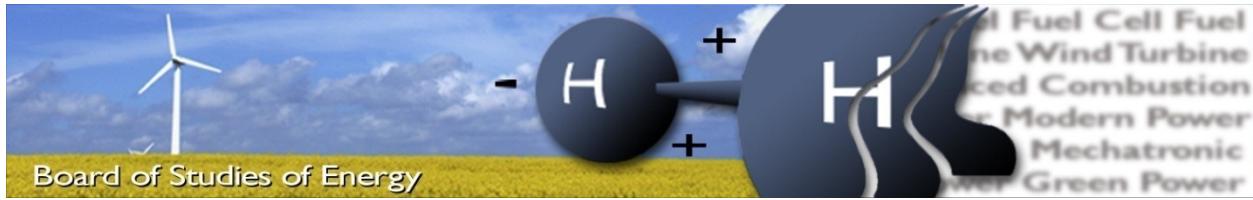


# **Control of Grid Connected PV Systems with Grid Support Functions**



*Conducted by group PED4 - 1043  
- Autumn/ Spring Semester, 2011-2012-*





**Title:** Control of Grid Connected PV Systems with Grid Support Functions  
**Semester:** 9-10th Semester 2011/2012  
**Semester theme:** Master Thesis  
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**ECTS:** 50 ECTS  
**Supervisor:** Bogdan Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu  
**Project group:** PED4/ 1043

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#### SYNOPSIS:

The increased number of grid connected photovoltaic (PV) inverters gave rise to problems concerning the stability and safety of the utility grid, as well as power quality issues. The aim of this project is to investigate and improve the standard regulation methods for grid connected PV inverters with focus on voltage support in LV distribution networks. Reactive power supply strategies proposed by the German grid code ( $\cos\phi(P)$  and  $Q(U)$ ) were investigated and simulated performing load flow analysis on a typical LV distribution system.

An improved  $Q(U)$  method was implemented which aims to minimize the reactive power consumption of the distribution system (DS) using the communication protocol IEC 61850. The Ethernet communication based on server/client architecture was used to exchange information.

Copies: [5]  
 Pages, total: [119]  
 Appendix: [27]  
 Supplements: [1CD]

**By signing this document, each member of the group confirms that all participated in the project work and thereby that all members are collectively liable for the content of the report.**



# Preface

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This report has been written by group PED4 1043 during 9<sup>th</sup> – 10<sup>th</sup> semester at the Department of Energy Technology, Aalborg University. The project has been carried out between the 15<sup>th</sup> of September 2011 – 31<sup>st</sup> May 2012.

The first 4 chapters have been written by both students from the group PED4 1043, while the Chapter 5 of the report was written only by the student Elena Anamaria Man. Due to unexpected circumstances, the student Vlad Alexandru Muresan could not continue the project work being involved in re-examinations for course modules. Therefore the project has been split in 2 different parts. The first project version is submitted by the student Elena Anamaria Man while the second project version is submitted by the student Vlad Alexandru Muresan with different Chapter 5 (laboratory work).

## ***Reading Instructions***

The main report can be read as an independent piece, from which the appendices derive including mathematical calculations, simulations and other details in order to make the main report more understandable. In this project, the chapters are arranged numerically, whereas appendixes are sorted alphabetically.

Frequently used constants and abbreviations are described in the report nomenclature list, which can be found after the table of contents. Sources are inserted using the IEEE method, with a [number], which refers to the bibliography in the back of the report. Additionally, a CD has been made, which features the report and other source files in digital format.

## ***Acknowledgement***

*First of all I would like to express my gratitude to Vlad Alexandru Muresan for his important contribution to this project and for his motivation during the past year.*

*I gratefully appreciate all the patience, guidance and support from our supervisors Remus Teodorescu, Tamas Kerekes, Dezso Sera and especially Bogdan-Ionuț Crăciun. I would like also to express my appreciation for PhD fellow Erhan Demirok and Ass.Prof. Henrik C. Pedersen for their cooperation and professional support.*

*Many thanks to my colleagues at AAU, but in particular to Krisztina Leban for her goodwill and support and to Daniela Boian for her friendly companion and constructive discussions at any time, no matter the place or the hour.*

*A kind thank you for Danfoss Solar for their financial support during my stay in Aalborg.*

*Finally, I would like to thank my family for their continuous moral support in the past 2 years.*



# Summary

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This project is structured in six chapters and studies different voltage regulation strategies for grid connected PV inverters with ancillary services.

In the first chapter, a brief description regarding the background of the solar energy is presented. Afterwards, the current status of PV technology and grid connected PV systems is given. The motivation of the project consists of the fact that the fast expansion of PV systems in the lower parts of the grid raised several concerns regarding grid reinforcement. To harmonize the behavior of all the distributed generators connected to the grid and also to improve the grid stability, measures have been considered consisting of equipping the PV inverters with grid support functions. One of the main functions of the smart inverters refers to their reactive power capability.

Furthermore, the GCs have been changed and they are more restrictive in order to overcome to problems which may appear in the grid. In Chapter 2, a short description of the problems that may appear in the network is given along with an overview of the regulations for LV grid connected PV systems presented as a parallel between the old and the new German GC, with focus on grid interface requirements, power quality issues and anti-islanding.

Because most of the PV installments are in the LV part, a European LV benchmark network was chosen to study the voltage rise problem. Chapter 3 also presents the load flow analysis using the Newton-Rapson method. Afterwards, the voltage regulation methods encouraged by the German GC ( $\cos\phi(P)$  and  $Q(U)$ ) have been studied, modeled and implemented on the chosen LV network. The simulation results of both strategies were presented, compared and discussed. The chapter concluded that the performance of the  $Q(U)$  is better compared to  $\cos\phi(P)$  in terms of reactive power absorption.

The aim of Chapter 4 is to improve the control strategy chosen in Chapter 3. A voltage regulation strategy was developed using optimal power flow calculations in order to improve the classical solution from the German GC in terms of reactive power consumption. The aim of this optimized algorithm is to use the communication concept for information exchange. The simulations results were presented and compared with the classical  $Q(U)$  method to emphasize the improvements brought by the coordinate control.

Chapter 5 describes the overview of the IEC 61850 communication concept. The development of the information model is explained along with the configuration of IEDs and the functions to build a server/client application. To access parameters or signals from/to the inverter, the dSPACE system was used and the C Library (CLIB) which is also provided by dSPACE. To implement a CLIB application, a source code was developed. Using CLIB, the user can access any parameter existing on the dSPACE processor board. Furthermore, a server/client application was developed to transmit the desired parameters to dSPACE. The information exchange between server and client is bi-directional; therefore data can be read from the

dSPACE processor by the client and transmitted to the server. To validate the experimental results, print shots of the console applications for CLIB, client and server have been presented and explained.

Chapter 6 presents the general conclusions of this project and the future work that can be done.

## Contributions

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An article was published during the period of the research. The focus of the article is on the results of the developed Q(U) algorithm compared with the ones of the best candidate from the German GC VDE-AR-N 4105 analyzed on the chosen European LV benchmark network.

