systems with inverter.

The edge conditions are that the simulations are verified for a LV network with generators and household based on created generator and load profiles and the battery storage systems including inverter is the main control component. The simulations are performed in DiGSILENT Powerfactory which is based on Newton Raphson based iterations of network and dynamic model equations combined with a non-linear representation of the electromechanical model.

The research shows a comparison of the resistive and inductive droop control to determine which strategy is more preferable to create an autonomous LV network. Both strategies are compared using the voltage and frequency dependency and performing stability analysis. Additionally, the performance of the control strategies is tested using fast energy production changes which provides a concluding answer to use resistive or inductive droop control in a LV network.

The control strategy based on resistive droop proves to be preferred to control voltage and frequency during grid-connected operation mode as well as autonomous operation mode in LV grid.

Simulation results using the resistive droop control strategy shows that voltage violation during excess, shortage and average scenarios are solved by the battery storage system with inverter.

However the simulation are according to 7 days simulation which does not show the battery becoming full. Thoroughly analyzing the numerical results shows that during April, May and June possible excess scenarios occur which can not be solved by the storage device with the chosen storage size (after 16 days). The trade off here is to discharge the battery and lose energy such that it can handle the over voltages and prevent violating the grid code [47] or adapting the dead band area in function of storage energy.

Additionally, the maximum transformer loading decreases when the battery
storage system is enabled.

Another important extra result is that a control strategy is developed to improve the voltage even during unbalanced loading. During unbalanced loading, voltage differences between phases are reduced using the unbalanced droop control strategy.

The unbalanced droop control strategy is able to operate multiple inverters in parallel and a data communication system is developed enhancing a better active and reactive power distribution between battery storage systems with inverters.

As a final result and one of the main goal for the research is that the micro-grid can operate permanently in autonomous operate mode. During shortage periods whereby the battery storage systems and PV systems can not deliver the required power demand an emergency case algorithm is enabled. The emergency case algorithm turns on $\mu$CHPs (no heat demand) via the communication system and guarantees energy supply. But the electrical efficiency of $\mu$CHPs is 15\% (heat is wasted) which is much lower than the average efficiency of the conventional grid [28]. As a result autonomous operation is not producing power efficiently during emergency cases.

In the end a control strategy is developed enabling a micro-grid to operate an efficient and reliable during grid-connected as well as autonomous operation mode.
Chapter 11

Recommendations

The most important recommendations which can be used for further research are:

- Matlab interface interconnecting with DiGSILENT
- Usage of μCHPs with higher electrical efficiency
- Experimental setup
- Transients and harmonics
- Adaptive droop control
- Robust control methods (LQGC and MPC)
- Price based droop control

The first recommendation is certainly required, to build the control strategy around a Matlab interface. Matlab has better debug and verification methods compared to DSL (DiGSILENT Simulation Language). Additionally Matlab has more possibilities to extent the control and to implement modern control strategies which requires matrix calculation (DiGSILENT lacks these features). It is required to build or use the interface between DiGSILENT and Matlab/Simulink.

During autonomous operation, μCHPs are forced to turn on (no heat demand) because the battery storage systems are unable to support the micro-grid (happens in case of shortage which is in total at least 735kWh for each household per year). However the electrical efficiency of the μCHPs is only 15% which is too low compared to the conventional grid. Therefore it is recommended to operate in autonomous operation mode using a μCHP with a higher electrical efficiency.

Simulations are performed to verify the control strategy but real experiments are still required. Therefore it is recommended to set up a experimental environment to test the control strategy.
Chapter 11. Recommendations

During this graduation, transients and harmonics are neglected but they can play a major role for the control strategy. E.g. during the transition of grid-connected towards autonomous operation mode transients occur, however these transients can be limited by applying special rules around the control strategy. It is recommended to do some research about the transients and adding harmonics in the control strategy.

Stability of the control strategy is limited by the droop gain and it depends on the output impedance, however in reality the inverter output impedance is not fixed. This problem can be solved by adaptive droop control, calculating in real-time the output impedance to control the micro-grid using resistive or inductive droop control.

Another way to enlarge the stability of the control strategy is to apply modern control theory instead of droop control. Recommended control methods are linear quadratic gaussian control (LQGC) and modern predictive control (MPC) which are more robust compared to droop control [7].

The last recommendation is to extend the developed communication system by sending dynamic droop gain information. The droop gain information can be used to reduce the electricity price (trader) or improving the voltage and frequency (grid-operator).
Chapter 12

Personal opinion

This section is out of the scope of the graduation assignment and contains my personal opinion for the proposed micro-grid.

From technical point of view the control strategy can satisfy all the constraints however there are some drawbacks considering social and economical impact.

In the Netherlands is a micro-grid which operates in autonomous mode rarely needed. Mostly autonomous operation mode is useful in third world countries, real islands and also e.g. in a warship. In those situations there is no possibility to connect with the upper-grid and therefore it is required to create an autonomous operation mode.

In my opinion it is better to enhance a micro-grid which operates in grid connected state and only operates during disturbances in autonomous operation mode. Additionally, an economical question will arise 'is it financial more attractive to solve these problems using an autonomous operation mode or is it sufficient to place larger cables and increase the transformer size?'. The comparison is not considered in this graduation project, however it would be nice to compare those two in an extended study.

As suggested in this report storage investment can be minimized in case the electrical car penetrates in the market (only possible in case the storage is managed correctly). The idea by using the electrical car storage to control voltage and frequency is very nice however is it allowed to use the storage from car owners. For example when a customer charge his car, assume that the battery is also used to control voltage and frequency. This can result in a slower charge time, the customer probably wants to take his car at the time he prefer and he does not want that the battery is empty because of the autonomous operation. Additionally, charging and discharging will decreases the lifetime of the battery and the customer does not want that his battery degrades due to this purpose. These issues can be solved, however carefulness is required and listening to the public opinion is very important.

In the end, a grid-connected micro-grid with DGs is certainly useful but to create a totally autonomous operating micro-grid is in my opinion not useful. Even in case of a grid-connected micro-grid control strategies are required. Control strategies should not only take into account the technical part but also the economic and the social part.
Part VII

Appendices
Appendix A

Elaborating Control Equations

A.1 Control Relations

\[ S_a = U_a \left( \frac{U_a - U_b e^{j\delta}}{Ze^{-j\theta}} \right) = U_a \left( \frac{U_a - U_b (\cos(\delta) + j\sin(\delta))}{Z(\cos(\theta) - j\sin(\theta))} \right) \]  
(A.1)

Multiplying numerator and denominator with \( \frac{\cos(\theta) + j\sin(\theta)}{\cos(\theta) + j\sin(\theta)} \) yields:

\[ S_a = \frac{U_a^2 \cos(\theta) - U_a U_b \cos(\delta) \cos(\theta) + U_a U_b \sin(\delta) \sin(\theta)}{Z} + \frac{j(U_a^2 \sin(\theta) - U_a U_b \cos(\delta) \sin(\theta) - U_a U_b \sin(\delta) \cos(\theta))}{Z} \]  
(A.2)

Replacing the impedance with the resistance and inductance using \( R = Z \cos(\theta) \), \( X = Z \sin(\theta) = \omega L \), \( R^2 + X^2 = Z^2 \) and multiply everything with \( \frac{Z}{Z} \) yields:

\[ P = \frac{U_a^2 Z \cos(\theta)}{Z^2} - \frac{U_a U_b Z \cos(\delta) \cos(\theta) - U_a U_b Z \sin(\delta) \sin(\theta)}{Z^2} = \frac{U_a^2 R - U_a U_b R \cos(\delta) + U_a U_b X \sin(\delta)}{R^2 + X^2} \]  
(A.3)

\[ Q = \frac{U_a^2 Z \sin(\theta)}{Z^2} - \frac{U_a U_b Z \cos(\delta) \sin(\theta) + U_a U_b Z \sin(\delta) \cos(\theta)}{Z^2} = \frac{U_a^2 X - U_a U_b X \cos(\delta) - U_a U_b R \sin(\delta)}{Z^2} \]  
(A.4)

Reordering equations A.3 and A.4 by multiplying \( P_a \) with \( X \) and \( Q_a \) with \( R \) and performing a substraction yields:

\[ XP - RQ = U_a U_b \sin(\delta) \]
\[ \frac{XP - RQ}{U_a} = U_b \sin(\delta) \]  
(A.5)
A second equation can be obtained by multiplying $P$ with $R$ and $Q$ with $X$ and performing an addition yields:

$$RP + XQ = U_a^2 - U_aU_b\cos(\delta)$$

$$\frac{RP + XQ}{U_a} = U_a - U_b\cos(\delta) \quad (A.6)$$

## A.2 Stability Calculations

Reordering the equation:

$$A = \tilde{U}_a - \tilde{U}_b = (R + j\omega L + L \frac{\partial}{\partial t})I(t) \quad (A.7)$$