- B.I. Craciun, E.A. Man, V.A. Muresan, D. Sera, T. Kerekes, and R. Teodorescu, *Improved Voltage Regulation Strategies by PV Inverters in LV Rural Networks*, accepted for publication, *The 3<sup>rd</sup> International Symposium on Power Electronics for Distributed Generation Systems, Aalborg June 2012, Denmark*



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# Nomenclature

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## List of abbreviations

API	Application Programming Interface
CDC	Common Data Classes
CLIB	C Library
CP	Connection Point
DA	Data Attribute
DER	Distributed Energy Resources
DER-Lab	Distributed Energy Resources Laboratories
DG	Distributed Generation
DO	Data Object
DS	Distribution System
DSO	Distribution System Operator
DR	Distributed Resources
EPIA	European Photovoltaic Industry Association
EPS	Electric Power System
GC	Grid Code
GOOSE	Generic Object Oriented Substation Events
GUI	Graphical User Interface
IEA	International Energy Agency
IED	Intelligent Electronic Device
IP	Internet Protocol
IPC2	Interface and Protection Card
LD	Logical Device
LN	Logical Node
LVRT	Low-Voltage Ride Through
MMS	Manufacturing Message Specification
MPPT	Maximum Power Point Tracking
PIS	Protocol Integration Stack
PLL	Phase Locked Loop
PV	Photovoltaic
SAS	Substation Automation System
SCL	System Configuration description Language
SCSM	Specific Communication Service Mapping
SNTP	Simple Network Time Protocol
SV	Sample Value
SMV	Sample Measurement Value

TCP	Transmission Control Protocol
THD	Total Harmonic Distortion
VU	Voltage Unbalance
VUF	Voltage Unbalance Factor

## List of symbols

$\zeta$	voltage variation
$\delta_i$	voltage angle at bus i
$\theta_{ij}$	voltage angle difference between bus i and j
$\Delta\delta_i$	corrections for voltage angle at bus i
$\Delta V_i$	corrections for voltage magnitude at bus i
$\Delta P_i$	active power mismatches at node i
$\Delta Q_i$	reactive power mismatches at node i
$B_{ii}$	self susceptance of bus i
$B_{ij}$	mutual susceptance between bus i and j
$G_{ii}$	self conductance of bus i
$G_{ij}$	mutual conductance between bus i and j
$P_i$	active power injected in node i
$P_i^{ref}$	active power reference at node i
$P_n$	rated active power of the PV inverters
$Q_i$	reactive power injected in node i
$Q_i^{ref}$	reactive power reference at node i
$Q_{max}$	maximum reactive power reference of the PV inverters
$S_i$	rated power of PV inverters
$V_i$	voltage magnitude at bus i
$Y_{ii}$	self-admittance
$Y_{ij}$	mutual admittance
$Y_{bus}$	admittance matrix
$Z_{bus}$	impedance matrix

# Chapter 1 Introduction

*This chapter presents a background of the solar energy followed by a short description of the current status of PV technology and grid connected PV systems. Afterwards, the motivation, objectives and limitations of the report are stated.*

## 1.1 Background of solar energy

The growth of world energy demand and the environmental concerns lead to an increase of the renewable energy production over the last decade. Energy sources such as solar, wind or hydro became more and more popular mainly because they produce no emissions and are inexhaustible. PV energy is the fastest growing renewable source with a history dating since it has been first used as power supply for space satellites. The increased efforts in the semiconductor material technology resulted in the appearance of commercial PV cells and consequently made the PVs an important alternative energy source [1].

One of the major advantage of PV technology is the lack of moving parts which offers the possibility to obtain a long operating time (>20 years) and low maintenance cost. The main drawbacks are the high manufacturing cost and low efficiency (15-20 %). As one of the most promising renewable and clean energy resources, PV power development has been boosted by the favorable governmental support [2].

According to European Photovoltaic Industry Association (EPIA), at the end of 2011 the total installed PV capacity in the world has reached over 67.4 GW, with an increase of 68.5 % compared to 2010. Europe still leads the market with over 50 GW of cumulative power installed with a 70 % increase in 2011. Italy became for the first time the top PV market in 2011 with 9 GW of newly connected capacity, with an impressive 290% increase from 2010. This increase was a consequence of advantageous tariffs if the systems were installed by the end of 2010 and connected until mid 2011. Germany was the second big player on the PV market in 2011 with 7.5 GW of new connected systems with a 44% increase from 2010 where more than 80% of the installed systems were located in the LV network [3].

In Figure 1-1, the total PV power installed in Europe at the end of 2010 is presented. The figure shows an unbalanced market, where Germany is leading with 24.7 GW of total installed capacity. Italy has increased its PV capacity at a total of 12.5 GW and holds the second place on the market. On the other side, Spain is third in 2011 after a low development of PV power. The rest of EU countries are still far behind, but progresses are expected in the future [3].

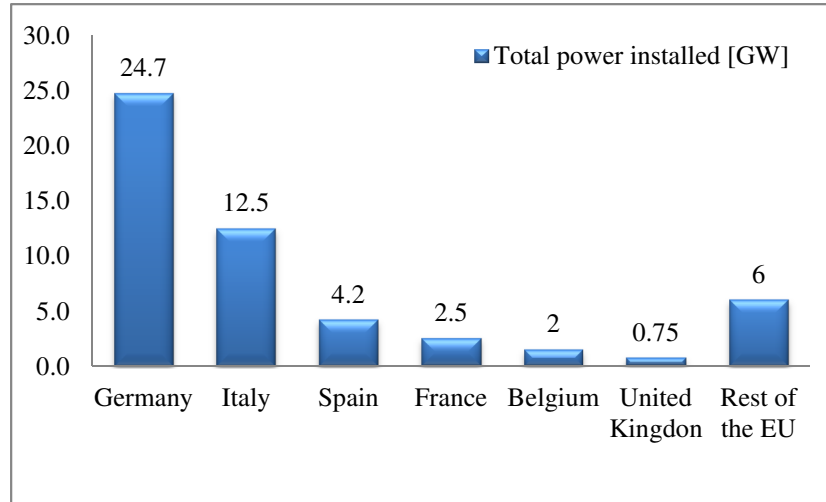


Figure 1-1 European total PV power installed at the end of 2010 [3]

The high penetration of the PV technology was induced by the continuous increase of energy price generated in traditional coal and gas power plants. PV power systems have been required to reduce costs in order to compete on the energy market, but on the same time to provide a good reliability. Usually the reliability of a PV system is associated with the inverter topology and the main components (switching devices, capacitors). The lifetime of a system regarding the PV panels has been approximated to be around 25 year, while in the inverter sector, future improvements are expected [4].

In Figure 1-2 the electricity generation costs for large PV systems are exposed.

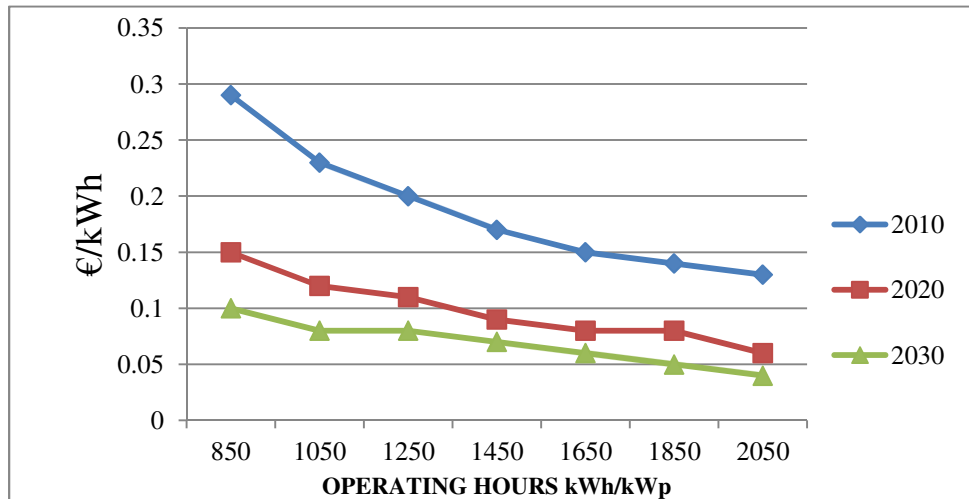


Figure 1-2 Levelised cost of electricity for large PV ground-mounted systems [5]

The energy generation costs in 2010 varied from €0.15/kWh in the north of Europe to €0.12/kWh in south of Europe and Asia. By 2020, the expected generation costs for large PV systems will vary between €0.07/kWh to €0.17/kWh. Also, the prices for the residential PV systems are expected to drop significantly in the next 20 years [5].

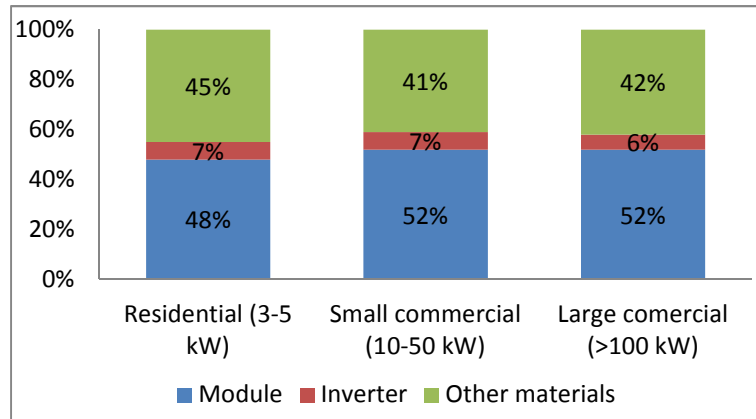


Figure 1-3 System percent share of each component for different power ratings [6]

In Figure 1-3, the typical percentage contribution to total cost for a variety of specific cost components (e.g. modules, inverters, installation labour, etc.) are shown. Typically, PV module costs are about 50% of total installed ones, while inverters represented approximately 6-7%. Other costs such as installation labour, materials, and regulatory compliance represent an important part from the total price [6].

The fast expansion of PV system into the lower parts of the grid raised several concerns for grid reinforcement. In consequence, grid operators had to impose strict operational rules in order to keep the LV grid under control and to harmonize the behaviour of all distributed generators connected to it in terms of reliability, efficiency and costs [7, 8].

The first cost-effective measure, which brought a major improvement to the grid stability, was for the grid operators to suggest PV systems manufacturers to equip their products with grid support functions [9]. It is expected that until the end of 2015, the shipments of smart inverters in terms of MW will have a market share of 60 %, overtaking the standard inverter (Figure 1-4). Still, most of them will have only reactive power capabilities [10].

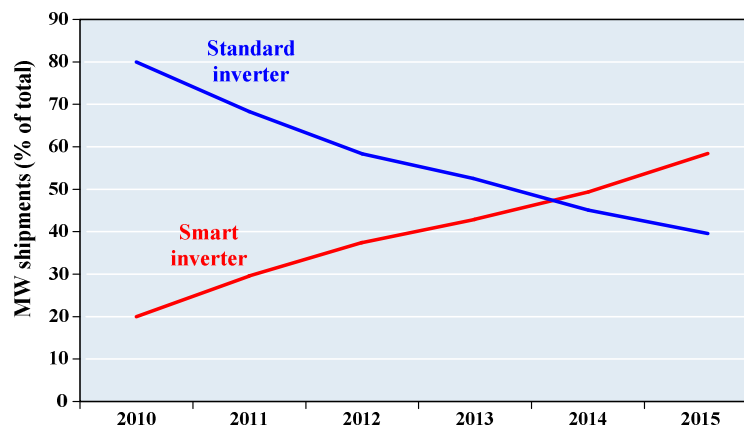


Figure 1-4 Total world market share for standard and smart PV inverters [10]

### 1.1.1 Grid connected PV systems

Grid connected PV systems represent around 92 % of the total PV installed power. Thyristor-based central inverters connected to the utility grid emerged on the market in the mid-1980s. Later, in the 1990s, SMA produced the first transistor-based inverters. Figure 1-5 briefly presents the evolution of grid connected PV systems together with off-grid systems up to the year 2010 [11].

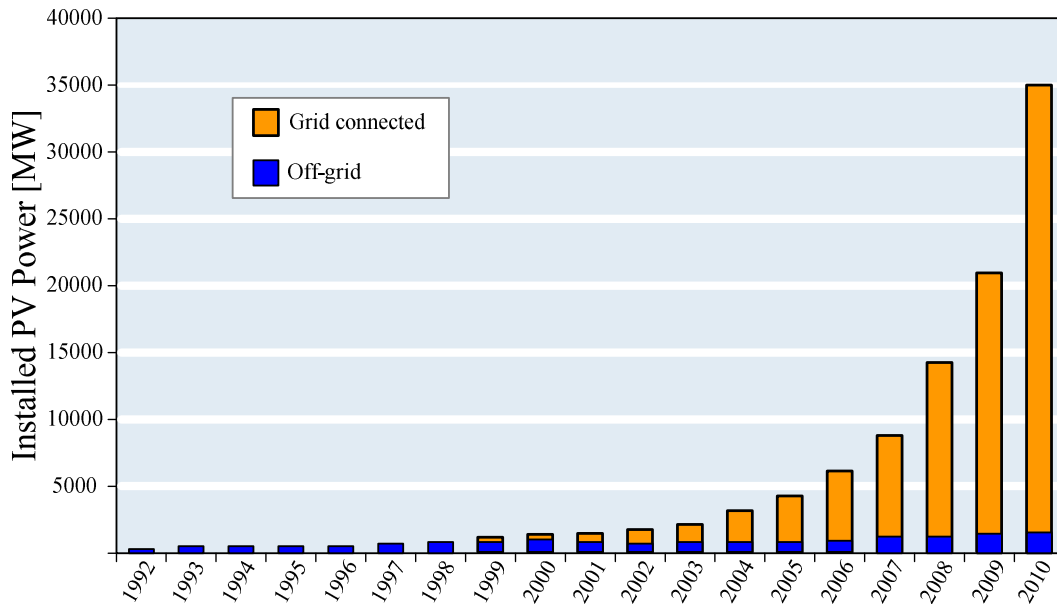


Figure 1-5 Cumulative installed grid connected and off-grid PV power in the reporting countries between 1992-2009 [11]

It can be observed that the off-grid development has slightly changed since 1999, whereas the installed power of grid connected systems increased significantly since 2006.