The equation is described in Laplace domain:

$$\text{Laplace}(A) = U_a(s) - U_b(s) = (R + j\omega L + sL)I(s) \quad (A.8)$$

Converting the equation into Laplace domain:

$$I(s) = \frac{U_a(s) - U_b(s)}{(R + j\omega L + sL)} \quad (A.9)$$

Power flowing through $A$ is defined using equation A.9 as:

$$\vec{S}_a = P_a + jQ_a = 3\tilde{U}_a(s)\vec{I}^* = \frac{3}{R - j\omega L + sL}\tilde{U}_a(s)[\tilde{U}_a(s)^* - \tilde{U}_b(s)^*] \quad (A.10)$$

whereby

$$P + jQ = \text{Re}(S_a) + j\text{Im}(S_a) \quad (A.11)$$

By using equation 6.18:

$$\vec{U} = U(\cos(\phi) + j\sin(\phi)) \quad (A.12)$$

and the phase angle information:

$$\angle(U_a) = 0$$

$$\angle(U_b) = -\delta$$

1Fourier transformation is not applied because when in a stable electrical system a step is applied means that at time is zero the signal is not zero. Thus the system is not causal before time is zero.
Chapter A. Elaborating Control Equations

results for the apparent power:

\[ S_a = \frac{3}{R + Ls - j\omega L} \bar{U}_a [\bar{U}_a(s) - \bar{U}_b(s)(\cos(\delta) - j\sin(\delta))] \]

\[ = \frac{3U_a^2}{R + Ls - j\omega L} \frac{R + Ls + j\omega L}{R + Ls + j\omega L} - \]

\[ \frac{3U_aU_b(\cos(\delta) - j\sin(\delta))}{R + Ls - j\omega L} \frac{R + Ls + j\omega L}{R + Ls + j\omega L} - \]

\[ \frac{3U_a^2(R + Ls + j\omega L)}{(R + Ls)^2 + (\omega L)^2} - \]

\[ \frac{3U_aU_b(R + Ls + j\omega L)(\cos(\delta) - j\sin(\delta))}{(R + Ls)^2 + (\omega L)^2} \]

\[ = \frac{(3U_a^2 - 3U_aU_b\cos(\delta))(Ls + R) - 3U_aU_b\omega L\sin(\delta)}{(R + Ls)^2 + (\omega L)^2} + \]

\[ j\left( \frac{3U_aU_b\sin(\delta)(Ls + R) - 3U_aU_b\omega L\cos(\delta) + 3U_a^2\omega L}{(R + Ls)^2 + (\omega L)^2} \right) \]

Equation A.13

and separate the real and imaginary part of equation A.13 yields:

\[ P_a = \frac{3U_a^2 - 3U_aU_b\cos(\delta))(Ls + R) - 3U_aU_b\omega L\sin(\delta)}{(R + Ls)^2 + (\omega L)^2} \] (A.14)

\[ Q_a = \frac{3U_aU_b\sin(\delta)(Ls + R) - 3U_aU_b\omega L\cos(\delta) + 3U_a^2\omega L}{(R + Ls)^2 + (\omega L)^2} \] (A.15)
Appendix B

Inverter Control Strategy
Block-sets

In this chapter, different functional blocks are explained which are required in practical experiments but not applied during the simulation. In section B.1 is explained in what way is it possible to retrieve fast and accurate the single phase voltages. Section B.2 describes the current regulator in case of inductive and resistive droop approach (Current regulator forces the reference currents as output current is not required because the inverter model is simulated using a current source (see D.3).

B.1 Single Phase dq Transformation

In balanced three phase system; standard theory can be used to determine the d-q components as already discussed in section 6.5. Firstly; the A,B,C phases are transformed towards an α and β frame using the Clarke transformation. In the next step the α and β values are transformed into the rotational d-q frame by Park transformation. Unfortunately applying the transformation for an unbalanced three phase system results in errors in the transformation. Therefore single phase d-q transformation should be applied instead of the conventional three phase balanced transformation theorem. There are several d-q transformation methods based on phase locked loop where three of those methods are enumerated.

- Using products and notch filters to obtain the d-q coordinates [52]
- Hilbert transformer to obtain the d-q coordinates [52], [53]
- Transport delay to obtain the d-q coordinates [52], [53]

These three methods can retrieve the single phase d and q voltage and current components as described in the next part.
B.1.1 Method 1

The first method is based on demodulating techniques whereby a single phase magnitude $i(t)$ can be represented as

$$i(t) = i_m(t) \sin(\omega t - \phi(t))$$

or

$$= i_m(t) \cos(\phi(t)) \sin(\omega t) - i_m(t) \sin(\phi(t)) \cos(\omega t)$$

where the most significant information is embedded in:

$$i_d(t) = i_m \cos(\phi(t))$$

$$i_q(t) = i_m \sin(\phi(t))$$

These terms are very slow compared to the line frequency $\omega(t)$, therefore the method is to remove the fast frequency components. Firstly a low pass filter eliminates the switching frequency harmonics; then a product of $\sin(\omega t)$ and another by $\cos(\omega t)$ is applied. Finally a notch filter tuned at twice the line frequency is applied; such that the terms from twice the frequency can be removed. After this operation the $i_d(t)$ and $i_q(t)$ are created. The demodulation steps are summarized in figure B.1.

![Diagram](image)

Figure B.1: Demodulating the d-q components

B.1.2 Method 2

Method 2 is creating the d-q components by injecting the single phase magnitude $i(t)$ through a Hilbert transformer. The Hilbert transformer is defined as

$$\hat{x}(t) = \frac{P}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau$$

where $P$ is Cauchy principal value [53]. By using the Hilbert transformer, it is possible to generate a second signal, which is orthogonal or 90 degrees phase shifted with the input signal. The d-q components are generated by applying the Park transformation on the output of the Hilbert transformer. Method 2 is summarized in figure B.2.

B.1.3 Method 3

The third method is similar to the second method; only difference is that there is no Hilbert transform required. This method make use of transport delay to generate a second component as shown in B.3.
Chapter B. Inverter Control Strategy Block-sets

In order to determine the active and reactive power, the d and q components are used [18]. In addition the phase and frequency can be retrieved by synchronizing the PLL rotating reference frame with the q current component using a phase locked loop (PLL). Figure B.4 shows that setting the q component to zero results in the lock in of the PLL output on the phase angle of the utility current vector. The feedforward frequency command ($\omega_{ff}$) is introduced to improve the overall tracking performance of the PLL [12].
B.2 Active and Reactive Current Calculation and Control

Droop equations are used to calculate the reference currents but to really inject the reference current towards the grid a current control or current regulator is required.

Current control for inverters are categorized into three major classes hysteresis regulator, Linear PI regulators and predictive regulators [59] [33] [16]. These classes can be further partitioned into stationary and synchronous d-q reference frame implementations. Stationary reference frame is to control the three phase signals directly without converting into another reference frame. The d-q reference frame transforms the stationary frame towards a rotating reference frame using traditional Clarke and Park transformations [29].

In droop controlled systems, a d-q reference frame is very convenient because it can control active and reactive currents separately. Secondly, three phase stationary frame regulators are regarded always as being unsatisfactory for AC current regulation since a conventional PI-regulator suffers from significant steady state amplitude and phase errors. Nevertheless the last reason can be neglected; there are stationary frame current regulator implementation which can satisfactorily solve this problem.

The most important reason is that using the d-q reference frame; active and reactive current can be controlled separately resulting in independently controlling the active and reactive power. Therefore the current control which is proposed during the design is based on synchronous PI control as shown in figure B.5.

\[ I_d \text{ and } I_q \text{ currents are compared with their reference values and the PI control and force the error to be zero. In addition a decoupling term } \omega L \text{ is used to establish a correct control because coupling terms are added during the d and q transformation [45].} \]
Appendix C

Excess, Shortage and Average Scenarios

Some examples of the weekly generator and load profiles based on the μCHPs, PV systems and detached households are illustrated in this section. The profiles are generated for 4 seasons (January, April, July and December) during excess, shortage and average scenarios. The generator and load profiles are produced using statistical weather information from solar radiation, wind velocity and temperature. The scenarios are deeply analyzed in the graduation report from [44] and a global summary how the profiles are created is shown in figure C.1. The scenarios are analyzed with/without the control strategy as described in section 8.2.

Figure C.1: Creating the overload and shortage scenarios [44]

A few changes are made during the creation of the load profiles.

- Profiles are calculated for the reference year 2020 resulting in an increase by 1.5% per year compared to the information provided by [43].
Appendix C

- Reactive power demand (consider cos(\phi) = 0.95 for detached household [57]) is added to the detached household load profiles from [43]
- The profiles are based on 40 aggregated households, \( \mu \text{CHPs} \) and PV systems.

In figure C.2 is shown the average active and reactive power demand (detached household) during 1 week and for all 4 seasons \(^1\). The power demand is higher during winter and autumn and less during spring and summer.

![Graph showing average active and reactive power demand](image)

Figure C.2: Average scenario: Load demand during 4 seasons

The active power production \( \mu \text{CHP}, \text{PV system} \) for average scenario is shown in figure C.3. The power production is the same for each day during one season, therefore only 1 day is shown for each season \(^2\).

![Graph showing active power production](image)

Figure C.3: Average scenario: Generators during 4 seasons

In the average scenarios, it is shown that during cold seasons (December and October) the \( \mu \text{CHPs} \) is more enabled than during warm seasons (July and April). Contrarily, the PV system is activated when there is much solar radiation (e.g. July) and less activated in January.

The other scenarios excess and shortage are created at the same way. The only difference is that for excess scenario more power is created by the generators.

---

\(^1\)Generation is denoted in negative sign and demand is numbered in positive sign

\(^2\)The power profiles are more clearly compared to seven days the same generator profile
and there is low electricity demand. Contrarily, the shortage scenarios are based on less power generation and high electricity demand.
Appendix D

Implementation Micro-Grid in DigSILENT

DiGSilent Powerfactory is the software which is used to implement the unbalanced voltage and frequency control for the urban area 'Meekspolder'. The assignment is to analyze long terms transients; the active and reactive power demand will change each 15 minutes and the system needs to be able to correct these differences. Powerfactory provides two ways to simulate dynamic results:

1. Electromechanical transient (EMT) simulations
2. Root mean square (RMS) simulations

The difference between those two is that EMT simulations are specifically used to analyze behavior up to 10 seconds which is called transient stability [35]. RMS simulations is more suited for mid- and long-term stability analysis (up to tens of minutes). Therefore RMS calculation are used to analyze the behavior of the urban area 'Meekspolder'. Powerfactory uses Newton Raphson based iterations of network and dynamic model equations combined with a non-linear representation of electromechanical model. The following simulation settings are used:

In the 'Meekspolder', there are Solar cells, CHP's and Households which are all single phase loads. The voltage and frequency control is based on the storage system which is connected to an unbalanced three phase inverter. Therefore simulation are made with:

1. An unbalanced RMS simulation

For RMS simulation, results in RMS values; \( E_{rms} = \sqrt{\int_0^T e^2 dt} \) can be applied to recalculate the actual power value. Additionally, the model should be dynamically changing in time and also a feedback control system should be included. The Powerfactory DiGSIILENT simulation language or shortly DSL can perform these tasks, DSL is the background control interface running on DiGSIILENT. This appendix shows the implementation of the micro-grid using DSL.
Appendix D

Figure D.1: Simulation settings

D.1 Implementation Households, Photovoltaic and $\mu$CHP’s

The PV systems, households and $\mu$CHPs are simulated as a single phase load connected to neutral. The generator and loads are connected to generator and load profiles based on a 15 minutes timescale. Generators (PV systems and $\mu$CHPs) are simulated as negative loads, contrarily positive loads are the households. In DigSilent an Elmfile (DSL measurement file) connects the production profile to the load. The Elmfile links the active and reactive power values (MW) with the connected load. In order to simulate the loads in kW a conversion from MW to kW is calculated [17].

D.2 Battery Storage System Choice

DigSILENT software toolbox is originally used to calculate high voltage simulations. Therefore low voltage grid components are rarely available in this software package. During the investigation of Powerfactory, there are three DSL solutions to apply a battery storage system into the network.

1. DC voltage source with an three phase balanced inverter
2. AC unbalanced voltage source
3. AC unbalanced current source

The first solution is based on a balanced three phase inverter which is driven by the d-q currents and the cosine and sine of the grid frequency. The inverter has already an internally current regulator which reduce the complexity to realize the battery storage system. Unfortunately it’s functioning as a balanced voltage source; meaning that the active and reactive power are equally distributed between the three phases. Generally, households are single phase where...
an unbalanced circuit is certainly possible. Therefore the proposed inverter by DiGILENT can never fulfill an correct demand and supply equilibrium.

Secondly, AC unbalanced voltages source are considered. This component is operating by adjusting the three phase voltages $U_a, U_b$ and $U_c$, the three voltage angles $p_a, p_b$ and $p_c$ and the nominal frequency. By implementing a voltage and frequency droop it is possible to mimic voltage and frequency changes. This means that by connecting a load; the control system can calculate the demand on active and reactive power and change the voltage and frequency of the grid. In this way it’s possible to create a voltage and frequency control in the system.

Unfortunately, the AC voltage source inside DiGILENT is an ideal voltage source which means that it’s impossible to limit the current flowing out of the voltage source. The voltage source always provides the active and reactive power demand even when an reactance with an high resistance is connected to the voltage source. This means that it’s impossible to create a battery storage behavior using the AC voltage source under normal operating conditions.

The final solution which can handle an unbalanced system, is to use an unbalanced current source. By adjusting the three phase currents $I_a, I_b$ and $I_c$, the three current angles $p_a, p_b$ and $p_c$ and the nominal frequency; it’s possible to create an unbalanced power supply. The battery behavior can be imitated by limiting the output current of the three phase current source. Active and reactive power droop equations can be build around this current source.

There is also a drawback; the current source isn’t a slack bus in Powerfactory which means that simulation can’t run by inserting only a current source. A final aspect is by using the current source it’s not required to implement a current regulator, however a current angle control is required.

The proposed battery storage model is based on an AC current source and AC voltage source whereby the AC voltage source is only enabled in combination with AC current sources during autonomous operation.

D.3 Implementation Voltage or Current Source Algorithm

The micro-grid model is built in DiGILENT. As DiGILENT does not support an unbalanced inverter model, the models for current- and voltage-source are used. Depending on the operation mode of the micro-grid, different models for the battery storage are used, as will be explained in this section. An overview is given in table D.1.

<table>
<thead>
<tr>
<th>Operation mode micro-grid</th>
<th>Battery storage model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid-connected</td>
<td>Current sources</td>
</tr>
<tr>
<td>Autonomous</td>
<td>Voltage source for battery with highest priority, current source for other batteries</td>
</tr>
</tbody>
</table>

Table D.1: Battery storage system operation mode

Reference active and reactive power current values are not imposed at the output using a current regulator. The active and reactive power reference values are forced out of the current source using a current angle regulator which is a
proportional-integrator which minimizes the power factor error by adjusting the current angle.

The current source is used during grid-connected operation mode, but during autonomous operation mode the current source cannot operate as slack to create a voltage and frequency. Therefore an unbalanced voltage source is used to create a voltage and frequency depending on the active and reactive power output. In DiGSI LENT the voltage source produces unlimited active and reactive power and it is not possible to limit this power. To overcome this constraint the use of current sources next to a voltage source is proposed. This means that the voltage source will create a voltage and frequency which deviates from the nominal voltage and frequency in case of active and reactive power demand. This error in voltage and frequency activates the control strategy inside the AC current source and as a consequence the deviation active and reactive power is injected. This amount of active and reactive power reduces the amount of active and reactive power from the voltage source.

A voltage and frequency is generated depending on the active and reactive power and additionally active and reactive power distribution is verified during autonomous operation.

An important issue is which battery storage system inverter will operate as voltage or current source. Fig. D.2 shows the corresponding criteria to operate as voltage source or current source.

Each battery storage system determines, using the gathered information, whether it operates as current source or voltage source. The inverter which operates as voltage source is the one with the highest absolute three phase voltage deviation compared to the nominal voltage denoted as $U_{\text{dev3abs}}$. However, to determine the inverter with the highest absolute three phase voltage deviation a kind of token-ring system (as described in [38]) is used. Every inverter receives the chosen id-number and absolute three phase voltage deviation denoted as $U_{\text{neighdev3abs}}$ from his neighbor. The battery storage system compares his own $U_{\text{dev3abs}}$ with $U_{\text{neighdev3abs}}$ for a short period (determined by the communication speed). When $U_{\text{dev3abs}}$ has the highest value during at least this short period, then the storage system will send his own unique id-number around to let every part of the network know that he is chosen to be the voltage source. In case that $U_{\text{neighdev3abs}}$ has a higher value then the battery storage system forwards the chosen id-number received from the neighbor. In special cases whereby every part of the system has the same absolute voltage deviation, the lowest unique id-number is chosen to be the voltage source. Moreover, at the initialization time, the lowest unique id-number is chosen to be the voltage source.

At the end the voltage, frequency, active and reactive power are equal as in case of applying the PWM inverter and additionally an unbalanced control can be realized.