According to International Energy Agency (IEA), the PV systems can be divided into two main categories: off-grid and grid connected, depending on their connection with the utility grid. Further, a short description of the configurations is presented [11].

The standalone systems are used in places where there is no connection to the utility grid. They provide electricity to small rural areas and are usually used for low power loads (refrigeration, lightning). Their power ratings are around 1 kW and they offer a good alternative to meet the energy demands of off-grid communities [11].

Grid connected distributed systems gained popularity in the last years, as they can be used as power generators for grid connected customers or directly for the grid. Different sizes are possible since they can be mounted on public or commercial buildings [11].

Grid connected centralized systems are specific for power plants. They produce and transform the power directly to the utility grid. The configuration is usually ground mounted and the power rating is above kW order [11].



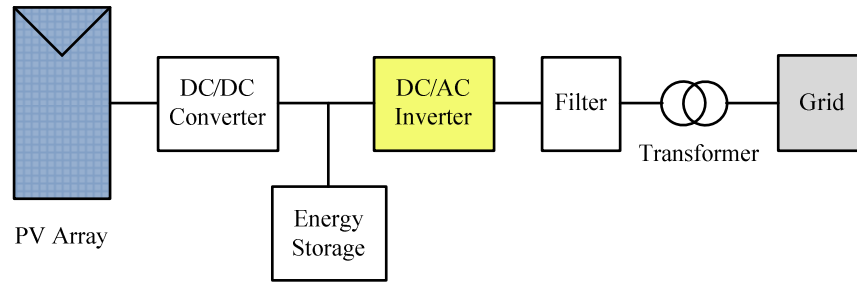


Figure 1-6 Components of a grid connected PV systems [12]

The typical configuration of a PV system can be observed in Figure 1-6. Depending on the number of the modules, the PV array converts the solar irradiation into specific DC current and voltage. A DC/DC boost converter is used when the voltage required by the inverter is too low. Energy storage devices can be included in order to store the energy produced in case of grid support connection. The power conversion is realized by a three-phase inverter which delivers the energy to the grid. High frequency harmonics that appear due to power semiconductors switching are reduced by the filter. The power transformer is used only for galvanic isolation between the PV system and the utility grid [12].

### 1.1.2 Topologies of grid connected PV systems

In PV plants applications, various technological concepts are used for connecting the PV array to the utility grid. Further, the existing configurations will be explained [13-17].

#### Central Inverters

For this architecture, presented in Figure 1-7a, the PV arrays are connected in parallel to one central inverter. The configuration is used for three-phase power plants, with power ranges between 10-1000 kW. The main advantage of central inverters is the high efficiency (low losses in the power conversion stage) and low cost due to usage of only one inverter. The drawbacks of this topology are the long DC cables required to connect the PV modules to the inverter and the losses caused by string diodes, mismatches between PV modules, and centralized maximum power point tracking (MPPT) [13-17].

#### String Inverters

The configuration presented in Figure 1-7b entered on the PV market in 1995 with the purpose of improving the drawbacks of central inverters. Compared to central inverters, in this topology the PV strings are connected to separate inverters. If the voltage level before the inverter is too low, a DC-DC converter can be used to boost it. For this topology, one string is connected to each inverter; therefore the need for string diodes is eliminated leading to total loss reduction of the system. The configuration allows individual MPPT for each string; hence the

reliability of the system is improved due to the fact that the system is no longer dependent on only one inverter compared to the central inverter topology [13-17].

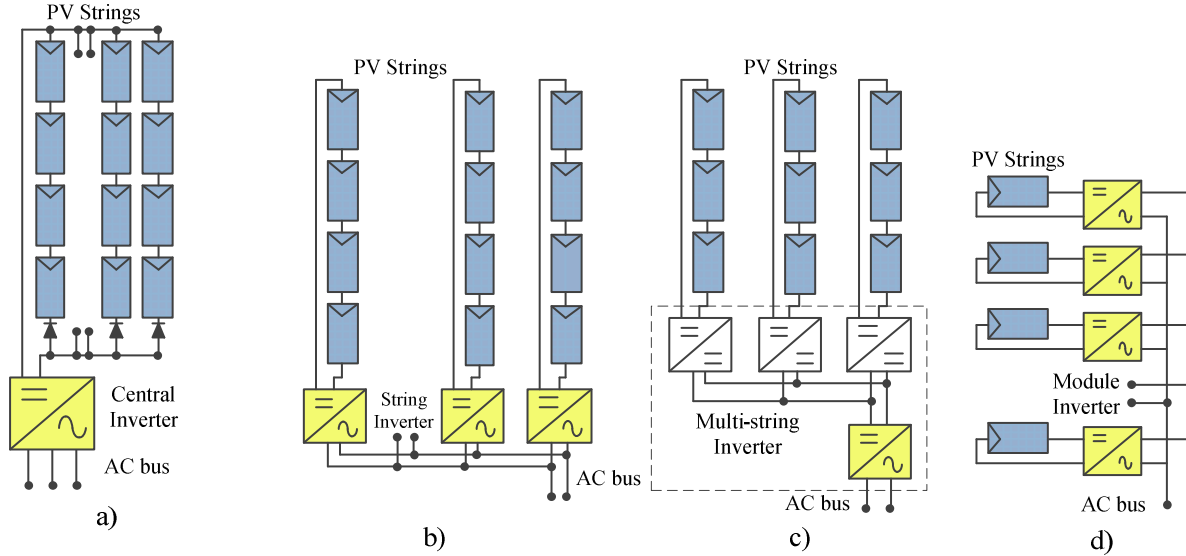


Figure 1-7 PV grid connected systems configurations a).Central Inverters; b). String Inverters; c).Multi-String Inverters; d). Module inverters [13]

### Multi-String Inverters

The multi-string inverter configuration presented in Figure 1-7c became available on the PV market in 2002 being a mixture of the string and module inverters. The power ranges of this configuration are maximum 5 kW and the strings use an individual DC-DC converter before the connection to a common inverter. The topology allows the connection of inverters with different power ratings and PV modules with different current-voltage (I-V) characteristics. MPPT is implemented for each string, thus an improved power efficiency can be obtained [13-17].

### Module Inverters

Module Inverters shown in Figure 1-7d consists of single solar panels connected to the grid through an inverter. A better efficiency is obtained compared to string inverters as MPPT is implemented for every each panel. Still, voltage amplification might be needed with the drawback of reducing the overall efficiency of the topology (losses in DC/DC converter). The price per watt achieved is still high compared to the previous configurations [13-17].

## 1.2 Motivation

Over the last decade various reasons have determined a continuous increase of the PV power systems. Some of them are the price drop of the PV modules manufacturing, better social acceptance of PV parks or government support for regenerative energy. At the same time, the grid connected systems development requires better understanding, evaluation and performance

of the PV inverters in case of normal and abnormal conditions in the grid, as well as the quality of the energy generated by the PV systems.

The increased number of grid connected PV inverters gave rise to problems concerning the stability and safety of the utility grid, as well as power quality issues. The main problems are:

- **Voltage rise problem**

The integration of large amounts of PV systems in the LV networks increases the generation of active power leading to voltage rise along the feeders. At the moment the voltage rise does not exceed the 2% limit imposed by the old GC [18], but it is expected in the future; therefore, the voltage limit has been increased in the new GC to 3% [19].

- **50.2 Hz problem**

According to VDE 0126-1-1, when the grid frequency reaches and exceeds 50.2 Hz an immediate shutdown is required from the grid connected generators to avoid risks which can appear in the operation of the network. It is possible that the shutdown occurs while high power infeed, therefore the resulting sudden deviation can cause the primary control to malfunction. In other words, if the power deviation is higher than the predefined power of the primary control, the system will not be able to stabilize the grid frequency. The solution to prevent system-critical states proposed by the new GC VDE-AN-R 4105 is a frequency-dependent active power control.

- **Increased harmonics**

Researches carried out show that the high penetration of PV systems lead also to an increase in harmonic content at the connection point (CP). Each PV system connected to the grid injects harmonics, therefore the more PV systems are connected the more harmonic content will increase. Furthermore, if one or more non-linear loads are present, the total harmonic distortion (THD) can increase above the allowable limit [19]. This increase can be noticed in both current and voltage [20].

- **Increased voltage unbalance**

Studies have shown that features of the installed PV systems such as their location and power generation capacity can lead to an increase in the voltage unbalance (VU). This affects most the power quality in the LV residential networks, due to the random location of the PV installations and their single-phase grid connection. In other words, the voltage profile of the three phases is different because the PV systems are installed randomly along the feeders and with various ratings. When the difference in amplitude between the phases is high, the VU increases [21]. According to the study described in [22] the VU will have the most significant impact at the end of the feeder where it could exceed the allowed limit [19]. Furthermore, a PV installation along a feeder will create a voltage unbalance that will be modified on all the feeders of the network.

- **Anti-islanding**

Islanding occurs when the PV generator is disconnected from the grid, but continues to power locally. The islanding problem is dominant in LV networks, therefore it is recommended for the generation units to disconnect within a narrow frequency band such as 49-51 Hz [23].

Taking into consideration the previously presented problems which are a high concern due to the increased amount of PV installations in the present and expected in the future, new and more restrictive grid codes have been issued. The integration of large amounts of PV systems to the LV networks increases the generation of active power leading to voltage rise along the feeders that can exceed the imposed limits.

In the past there were no requirements that the PV inverters contribute to the grid stability. German standard VDE 0126.1.1 from 2005 specifies that inverters connected to LV network must disconnect in the following cases [18]:

- When voltage changes exceed the limits  $80\%V_n < V_{pcc} < 115\%V_n$ , disconnection is necessary within 200 ms. In case the upper limit is exceeded, according to DIN EN 50160:2000-03, inverter must shut down.
- Frequency limits are  $47.5\text{Hz} < f < 50.2\text{Hz}$ . If these values are exceeded, the inverter must disconnect in 200 ms.
- If the DC current exceeds the limit of 1A due to abnormal operation, inverter must shut down in 200 ms

Nowadays, the concept of smart inverter raised new challenges in terms of converter control. At the moment, the PV inverters are required to contribute to the grid stability and provide support functions during normal and abnormal operation of utility grid such as [9]:

- *Grid Voltage Support*: - it involves trade-off between active and reactive power production in order to maintain the voltage between specific limits
- *Grid Frequency Support*: - implies active power supply to the grid to reduce sudden unbalance and keep frequency between specific limits
- *Grid Angular (Transient) Stability*: - oscillations reduction when sudden events occur by means of real power transfer
- *Load Leveling/Peak Shaving*: - loads management during peak periods
- *Power Quality Improvement*: - mitigation of problems (harmonics, power factor, flicker, etc.) that affect the magnitude and shape of voltage/current
- *Power Reliability*: - ratio of interruptions in power delivery versus a period of time
- *Ride Through Support*: - ability of the electric devices to stay connected and provide energy during system disturbances

The specific behaviour of the inverters under grid faults is very important, since it is desired that the system avoids as much as possible disconnection. The services delivered by the inverters are based on grid monitoring and have to follow the demands from the Distribution System Operator (DSO). Is it very important also that the quality and services delivered to meet

the new grid codes requirements [19] for interconnection of PV systems, where certain limits are stated (in terms of voltage rise, harmonics, unbalance, etc).

### 1.3 Problem Formulation

More than 80% of the PV installations in Germany were on LV network. The main problem which arises due to massive PV penetration is the voltage variation caused by the injection of active power and reverse power flow (see Figure 1-8). Usually, over voltages affect the network in case of high irradiation and light load. In consequence, the inverters can trip, the operation of the loads can be affected and the lines and/or transformers can become overloaded.

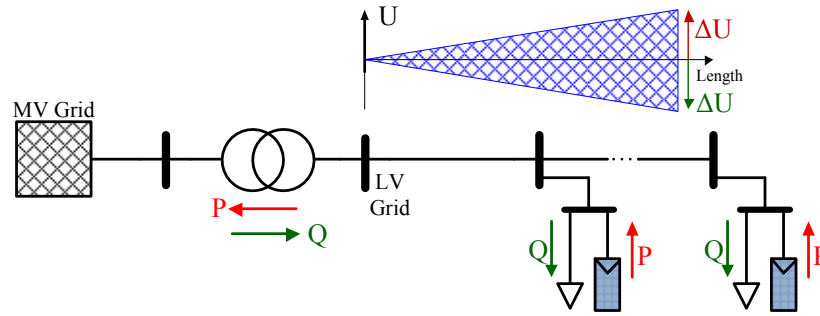


Figure 1-8 Reverse power flow and voltage variations in LV networks with PVs [1]

To achieve further PV capacity of the network and to overcome the voltage variation problem with minimum reinforcement of the grid, the system operators recently adopted new GCs [19] which require PV inverters to be more flexible and to participate with ancillary functions to the grid stability. For LV networks, the main requirement refers to voltage regulation techniques and different methods are proposed with the focus on fixed reference or static droop characteristics. The fixed reference values for reactive power provision or the droop curve will be specified by the network operators.

Due to high amount of space for the PV arrays to be connected in the rural area, the chance of violating voltage limitations is higher than in suburban networks. Therefore, the project will analyze a LV rural network from Europe where high PV penetration can be achieved and consequently the risk for voltage variations outside the prescribed limits is higher.