The design of this control have some drawbacks, during autonomous operation mode when the voltage source becomes empty, the voltage source will disconnect from the grid. This disconnection will result in losing a slack voltage source and as a consequence the voltage and frequency in the grid can’t be controlled. This issue is only during the simulation but in a practical setup situation, this will not happen.
Figure D.2: Flow diagram determining to operate as voltage source or current source
Each inverter has a lithium ion battery storage container

III. ANALYSIS OF DROOP CONTROL METHODS

In literature different control strategies to operate parallel inverters are described, based on inductive droop or resistive droop methods. With the inductive droop method, the frequency reacts under influence of a change in active power and reactive power is injected to influence the voltage. With the resistive droop method the voltage is controlled by active power and the frequency is controlled by reactive power. Both approaches are recommended by researchers [1], [10], [20]. In this section the voltage and frequency dependencies on active and reactive power are explained in more detail and some technical possibilities are discussed for both approaches.

The PWM inverter output impedance (behind the PWM output filter) plays a major role in the way to control voltage and frequency efficiently. The control dependency can be described by means of the power transfer through an impedance as depicted in fig. 2. \( U_a \) and \( U_b \) are respectively input and output voltages with a specific power angle. For simplicity the power angle for \( U_a \) is fixed at 0 degree. The angle \( \phi \) between the current and voltage \( U_a \) is the power factor angle at point \( a \). The cable inductive reactance \( X \), resistance \( R \) and a possible additional inductive term are united in the impedance \( Z \) with a specific angle \( \theta \) (\( Z=R+jX \), \( Z=Z\cos(\theta) \) and \( X=Z\sin(\theta) \)). Cable capacitances are ignored due to the high impedance which results in a negligible influence in the voltage.

The dependency of active \( P \) and reactive power \( Q \) with voltage and frequency can be described by using the impedance model as explained in [3],[13],[20].

\[
U_a - U_b \cos(\delta) = \frac{RP + QX}{U_a} \tag{1}
\]
\[
U_b \sin(\delta) = \frac{XP - RQ}{U_a} \tag{2}
\]

From (1) and (2), a relation in case of a resistive output impedance (small \( \delta \), \( R \gg X \) and \( X \approx 0 \)) can be described:

\[
U_a - U_b \cos(\delta) \approx U_a - U_b \approx \frac{RP}{U_a} \tag{3}
\]
\[
U_b \sin(\delta) \approx U_b \delta \approx -\frac{RQ}{U_a} \tag{4}
\]

while for purely inductive output impedance (small \( \delta \), \( X \gg R \) and \( R \approx 0 \)):

\[
U_a - U_b \cos(\delta) \approx U_a - U_b \approx \frac{QX}{U_a} \tag{5}
\]
\[
U_b \sin(\delta) \approx U_b \delta \approx \frac{XP}{U_a} \tag{6}
\]

Fig. 3a and 3b show a graphical polar representation for both set of dependencies.

In case of resistive output impedance, from operation point \( S_1 \), an increase of voltage \( U_{in} \) from \( U_1 \) to \( U_2 \) leads to a higher apparent power operation point \( S_2 \). This causes a small change (increase) of reactive power and a larger change (increase) active power as depicted in fig. 3a. Furthermore a transition from operating point \( S_2 \) to \( S_3 \), caused by an increase of power angle from \( \delta_1 \) to \( \delta_2 \), tends to significantly increase the reactive power and create a small change of active power towards a lower output power value. These relations can also be considered in the other way around, analyzing the influence of changing active and reactive power on the voltage and power angle \( \delta \).

For the situation of inductive output impedance an increase of voltage \( U_1 \) to \( U_2 \) leads to e.g. increasing reactive power and a small increase in active power. Additionally a reasonable increase of active power is achieved by increasing the power angle which also causes a small decrease in reactive power.

The change of phase angle \( \delta \) is related to the frequency deviation \( df \) according to (7) (Laplace domain)

\[
\frac{d\delta}{df} = \frac{2\pi}{s} \tag{7}
\]

A comparison of controlling voltage and frequency by resistive or inductive approach regarding technical possibilities is shown in Table I [7].
Development of a Voltage and Frequency Control Strategy for an Autonomous LV Network with Distributed Generators

Justin Au-Yeung

Abstract—This paper presents a novel control strategy to operate a low-voltage (LV) micro-grid in grid connected operation mode as well as autonomous operation mode. Depending on the inverter output impedance which is mainly resistive due to the LV cables a proper control strategy based on an unbalanced resistive droop approach is developed. The control strategy is verified using stability analysis, simulating fast changes of power production and simulating excess, shortage and average scenarios. Additionally, the control system can operate in an unbalanced network and can improve the active and reactive power distribution using a data communication system.

I. INTRODUCTION

In the future, a transition in the low voltage network might take place from the conventional design towards a micro-grid concept. The micro-grid is formed by small-scale single phase distributed generators such as Micro Combined Heat and Power (μCHP), Photovoltaic (PV) systems and storage devices (flywheels, batteries and energy capacitors) close to the loads (households and shopping centers). The shift towards small-scale generation close to the loads can increase the reliability, efficiency and voltage quality of the grid on the condition that the network is adequately managed and coordinated [3],[16]. The management and coordination of a micro-grid is complex because the energy production of the distributed generators mainly depends on the weather conditions (solar, temperature and wind) and is less predictable. Additionally, different stability problems can be caused by mismatching of supply and demand [13]. Moreover during disturbances (voltage drops, interruptions, faults etc.) inside or outside the micro-grid, the micro-grid must be able to operate in an autonomous operation mode, isolating the micro-grid from the upper-grid and comply with the standard as described in the Dutch grid code [18]. In case of autonomous operation mode sufficient storage capacity should be provided.

The main objective of this research is to create a safe, efficient and reliable control strategy to operate a micro-grid connected to the grid or as isolated island using 'DiGSILENT PowerFactory'. This research fully concentrates on strategies based on inverter technology connected with a storage device.

Relevant side targets for the control strategy are:

1) The ability to maintain service under excess, shortage and average (demand) scenarios
2) The ability to react rapidly under fast energy production changing [4].
3) The ability to operate multiple inverters in parallel to manage and coordinate the micro-grid.

The research leads to a micro-grid simulation model based on an unbalanced droop controlled inverter including a communication interface between the inverters, implemented in DiGSILENT Powerfactory.

Section II provides a description of the analyzed micro-grid system and in section III droop control methods are analyzed. Section IV describes the proposed control strategy and section V the implementation in DiGSILENT PowerFactory. Simulation results illustrating the performance of the control strategy and the effects on the low voltage (LV) network are presented in section VI. The research results are discussed in section VII. Finally, section VIII gives conclusions and recommendations.

II. SYSTEM DESCRIPTION

The analyzed micro-grid system consist of a combination of 3 storage devices including inverter front-end and 360 households with PV systems, μCHP systems as shown in fig. 1. The micro-grid can be connected to or disconnected from the upper-grid and transformer (10 kV/400 V, 630 kVA) by operating a breaker.

The houses are equally distributed among the 3 phases of 3 feeders (Al, 95mm², lengths of 400m, 450m and 500m). To simplify the simulations, the 40 houses connected to the same phase of a feeder are aggregated to 1 load and 1 generator (simulated as 1 negative load representing 40 μCHPs and 40 PV systems).

Loads (power demand of detached households), μCHPs (1 kW_e, 4 kW_θh) and PV systems (1 kW_peak) are modeled based on load and generator power profiles from weather records (wind, solar and temperature data sets) acquired from [17]. The main reason to simulate detached households is the higher demand of heat leading to a higher electricity production and therefore to possible excess scenarios.

The analysis is performed for the year 2020 considering an electrical power demand increase by 1.5% per year compared to the information provided by [17]. The voltage and frequency stability is guaranteed by the storage system and inverter during autonomous operation mode. The storage systems are placed on each feeder (at distances of 630 m, 680 m and 730 m from the transformer). Lithium-ion battery storage is chosen because of the high performance and high energy density (210
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Both strategies have advantages and disadvantages. The first advantage for the inductive droop approach is that it can enable active power dispatch because frequency is a global parameter. Since voltage can only be influenced locally the resistive droop approach is not applicable for active power dispatch.

Moreover, the inductive approach is compatible with the high voltage level while this is not the case for the resistive approach. Finally, synchronous generators are also using the inductive droop approach, which makes it a well known approach.

In case of resistive droop, voltage can be controlled directly by injecting active power which is impossible for the inductive droop approach.

In addition, the impedance in LV networks is predominantly resistive \((R >> X)\). Applying inductive droop control in LV grid requires the addition of a series inductor (at the inverter output filter or in front of the load) or assuming a large inductor value at the output of the filter to increase the \(R\) ratio. However assuming a large inductive value at the output filter is not always true as it also depends on the control strategy. E.g. in [10] is an inverter design with resistive virtual output impedance proposed.