### 1.4 Objectives

The main objectives of this project are the following:

- Classical voltage regulation strategies:
  - ❖ Model and implement the voltage regulation strategies encouraged by German GC
  - ❖ Study the German GCs and the requirements for LV networks (VDE 0126-1-1 and VDE-AR-N 4105)
  - ❖ Study and model the voltage regulation methods proposed by the German GC

- ❖ Choose and model a LV benchmark network to analyze the voltage variations and test the voltage regulation methods to maintain the voltage variations between the imposed limits
- ❖ Asses the performance of the control strategies and choose the best candidate
- Improved voltage regulation strategies using coordinate control:
  - ❖ Design and simulate an optimized voltage regulation method to improve the best candidate from the German GC with focus on reducing the reactive power consumption and increase PV capacity in the LV network. The optimized algorithm should use the communication approach.
  - ❖ Implement the optimized algorithm on a laboratory setup and use coordinated control of the inverters with information exchange using protocol IEC 61850.
  - ❖ Asses the performance of the optimized control algorithm and demonstrate the improvements brought using the communication concept.

## **1.5 Limitations**

This project will consider the following limitations:

- The simulations will consider the inverter as an average model, therefore the switching is neglected.
- Overall response of the system will be considered, with no focus on power quality or anti-islanding.
- No meshed networks for analysis are considered (only radial).
- The study carried assumes that all PVs are grid connected units and no energy storage is considered.
- For simulating the worst case scenario, in terms of voltage variation, no load consumption is assumed.
- Laboratory tests are implemented only on one inverter.
- Test are implemented on a single-phase inverter due to CLIB license limitation

# Chapter 2 Grid codes and regulations

*The chapter describes the German GC regulations for the connection of PV systems to the LV grid. The main faults and disturbances which appear in the utility grid are briefly presented.*

## 2.1 Introduction

In the last years, an important amount of distributed generation (DG) systems were connected to the grid with the main purpose of increasing renewable power production. The utility grid is not ideal; therefore the grid voltage and frequency may exceed the prescribed limits, which is undesirable and unacceptable [4].

The electrical power systems require ancillary services such as voltage and frequency regulation, power quality improvement and energy balancing to operate efficient and reliable. In a power system, the DSO is responsible to maintain the correct operations and can purchase ancillary services directly from the PV generators. Until recently, the inverter requirements in case of abnormal grid conditions and faults were to disconnect and wait for fault clearance. The massive development in the PV sector faced new challenges for the inverter which is now required to contribute to grid stability by providing support functions [24-26].

In Figure 2-1, the main challenges which inverters face are presented.

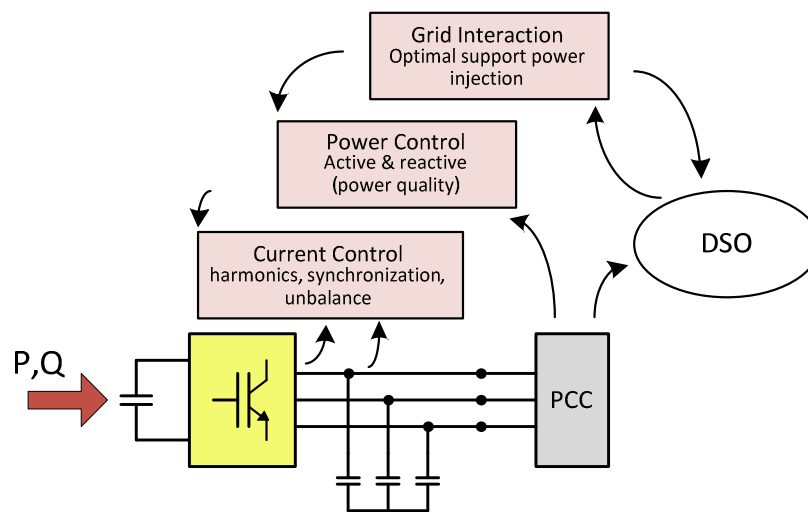


Figure 2-1 PV Inverter control functions [27]

As shown in Figure 2-1, the control functions can be divided in three separate levels: current control, power control and grid interaction. The first part deals with the current control which can be considered to be the basic one as it decides the performance of the entire system. The second part is in charge with the generation of current control references for the first control level having a time response 10 times slower compared to the current control part [27]. The third

level is in charge with the requirements specified by the DSO and also provides the reference values for active and reactive power.

Increasing PV penetration into the grid leads to elaboration of specific technical requirements for grid integration. The wide variety of regulations and norms are a major barrier for the PV industry. Interconnection requirements in certain European countries are available with the main focus on reducing the cost of PV systems by achieving further growth in the future market [28].

In order to diminish the diversity of requirements and standards, the ongoing activities of Distributed Energy Resources Laboratories (DER-Lab) are focused on developing and implementing a coordinated European standard [28].

There are two main steps for developing jointly grid codes: structural and technical harmonization. The aim of the structural process is to set a common grid code template while the technical one is more of a long-term implementation. The process aims to expand PV systems which would lead to an increasing propagation of renewable energies [28, 29].

Further in the chapter, the requirements for the grid connected PV systems will be presented in form of a parallel between the previous (VDE 0126-1-1) and the new (VDE-AR-N 4105) German GC for LV networks [18, 19]. The most relevant requirements concern the grid interface, power quality and anti-islanding [14].

## **2.2 Grid interface requirements**

### ***a) Voltage variations***

- **Undervoltage**

This particular fault is also known as voltage ‘dip’ or ‘sag’. It is characterized by a reduction in voltage amplitude to less than 90 % from nominal value with a duration time from 10 ms to several seconds, depending on the location of the fault which occurs in the network. The common cause for these types of failures are short circuits, faults to ground, transformer energizing inrush currents and connection of large induction motors. The consequences of voltage sags are the disconnection of power electronic devices from the grid with fault clearance in the range of 0.1- 0.2 s [14, 30].

- **Overvoltage**

These faults are less frequent than sags and appear usually due to lightning on transmission cables, with voltage magnitude of several kV introduced in overhead LV networks. Overvoltages can be caused also by the switching of LV appliances (pumps, fans, electric boilers etc), large loads which are switched off, capacitor bank energizing or voltage increase on the unfaulted phases during a single line to ground fault. In this case, the voltage magnitude increase is between 1.1 and 1.8 p.u. and accepted time duration is up to 1 minute [31].

Under normal operating conditions, the voltage variations should not exceed the standard limits from Table 2-1.



Table 2-1 Supply voltage variation limits from German GCs [18, 19]

VDE 0126-1-1		VDE-AR-N 4105	
Voltage range [Hz]	Disconnection time [s]	Voltage range [Hz]	Disconnection time [s]
V < 85 V ≥ 110	0.20	V < 80 V ≥ 110	0.10

In Table 2-1, the disconnection time for voltage variations is also available. The voltage deviations are detected by voltage measurements made at the CP, which is the default according to the standards [32].

- **Low-Voltage Ride Through (LVRT)**

According to VDE-AR-N 4105, there are no requirements for LVRT.

**b) Frequency variations**

Frequency variations are a common problem that affects the power systems being caused by the unbalanced power ratio between energy production and consumption. The frequency variation is defined by the following relation [33]:

$$\Delta f = f - f_r \quad (2.1)$$

Where:  $f$ - real frequency;

$f_r$ - rated frequency;

The nominal frequency of the supply voltage in Europe is 50 Hz. The value of the fundamental frequency measured over 10 s should be in range of:

Table 2-2 Frequency variation limits from German GCs [18, 19]

VDE 0126-1-1		VDE-AR-N 4105	
Frequency range [Hz]	Disconnection time [s]	Frequency range [Hz]	Disconnection time [s]
47.5 < f < 50.2	0.20	47.5 < f < 51.5	0.10

In case of abnormal grid conditions, PV inverters need to disconnect from the grid to ensure safety of humans and equipment. In Table 2-2, disconnection time for frequency variations is also available.

### c) Frequency requirements

An important issue in a power system is balancing power production and consumption because changes in power supply or demand can lead to temporary unbalance; hence the operating conditions of the power plants and consumer loads can be affected. To avoid unbalanced conditions, power plants must be capable to adjust power production by means of frequency regulation [34]. The requirements regarding active power control aim to ensure a stable frequency in the power system [35].

The frequency requirements for active power reduction in LV networks were added for the first time in the VDE-AR-N 4105 (Figure 2-2). According to this standard, the generating plants with the capacity over 100 kW have to reduce their real power in steps of at most 10% of the maximum active power  $P_{\max}$ . Systems with power lower than 30 kW are allowed to participate in frequency regulation with a rate limit specified by the DSO. This power reduction must be possible in any operating condition and from any operating point to a target value imposed by the DSOs. The plant have to accept any set point in active power reduction. In the present, the set points are: 100% / 60% / 30% / 0% if technical feasible, otherwise shutdown of the generating plant must be performed.

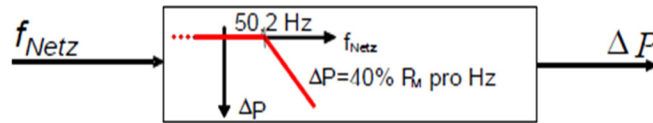


Figure 2-2 Active power reduction in case of over frequency [19]

The gradient for active power reduction can be calculated using the following formula:

$$\Delta P = 20 P_M \frac{50.2 \text{ Hz} - f_{\text{Netz}}}{50 \text{ Hz}} \quad \text{when } 50.2 \text{ Hz} < f_{\text{Netz}} < 51.5 \text{ Hz} \quad (2.2)$$

Where:

$\Delta P$  - active power reduction gradient

$P_M$  - power generated after exceeding the 50.2 Hz limit

$f_{\text{Netz}}$  - network frequency

Generating units have to reduce with a gradient of 40%/ Hz their power output when a certain frequency limit is surpassed (50.2 Hz for Germany). The output power is allowed to increase again when the frequency is below a specific limit (50.05 Hz for Germany). Outside the frequency limits imposed by the GC, the plant has to disconnect from the grid [35].

Controllable power plants have to reduce the power output to the target value within a maximum period of time of 1 minute. If the set point is not reached in the mentioned period of time, the generating plant must be shutdown.

**d) Reconnection after trip**

The inverter allows reconnection after fault as soon as the conditions from Table 2-3 are satisfied. The purpose of the allowed time delay is to ride-through short-term disturbances.

Table 2-3 Conditions for reconnection after trip [19]

VDE 0126-1-1	VDE-AR-N 4105
90 < V < 115 [%] AND 47.5 < f < 50.2 [Hz] AND Min. Delay of 30 seconds	85 < V < 110 [%] AND 47.5 < f < 50.05 [Hz] AND Min. Delay of 5 seconds

**e) Voltage rise**

• **Admissible voltage changes**

During normal operation, the magnitude of the voltage change caused by the generating plants must not exceed, in any CP, a value of 3% compared with the voltage when the generating plants were not connected. The preferred method to calculate the voltage changes is using complex load-flow calculations [19].

$$\Delta u_a \leq 3\% \quad (2.3)$$

• **Sudden voltage changes**

The voltage change at CPs when the generators are connected or disconnected is limited at 3% per generating unit and should not occur more frequently than once every 10 minutes. In this case the disturbances caused by the switching operation remain between admissible limits.

The maximum allowed voltage rise is calculated in terms of short circuit power at CP [19] :

$$\Delta u_{\max} = \frac{I_a}{I_{rE}} \cdot \frac{S_{E\max}}{S_{kV}} \quad (2.4)$$

Where:

$S_{kV}$  - network short circuit power at CP

$S_{E\max}$  - maximum generating power at CP

$I_a$  - starting current

$I_{rE}$  - rated current

### f) Reactive Power Control and Real Power Curtailment

Under normal operation, when required by the DSO, the generating plants have to supply static grid support functions, meaning voltage stability by means of reactive power control. The working point for reactive power exchange should be determined in accordance with the need of the grid.

The reactive power provision must be available in any operating point. The operation of the generating plant must be possible with a reactive power output corresponding to the power factor (PF) values and depending also on the rated power of the generating unit.

- if  $\sum S_{E_{\max}} < 3.68kVA$  - the generating plant should operate in:  $\cos\varphi=0.95$  (under excited) to  $\cos\varphi=0.95$  (over excited), according with EN 50438
- if  $3.68kVA < \sum S_{E_{\max}} < 13.8kVA$  - the generating plant shall accept any set point from the DSO:  $\cos\varphi=0.95$  (under excited) to  $\cos\varphi=0.95$  (over excited)
- if  $\sum S_{E_{\max}} > 13.8kVA$  - the generating plant have to accept any set point from the DSO:  $\cos\varphi=0.90$  (under excited) to  $\cos\varphi=0.90$  (over excited)

When the active power output is fluctuating, the reactive power has to be adjusted according to the specified power factor; hence the name of the method:  $\cos\varphi(P)$ . The type of the regulation method and the nominal values of the reactive power adjustment are dependent on the network conditions and can therefore be determined individually by the DSO. Each generating unit has to automatically adjust their set point according to the characteristic curve received from the DSO within 10 seconds (Figure 2-3).

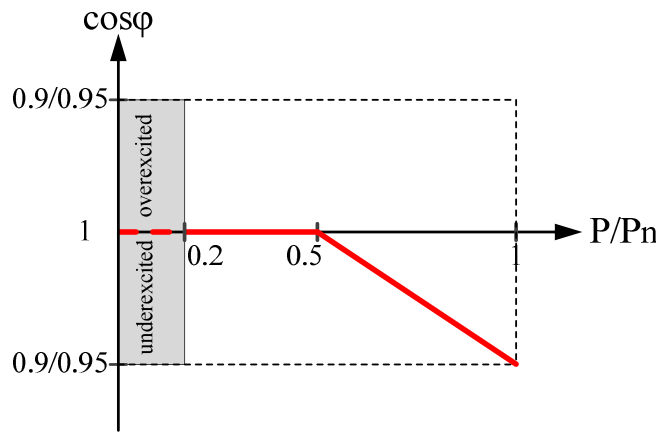


Figure 2-3  $\cos\varphi(P)$  droop characteristic for LV networks [19]

In case the generators can supply a constant active power output, the fixed PF control method is more suitable. The generating units directly connected to the power grid have a transition time to reach the reactive power set point of 10 minutes.