Furthermore, the inductive coupling can cause problems for the voltage stability of the system. This occurs due to a possible decrease of resonance frequency towards the grid frequency [8], [10], [14].

Both approaches are able to control voltage and frequency. An investigation is performed for the resistive and inductive droop approach to determine which implementation is more preferable to create a micro-grid. In section IV stability analysis will be performed for both strategies. In section VI the performance of the control strategies is validated by fast energy production changes.

IV. PROPOSED CONTROL STRATEGY

Fig. 4 shows the block diagram of the proposed control strategy to operate the micro-grid in grid-connected and autonomous operation mode.

Firstly, the single inverter control strategy is illustrated in section IV-A using fig. 4, followed by stability analysis to determine a proper controller in case of resistive and inductive droop. In section IV-B the control strategy to operate multiple inverters using a communication interface is described.

A. Single Inverter

1) Voltage and Frequency Control Strategy: Depending on the droop control approach the battery storage system injects/consumes active and reactive power to control voltage and frequency. In case the inverter output voltage is below the nominal value, active or capacitive reactive power will be injected in the grid. During over-voltage, active or capacitive reactive power will be consumed by the battery storage system. The inverter active and reactive power output is controlled by regulating the inverter output current.

At the end of the inverter output filter, the single phase voltages and currents \(U_a, U_b, U_c, I_a, I_b, I_c\) are measured and separated into a real (d) and imaginary part (q). The phase locked loop calculates the frequency \(f\) and phase \(\phi\) using the real and imaginary voltage values as described in [6]. Then depending on one of the two droop control approaches, reference active and reactive power are determined.

Equation (8) describes the inductive droop control where \(k_{pi}\) is the proportional coefficient for active power and \(k_{qi}\) for reactive power. The storage system injects only active and reactive power when the actual frequency and voltage deviates from the nominal voltage and frequency, therefore active and reactive power set-points, \(P_0\) and \(Q_0\) are set to zero.

Additionally, a dead band \((D_{pb} \text{ and } D_{qb})\) around the nominal voltage and frequency is implemented. The dead band prevents control during each small voltage and frequency deviation which can cause stability problems such as oscillations in the system.
Besides the stability issue, a dead band is placed to prevent the transformer tap changer switching continuously around nominal voltage.

According to the Dutch grid code [21], the nominal voltage and nominal frequency are fixed at $230\ V_{RMS}$ and $50\ Hz$. The resistive droop control (9) is described similarly as the inductive droop control, whereby the proportional coefficients are named as $k_{pr}$ and $k_{qr}$.

$$P = P_0 - k_{pr}(f - f_0) \quad (8)$$
$$Q = Q_0 - k_{qr}(U - U_0)$$

$$P = P_0 - k_{pr}(U - U_0) \quad (9)$$
$$Q = Q_0 + k_{qr}(f - f_0)$$

The reference current values are determined by dividing the single phase $P$ and $Q$ reference values denoted by $P_a, P_b, P_c, Q_a, Q_b,$ and $Q_c$ with $U_{da}, U_{db}$ and $U_{dc}$. The current regulator, a proportional-integrator controller force the reference currents to be the output current by adjusting the output voltage $U_a, U_b$ and $U_c$. By controlling each phase separately, an unbalanced droop control is created to handle unbalanced loading in the network.

The reference currents are determined by a proportional control without integral terms, because frequency and voltage measurement errors can lead to instability in the system when more than one inverter is connected to the grid. This happens because each inverter attempts to control it towards a different voltage or frequency value which means that the inverters will control against each other, resulting in an unstable system.

A control strategy with an unbalanced droop control and enabling parallel operation between inverters is proposed.

### TABLE II: Parameters of the Inverter and LV Grid

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Nominal Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable impedance [section III]</td>
<td>$Z$</td>
<td>$0.16 + j0.041$</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Series inductor [section III]</td>
<td>$Z_l$</td>
<td>$1.559$</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>LPF cut-off Frequency [eq. 22]</td>
<td>$\omega_c$</td>
<td>$10$</td>
<td>$rad$</td>
</tr>
<tr>
<td>Nominal Frequency [21]</td>
<td>$f_e$</td>
<td>$50$</td>
<td>$Hz$</td>
</tr>
<tr>
<td>Nominal Amplitude [21]</td>
<td>$U_a$</td>
<td>$230$</td>
<td>$V_{RMS}$</td>
</tr>
<tr>
<td>Dead band voltage</td>
<td>$D_{vb}$</td>
<td>$\pm 2$</td>
<td>$V_{RMS}$</td>
</tr>
<tr>
<td>Dead band frequency</td>
<td>$D_{fb}$</td>
<td>$\pm 0.05$</td>
<td>$Hz$</td>
</tr>
</tbody>
</table>

2) Stability Analysis Droop Control: As described previously, the control is implemented using the droop controllers. The problem arises that by increase of the proportional droop gains leads to instability [19]. However, by applying stability analysis using the model shown in fig. 2, the control range for the droop gains can be determined.

To make the dynamic analysis of the network more comprehensive, a dynamic phasor model as shown in [3], [5] is developed. The traditional phasor representation of sinusoidal signals is limited by the quasistationary assumption on the speeds of the phasor states [2]. The conversion method as described in [24] is applied on the three phase signal and has no restrictions on the speed.

Assume cable and possible series inductor denoted by $Z$, where the voltage across the impedance is described by:

$$U_a - U_b = R\vec{i} + L\frac{\partial}{\partial t}\vec{i} \quad (10)$$

By using a special feature of the time varying phasor representation (11) as mentioned in [24]:

$$\text{Phasor}(\frac{\partial}{\partial t}\vec{e}(t)) = j\omega\vec{E}(t) + \frac{\partial}{\partial t}\vec{E}(t) \quad (11)$$

where $\vec{e}(t)$ is a time-varying phase signal and $\vec{E}(t)$ is the phasor representation and transforming (10) into Laplace domain yields:
Fig. 5: Root-locus plots resistive droop control

\[ P = \frac{(3U_a^2 - 3U_a U_b \cos(\delta))(Ls + R) - 3U_a U_b \omega L \sin(\delta)}{(R + Ls)^2 + (\omega L)^2} \]  
\[ Q = \frac{3U_a U_b \sin(\delta)(Ls + R) - 3U_a U_b \omega L \cos(\delta) + 3U_a^2 \omega L}{(R + Ls)^2 + (\omega L)^2} \]  

In order to linearize (12) and (13), (14) and (15) are used.

\[ dP = \frac{\partial P}{\partial U_b} dU_b + \frac{\partial P}{\partial \delta} d\delta \]  
\[ dQ = \frac{\partial Q}{\partial U_b} dU_b + \frac{\partial Q}{\partial \delta} d\delta \]

The two parts can be classified as one that belongs to the resistive output impedance and the other one for the inductive output impedance. In case of resistive output impedance the open loop system consist of two complex conjugated poles and one zero. In case of inductive output impedance, the system consist of two conjugated poles as described in (18) and (19). There is a small difference between the voltage \( U_a \) and \( U_b \), \( U_a U_b \approx U_a^2 \).

Additionally consider also a small angle \( \delta \) which means \( \cos(\delta) = 1 \), \( \sin(\delta) \approx 0 \) yielding:

Fig. 6: Root-locus plots inductive droop control

\[ \frac{dP}{d\delta} = \frac{-3U_a(R + Ls)}{(R + Ls)^2 + (\omega L)^2} \]  
\[ \frac{dQ}{d\delta} = \frac{3U_a^2(R + Ls)}{(R + Ls)^2 + (\omega L)^2} \]

While for inductive droop control \( \frac{\partial P}{\partial U_b} = 0 \) and \( \frac{\partial Q}{\partial \delta} = 0 \) and the dynamic model for inductive droop control becomes

\[ \frac{dP}{d\delta} = \frac{-3U_a^2 \omega L}{(R + Ls)^2 + (\omega L)^2} \]  
\[ \frac{dQ}{d\delta} = \frac{-3\omega U_a}{(R + Ls)^2 + (\omega L)^2} \]

Equations (16) and (17) show that in case of resistive output impedance the open loop system consist of two complex conjugated poles and one zero. In case of inductive output impedance, the system consist of two conjugated poles as described in (18) and (19). The resistive output impedance is more damped due to the zero than the inductive output.
impedance and both control approaches are located at the left half plane and therefore in a stable region. Decreasing the \( \frac{X}{R} \) ratio will move the poles of the system close to the right half plane and causing a decrease of possible droop gains.

Equations (16), (17), (18) and (19) assumed the droop control model without an output filter. In the real situation a filter is connected to the inverter output preventing harmonics towards the grid, therefore the droop gain is analyzed together with a first order low pass filter (LPF) with cutoff frequency \( \omega_c \). At the end, using relation (7), the open loop system can be described by:

\[
\frac{dP_i}{df} = \frac{2\pi \omega_c}{s + \omega_c (R + Ls)^2 + (\omega L)^2} - 3U_o^2 \omega L \tag{20}
\]

\[
\frac{dQ_i}{dU_b} = \frac{\omega_c}{s + \omega_c (R + Ls)^2 + (\omega L)^2} - 3\omega U_o \tag{21}
\]

and

\[
\frac{dP_r}{dU_b} = \frac{\omega_c}{s + \omega_c (R + Ls)^2 + (\omega L)^2} - 3U_o (R + Ls) \tag{22}
\]

\[
\frac{dQ_r}{df} = \frac{2\pi \omega_c}{s + \omega_c (R + Ls)^2 + (\omega L)^2} + 3U_o^2 (R + Ls) \tag{23}
\]

Adjusting the LPF parameter can improve the range of possible droop gains but will decrease the settling time of the control. The root-locus for the inductive and resistive dynamic models are depicted in fig. 5 and 6 using the parameters enumerated in table II and in order to simulate an inductive output impedance for the inductive droop approach a \( \frac{X}{R} = 10 \) is chosen. The allowed droop gain range to control voltage and frequency is also listed in the root-locus plots. ²

Fig. 5a shows the influence of active power on voltage by increasing the droop gains. The overshoot will increase due to the poles which are moving more towards the imaginary axis. However, the system is still stable because the poles are still located in the left half plane. The influence of reactive power on frequency is shown in fig. 5b where an increase in droop gain tend to move the poles towards the right half plane causing an unstable system.

In case of inductive droop, increasing the droop gain tends to move the closed loop poles to the right half plane causing an unstable system. This applies for the active power to frequency droop as well as the influence of reactive power on voltage.

Considering the stability, resistive droop control is more damped and more stable than inductive droop control.

B. Multiple Inverters

1) Battery Storage System and Communication Interface between Multiple Storage Systems: The battery storage system can be explained by the flow diagram shown in fig. 7.

In normal situations the storage system recharges during voltage above the nominal value. During critical shortage periods, it can happen that the battery is not sufficient charged by the DGs, therefore an emergency case enables the possibility of recharging the battery. The emergency case activates when the remaining battery energy is lower than 5% even when the other battery storage systems are fully charged. The battery storage system sends an activation request to turn on a certain

²Inverse relations are used compared to (8) and (9)
amount \( (x_1) \) of \( \mu \)CHPs using a data communication link. Each battery storage system can only turn on the \( \mu \)CHPs located at its feeder, e.g. the battery storage system with inverter 1 can only enable the \( \mu \)CHPs connected to household cable 1 as depicted in fig. 1.

As a consequence extra electricity is produced by the \( \mu \)CHPs. Between 1.25%–0.001% another amount \( (x_2) \) of \( \mu \)CHPs are turned on to solve the mismatch in supply and demand. When the battery is recharged above 10\%, the battery storage system restores the \( \mu \)CHPs heat demand operation.

In the very unlikely situation when the remaining energy is lower than 0.001\% the storage system automatically shuts down. Normally, it should be sufficient to supply 40 households with 40 \( \mu \)CHPs. When the remaining energy keeps dropping, this can be caused by a problem inside/outside the micro-grid. In case the battery storage system is fully charged, the storage system is disabled to prevent it from consuming power.

Besides satisfying the electricity demand the excess heat is stored in a storage vessel as described in [17].

The second feature uses the data communication system to optimize the active and reactive power distribution as shown in fig. 8. The battery storage system continuously receives active and reactive power average values from the connected neighbor battery storage system using the data communication link (comlink). After receiving the average values \( P_{\text{comav}} \) and \( Q_{\text{comav}} \), the droop control recalculates the active and reactive power reference values \( P_{\text{ref}} \) and \( Q_{\text{ref}} \) as described with \( (24) \) and \( (25) \). \( P_{\text{ownref}} \) and \( Q_{\text{ownref}} \) are the calculated active and reactive power reference values according to the local voltage and frequency measurement without the communication system.

\[
P_{\text{ref}} = \frac{P_{\text{ownref}} + P_{\text{comav}}}{2} \tag{24}
\]

\[
Q_{\text{ref}} = \frac{Q_{\text{ownref}} + Q_{\text{comav}}}{2} \tag{25}
\]

V. IMPLEMENTATION IN DIGSILENT POWERFACTORY

The micro-grid model is built in DIGSILENT. As DIGSILENT does not support an unbalanced inverter model, the models for current- and voltage-source are used. Depending on the operation mode of the micro-grid, different models for the battery storage are used, as will be explained in this section. An overview is given in table III.

Reference active and reactive power current values are not imposed at the output using a current regulator. The active and reactive power reference values are forced out of the current source using a current angle regulator which is a proportional-integrator which minimizes the power factor error by adjusting the current angle.

The current source is used during grid-connected operation mode, but during autonomous operation mode the current source can not operate as slack to create a voltage and frequency. Therefore an unbalanced voltage source is used to create a voltage and frequency depending on the active and reactive power output as illustrated in section IV-A1. In DIGSILENT the voltage source produces unlimited active and reactive power and it is not possible to limit this power. To overcome this constraint the use of current sources next to a voltage source is proposed. The created voltage and frequency will deviate from the nominal voltage and frequency establishing an error which activates the corresponding droop control inside the current source. A voltage and frequency is generated depending on the active and reactive power and additionally active and reactive power distribution is verified during autonomous operation.

An important issue is which battery storage system inverter will operate as voltage or current source. Fig. 9 shows the corresponding criteria to operate as voltage source or current source.

<table>
<thead>
<tr>
<th>TABLE III: Battery storage system operation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operation mode micro-grid</strong></td>
</tr>
<tr>
<td>Grid-connected</td>
</tr>
<tr>
<td>Autonomous</td>
</tr>
</tbody>
</table>

Each battery storage system determines, using the gathered information, whether it operates as current source or voltage source. The inverter which operates as voltage source is the one with the highest absolute three phase voltage deviation compared to the nominal voltage denoted as \( U_{\text{dev3abs}} \). However, to determine the inverter with the highest absolute
three phase voltage deviation a kind of token-ring system (as described in [15]) is used. Every inverter receives the chosen id-number and absolute three phase voltage deviation denoted as \( U_{\text{neighdev3abs}} \) from his neighbor. The battery storage system compares his own \( U_{\text{dev3abs}} \) with \( U_{\text{neighdev3abs}} \) for a short period (determined by the communication speed). When \( U_{\text{dev3abs}} \) has the highest value during at least this short period, then the storage system will send his own unique id-number around to let every part of the network know that he is chosen to be the voltage source. In case that \( U_{\text{neighdev3abs}} \) has a higher value then the battery storage system forwards the chosen id-number received from the neighbor. In special cases whereby every part of the system has the same absolute voltage deviation, the lowest unique id-number is chosen to be the voltage source. Moreover, at the initialization time, the lowest unique id-number is chosen to be the voltage source.

At the end the voltage, frequency, active and reactive power are equal as in case of applying the PWM inverter and additionally an unbalanced control can be realized.

VI. SIMULATION RESULTS

A. Control Strategy Performance

The control strategy performance is verified for inductive and resistive droop control using the micro-grid shown in fig. 1. E.g. at July, due to the high temperature the \( \mu \text{CHP} \) is not producing any electricity and the active power production is fully supported by the PV system. Suddenly, a large cloud appears above the solar systems causing a fast decrease in active power production as shown in fig. 11. As a consequence of the sudden decrease in active power, the voltage level collapsed towards 210V as shown in fig. 12a.

1) Inductive Droop Control: The inductive droop control strategy is tested using the load profile from the previous example. Fig. 10 shows the reactive power produced by the battery storage system. Under influence of a change in voltage, capacitive (-) or inductive (+) reactive power is injected into the network. Due to the injected reactive power a decrease in voltage deviations is expected. However, as mentioned in the stability analysis and shown in 6, by increasing the inductive droop gain a large overshoot can occur. This overshoot is clearly visible in the voltage profile as illustrated in fig. 13a. Furthermore, fig. 13b shows that the transformer loading has barely decreased. These results verify that inductive droop control has stability problems in case the droop gain increases.

2) Resistive Droop Control: In case a resistive droop control is applied on the previous example, active power is injected to correct the voltage deviations as illustrated in fig. 11. Due to the active power injection, the voltage has visibly improved in every part of the network and fig. 12a shows that the single phase voltage is equal at each part of the network due to the droop control. The droop control is set at 4.5 \( \frac{kW}{V} \) to achieve good results, and to limit the overshoot and steady state error. Additionally, the transformer loading significantly decreases as shown in fig. 12b. This shows that resistive droop control should be applied into a low voltage network to prevent system instabilities. In the remaining simulation results the resistive droop control strategy is applied.

B. Balanced Loading

In this section simulation results for a week based on 15-minute-mean load and generator profiles during excess, shortage and average scenarios are illustrated [17]. The simulations results are illustrated using a box plot diagram which is divided into 6 vertical levels as described in table IV [22].

<table>
<thead>
<tr>
<th>Level</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The upper adjacent value</td>
<td>Maximum percentile at 99.65 %</td>
</tr>
<tr>
<td>2</td>
<td>The upper whisker</td>
<td>Top of the box</td>
</tr>
<tr>
<td>3</td>
<td>The box</td>
<td>The tops and bottoms are the 25\text{th} and 75\text{th} percentiles of the samples</td>
</tr>
<tr>
<td>4</td>
<td>The median</td>
<td>Separating the higher half of a sample from the lower half</td>
</tr>
<tr>
<td>5</td>
<td>The lower whisker</td>
<td>Tail of the box</td>
</tr>
<tr>
<td>6</td>
<td>The lower adjacent value</td>
<td>Minimum percentile at 0.35 %</td>
</tr>
</tbody>
</table>
1) Voltage Levels: Fig. 14 shows that due to the DG's penetration, the voltage level does not always comply with the standard as described in [21]. Especially, for the shortage scenario in January, excess scenario in July, average and shortage scenario in October. However, when the control strategy is enabled a clear improvement in voltage level is shown. The control strategy enables that shortage and excess periods are solved by injecting or consuming active power. Due to the control strategy, the allowed voltage range is not violated.

2) Transformer Loading: The control strategy significantly decreases current flowing through the transformer as shown in fig. 15. E.g. the transformer loading during excess scenarios in April is around 75%. When the control strategy is enabled, the transformer loading decreases with 20 %.

C. Unbalanced Loading

This section shows an example that the control strategy can improve the voltage level even in an unbalanced network.

The unbalanced network is caused by differences in electricity demand in each phase. In fig. 16a the simulated unbalanced load profile is shown. In case the storage device is not enabled and only the upper-grid is supporting the network an unbalanced voltage is clearly visible as shown in fig. 16b. When the unbalanced droop control is activated a visible improvement in the voltage profile is shown. The single phase voltages are closer to each other compared to the one without control (voltage difference phase to phase from dx1 to dx). This example shows that the control can improve an unbalanced network in a more equal distributed voltage at each phase.

D. Autonomous operation and communication system

This section shows the micro-grid changing from grid-connected to autonomous operation mode. Consider an example without active power production from DG's and only the storage devices inject active and reactive power into the grid. The active and reactive power demand and supply from the households and storage devices are shown in fig. 17.
On the left side of fig. 18, the micro-grid disconnects from the upper-grid. The disconnection causes at the beginning an activation phenomenon for the voltage and frequency as shown in fig. 18a and fig. 18b. The frequency follows the reactive power demand (Qload) as depicted in fig. 17.

A second example illustrates the battery energy management system using the same demand. The remaining battery storage system energy becomes lower than 5% at t=850 s, resulting in activation of the μCHPs as depicted in fig. 19.

VII. DISCUSSION

This research has developed a control strategy for the micro-grid in order to fulfill the technical requirements. However the question remains what the developed control strategy using storage devices improves in terms of environmental impact. In this section a comparison for CO₂ emission is described using a combination of μCHPs and PV systems where the temporary excess and shortage is solved by only the steam and gas electricity generator (STEG) (scenario 1) or in combination with the battery storage system including control strategy (scenario 2).

The yearly energy production from one μCHP and solar cell is estimated at 3000 kWh [11] and 865 kWh (inclination angle of 36° and southern orientation) as described in PVGIS. Additionally, the yearly energy demand for a detached household is equal to 4600 kWh (in the year 2020) [23] leading to a yearly shortage of 4600-3000-865=735kWh which is solved by the STEG in both scenarios. The electrical efficiency for the battery storage systems is according to [12] 84.6 %. Moreover, the CO₂ emission (excluding manufacturing process) for μCHP and STEG are 0.22 kg/kWh [11] and 0.385 kg/kWh [9] assuming 0 CO₂ emission for PV systems.

However, the battery storage system is only activated when the voltage deviates from the nominal voltage and the voltage dead band $D_v$ as described in IV-A1. According to average

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scenarios simulations is the total battery storage system energy consumption equal to 372.6 kWh.

The yearly CO₂ emission for scenario 1 is equal to 
\[(3000)(0.22)+(735+372.6)(0.385) \approx 1112.54 \text{ kg CO₂}\]
and in case of scenario 2 is the CO₂ emission 
\[(3000)(0.22)+(735+372.6)(1-0.846)(0.385)) \approx 969.05 \text{ kg}\].

At the end a significantly CO₂ reduction of nearly 11 % is achieved by solving temporary excess and shortage using the storage device instead of STEG.

VIII. CONCLUSIONS AND RECOMMENDATIONS

In this paper an overview of the resistive and inductive droop control is shown to determine which strategy is more preferable to create an autonomous network. Both strategies are compared using the voltage and frequency dependency and performing stability analysis. Additionally, the performance of the control strategies are tested using fast energy production changes which provides a concluding answer to use resistive or inductive droop control in a LV network.

The control strategy based on resistive droop proves to be preferred to control voltage and frequency during grid-connected operation mode as well as autonomous operation mode in LV grid.

Additionally, a control strategy is developed to improve the voltage even during unbalanced loading. A data communication system is developed to enhance a better active and reactive power distribution between battery storage systems.

A choice is made between inductive and resistive droop, however in reality the inverter output impedance is not fixed. This suggest to apply adaptive droop control, calculating in real-time the output impedance to control the micro-grid using resistive or inductive droop control.

Furthermore, the developed communication system can be extended by sending dynamic droop gain information. The droop gain information can be used to reduce the electricity price (trader) or improving the voltage and frequency (grid-operator).

A final aspect is to verify the simulation results by laboratory test.

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Fig. 18: Autonomous operation voltage and frequency at the load

(a) Single phase voltage (kV) at the load

(b) Grid frequency controlled by $k_q = 0.005 \frac{Hz}{kW}$

Fig. 19: Communication system activates μCHPs


Abstract—This paper presents a novel control strategy to operate a low-voltage (LV) micro-grid in grid connected operation mode as well as autonomous operation mode. Depending on the inverter output impedance which is mainly resistive due to the LV cables a proper control strategy based on an unbalanced resistive droop approach is developed. The control strategy is verified by simulating fast changes of power production and simulating excess, shortage and average scenarios. Additionally, the control system can operate in an unbalanced network and can improve the active and reactive power distribution using a data communication system.

Index Terms—Active and Reactive Power, Autonomous Operation, Data Communication System, Droop Control, LV Network, Micro-Grid, Output Impedance, Unbalanced Network

1. INTRODUCTION

In the future, a transition in the low-voltage (LV) network might take place from the conventional design towards a micro-grid concept. The micro-grid is formed by small-scale distributed generators such as Micro Combined Heat and Power (μCHP), Photovoltaic (PV) systems and storage devices (flywheels, batteries and energy capacitors) close to the loads (households and shopping centers). The shift towards small-scale generation close to the loads can increase the reliability, efficiency and voltage quality of the grid on the condition that the network is adequately managed and coordinated [2], [7]. This is complex and is less predictable because the energy production of the distributed generators mainly depends on the weather conditions (solar, temperature and wind). Additionally, different stability problems can be caused by mismatching of supply and demand [6]. Moreover during disturbances (voltage drops, interruptions, faults etc.), the micro-grid must be able to operate in an autonomous operation mode, isolated from the upper-grid and complying with the voltage and frequency quality as described in the Dutch grid code [9]. In case of autonomous operation mode sufficient storage capacity must be provided.

The main objective of this research is to create an efficient and reliable control strategy to operate a micro-grid connected to the grid or as isolated island. This research fully concentrates on strategies based on inverter technology connected to a storage device.

Relevant side targets for the control strategy are:

1) The ability to maintain service under excess, shortage and average (demand) scenarios

2) The ability to react rapidly under fast energy production changes [3].

3) The ability to operate multiple inverters in parallel to manage and coordinate the micro-grid.

The research leads to a micro-grid simulation model based on an unbalanced droop controlled inverter including a communication interface between the inverters, implemented in DiGSIILENT Powerfactory.

Section II provides a description of the analyzed micro-grid system and in section III the proposed control strategy is described. Simulation results illustrating the performance of the control strategy and the effects on the LV network are presented in section IV. Finally, section V gives conclusions and recommendations.

II. SYSTEM DESCRIPTION

The analyzed micro-grid system consists of a combination of 3 storage devices including inverters and of 360 households with PV systems and μCHP systems as shown in fig. 1. The micro-grid can be connected to or disconnected from the upper-grid and transformer (10 kV/400 V, 630 kVA) by operating a breaker.

The houses are equally distributed among the 3 phases of 3 feeders (AI, 95mm², lengths of 400m, 450m and 500m). To simplify the simulations, the 40 houses connected to the same phase of a feeder are aggregated to 1 load and 1 generator (simulated as a negative load representing 40 μCHPs and 40 PV systems).
Loads (power demand of households), $\mu$CHPs (1 kW, 4 kW_{th}) and PV systems (1 kW_{peak}) are modeled based on load and generator power profiles from weather records (wind, solar and temperature data sets) acquired from [8].

The analysis is performed for the year 2020 considering an electrical power demand increase by 1.5% per year compared to the information provided by [8]. The storage systems are placed on each feeder (at distances of 630 m, 680 m and 730 m from the transformer). Lithium-ion battery storage is chosen because of the high performance and high energy density (210 Wh/kg) as described in [5]. A storage size of 6300 kWh (in combination with $\mu$CHPs and PV systems) is chosen to operate a minimum of 16 days in autonomous operation.

III. PROPOSED CONTROL STRATEGY

The proposed voltage and frequency control strategy is based on unbalanced droop controlled inverters connected to a storage device. A communication interface (Fig. 2) is developed to allow data exchange between the inverters for active (P) and reactive power (Q) set-points and to send requests to (de)activate allocated $\mu$CHPs for storage energy management purposes.

A. Voltage and Frequency Droop Control Strategy

Fig. 3 shows the block diagram of the proposed control strategy to operate the micro-grid in grid-connected and autonomous operation mode [2], [4], [7].

Depending on the control approach the battery storage system injects/consumes active and reactive power to control voltage and frequency. In case the inverter output voltage is below the nominal value, active or capacitive reactive power will be injected in the micro-grid. During over-voltage, active or capacitive reactive power will be consumed by the battery storage system. The inverter active and reactive power output is controlled by regulating the inverter output current.

At the end of the inverter output filter, the single phase voltages ($U_a$, $U_b$, $U_c$) and currents ($I_a$, $I_b$ and $I_c$) are measured and separated into a real (d) and imaginary part (q). The phase locked loop (PLL) calculates the frequency $f$ and phase $\phi$ using the real and imaginary voltage values. Then depending on the control approaches, $P$ and $Q$ are determined.

$$P = P_0 - k_p (f - f_0) \quad (1)$$
$$Q = Q_0 - k_q (U - U_0) \quad (2)$$

Equation (1) describes the inductive droop control \(^1\) where $k_p$ is the proportional coefficient for active power and $k_q$ for reactive power. Resistive droop control (2) is described similarly as the inductive droop control, whereby the proportional coefficients are named as $k_p$ and $k_q$.

The storage system injects only active and reactive power when the actual frequency and voltage deviates from the nominal voltage and frequency, therefore active and reactive power set-points, $P_0$ and $Q_0$ are set to zero.

Additionally, a dead band around the nominal voltage and frequency is implemented. The dead band prevents control during each small voltage and frequency deviation which can cause stability problems such as oscillations in the system.

Besides the stability issue, a dead band is placed to prevent the transformer tap changer switching continuously around the nominal voltage.

According to the Dutch grid code [9], the nominal voltage and nominal frequency are fixed at 230 V_{RMS} and 50 Hz.

The reference current values are determined by dividing the single phase P and Q reference values denoted by $P_{ref}$, $Q_{ref}$, $P_{ref}$, $Q_{ref}$, $Q_{ref}$, and $Q_{ref}$ with $U_{ref}$, $U_{ref}$, and $U_{ref}$. The current

\(^1\)Droop approaches are named differently in several papers. In [1] it is denoted as conventional and opposite droop. In this paper inductive and resistive droop control is consistently used as it is more clear to name the approaches according to the output impedance at the power injection point (impedance of LV cables and inverter low pass filter).
Control System

Battery inverter front end

P&Q decoupling and calculate single phase

Current regulator

Inverse dq transformation

Droop curves

Voltage

PLL

U to f and f

dq transformation

dq transformation

P, Q, r

V in, Iq,

Iref

Uref

Iref

Battery

PWM output filter

PWM inverter

Micro-grid

Fig. 3: Applied inverter control strategy including unbalanced droop control

regulator, a proportional-integrator controller forces the reference currents to be the output current by adjusting the output voltage $U_a$, $U_b$ and $U_c$. By controlling each phase separately, an unbalanced droop control is created to handle unbalanced loading in the micro-grid.

B. Optimizing Active and Reactive Power Distribution

A data communication system is used to optimize the active and reactive power distribution. The battery storage system continuously receives active and reactive power reference values from the connected neighbor battery storage system. After receiving the average values ($P_{comav}$ and $Q_{comav}$), the droop control recalculates the active ($P_{ref}$) and reactive power ($Q_{ref}$) reference values as described in 3 and 4. $P_{ownref}$ and $Q_{ownref}$ are the calculated active and reactive power reference values according to the local voltage and frequency measurements.

$P_{ref} = \frac{P_{ownref} + P_{comav}}{2}$  \hspace{1cm} (3)

$Q_{ref} = \frac{Q_{ownref} + Q_{comav}}{2}$  \hspace{1cm} (4)

C. Storage Energy Management

During critical shortage periods, it can happen that the battery is almost empty, therefore an emergency case enables the possibility of recharging the battery. The emergency case activates when the remaining battery energy is lower than a certain value even when the other battery storage systems are fully charged. The battery storage system sends an activation request to turn on a certain amount of $\mu$CHPs using the data communication link. Each battery storage system can only turn on the $\mu$CHPs located at its feeder (fig. 2).

IV. SIMULATION RESULTS

A. Control Strategy Performance

The control strategy performance is verified for inductive and resistive droop control using the micro-grid shown in fig. 1. E.g., in July, due to the high temperature the $\mu$CHP is not producing any electricity and the active power production is fully supported by the PV system. Suddenly, a large cloud appears above the solar systems causing a fast decrease in active power production as shown in fig. 4. As a consequence of the sudden decrease in active power, the voltage level drops towards 210V as shown in fig. 5.

The inductive droop control strategy is tested using the load profile from fig. 4. Fig. 4a shows the reactive power produced by the battery storage system. Under influence of a change in voltage, capacitive (-) or inductive (+) reactive power is injected into the network. Due to the injected reactive power a decrease in voltage deviation is expected. However an overshoot is clearly visible in the voltage profile as illustrated in fig. 5a.

In case resistive droop control is applied on the previous example, active power is injected to correct the voltage deviations as illustrated in fig. 4b. Due to the active power injection, the voltage has improved in every part of the network and fig. 5b shows that the single phase voltage is equal everywhere in the micro-grid.

The resistive droop control has a more damped response compared to inductive droop control. In the remaining simulation results the resistive droop control strategy is applied.

B. Balanced Loading

In this section the simulation results for a week based on 15-minute-mean load and generator profiles during excess, shortage and average scenarios are illustrated [8]. The simulations results are illustrated using a box plot diagram (the box
contains 50% of the data and in addition minimum, maximum and median levels are shown) as described in [10].

Fig. 6 shows that due to the DG’s penetration, the voltage level does not always comply with the standard as described in [9]. Especially, for the shortage scenario in January, excess scenario in July, average and shortage scenario in October. However, when the control strategy is enabled a clear improvement in voltage level is shown. The control strategy enables that shortage and excess periods are solved by injecting or consuming active power. Due to the control strategy, the allowed voltage range is not violated.

**C. Autonomous Operation**

Consider an example without active power production from DGs and only the storage devices inject active and reactive power into the grid. The active and reactive power demand varies during the 1200 seconds period (maximum and minimum power demand values: \(t=0\)s, 27.5 kW, 8.6 kvar; \(t=200\)s, 11 kW, 3.4 kvar; \(t=600\)s, 45kW, 14.1 kvar; \(t=1000\)s, 11 kW, 3.4 kvar).

On the left side of fig. 7, the micro-grid disconnects from the upper-grid. The disconnection causes at the beginning an activation phenomenon for the voltage and frequency as shown in fig. 7a and fig. 7b. The frequency follows the reactive power demand and voltage is controlled by active power demand.

**V. CONCLUSIONS AND RECOMMENDATIONS**

In this paper the control strategy based on resistive droop proves to be preferred to control voltage and frequency during grid-connected operation mode as well as autonomous operation mode in LV grid.

Additionally, a control strategy is developed to improve the voltage during excess, average and shortage scenarios. A data communication system is developed to enhance a better active and reactive power distribution between battery
storage systems.
Research concerning the transition of grid-connected towards autonomous operation (transients) are still required.
A final aspect is to verify the simulation results by laboratory test.

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