The future requirements, in terms of voltage stability, are to use the voltage-dependent Q(U) method, which calculates the reactive power reference according to the droop characteristic Q-U set by the DSO.

## 2.3 Power quality

Power quality is an important aspect in grid connected PV systems, as the utility grid can be affected by reliability problems. In Figure 2-4, an overview of the power quality aspects can be observed.

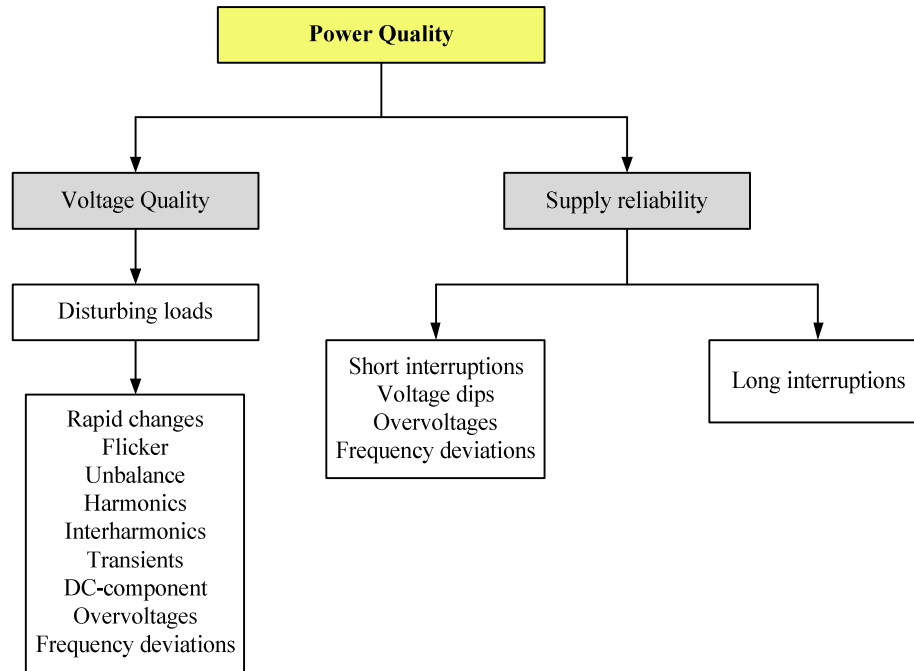


Figure 2-4 Power quality aspects classification, depending on the disturbances that can appear in the grid [30]

Voltage quality is regulated in Europe according to EN 50160 [36]. The following requirements are general:

- Voltage unbalance for three-phase inverters: max. 3%
- Voltage amplitude variations: max.  $\pm 10\%$
- Frequency variations: max.  $\pm 1\%$
- Voltage dips: duration  $< 1\text{s}$ , deep  $< 60\%$

### a) *Harmonic requirements*

Harmonics are sinusoidal components of voltage or current signals with the frequency equal to an integer multiple of the fundamental frequency. The main source of harmonics currents in DS are non-linear loads.

Harmonic currents are transferred into harmonic voltages through the grid impedance. The harmonics present in the grid appear most likely as a consequence of high harmonics in the customer load, saturation of transformers caused by higher voltage during light load demand conditions and amplified by resonance in the utility system. Excessive harmonic current leads to

voltage stress which reduces the reliability of equipment due to temperature increase [37]. The current harmonic requirements present in VDE-AR-N 4105 are outlined in Table 2-4.

Table 2-4 Allowable harmonic limits based on network short circuit power at CP [19]

<b>Harmonic number</b>	<b>Allowable, Ssc based harmonic current <math>i_{v,\mu \text{ zul}}</math> in A/MVA</b>
3	3
5	1,5
7	1
9	0,7
11	0,5
13	0,4
17	0,3
19	0,25
23	0,2
25	0,15
$25 < v < 40$	$0,15 \times 25/v$
even	$1,5/v$
$\mu < 40$	$1,5/v$
$\mu, v > 40$	$4,5/v$

**b) Voltage Unbalance**

Voltage unbalance occurs when the three-phase voltages differ in amplitude or they are displaced from their normal 120° phase relationship or both. The voltage unbalance of a DS is defined by the Voltage Unbalance Factor (VUF), which can be expressed as the ratio between the negative ( $V_-$ ) and the positive ( $V_+$ ) sequence voltage component or between the negative ( $I_-$ ) and the positive ( $I_+$ ) sequence currents.

$$VUF = \frac{V_-}{V_+} = \frac{I_-}{I_+} \quad (2.5)$$

The limit for the %VUF allowed in European networks according to EN 50160 is 3% [38].

Voltage unbalance is caused by:

- Impedance asymmetry of the LV network
- Single-phase connection of the generators
- Uneven distribution of loads across each phase of the LV network

However, according to [39], LV networks are affected predominantly by the voltage rise problem than voltage unbalance. Furthermore, control of generation and controllable load could bring benefits in terms of equalizing the load distribution and generation across the three-phases.

According to VDE-AR-N 4105, the maximum allowed unbalance for three phases connection is 4.6 kVA and 10 kVA for single-phase connection. If the rated power of the systems is bigger than 30 kVA, only a three-phase connection is allowed. Table 2-5 presents some examples of unbalance in systems.

Table 2-5 Example of unbalance for different systems

L1	L2	L3	Unsymmetric	Allowed?
4,6 kVA	0	0	4,6 kVA	Yes
4,6 kVA	2,5 kVA	0	4,6 kVA	Yes
10 kVA	6 kVA	8 kVA	4 kVA	Yes
10 kVA	5 kVA	3 kVA	7 kVA	No
10 kVA	7 kVA	11 kVA	4 kVA	No
10 kVA	10 kVA	11 kVA	1 kVA	No
50 kVA (3-phase ac)			0	Yes

*c) DC current injection*

DC current injection introduced by the PV inverter generates a DC offset in voltage waveform which can cause significant malfunctions to the distribution transformers. Saturation of transformers results in harmonic current injection into the power system. In addition, DC current injection can cause increased heating of magnetic components, audible noise and reactive power demand [17]. Standards limit the maximum allowable amount of injected DC current into the grid and according to [40], Germany follows VDE 0126-1-1 standard [18] which is the most restrictive in terms of DC current injection. The limit set by the previously mentioned GC is presented in Table 2-6.

Table 2-6 Limit for injected DC current [18, 19]

VDE 0126-1-1	VDE AR-N 4015
Idc < 1A Max Trip Time 0.2 s	No specifications

*d) Flicker*

Flicker phenomena are produced by the system loads which are experiencing rapid changes in power demand and they can cause voltage variations in the electrical system [32]. Usually, the amplitude of voltage fluctuation does not exceed 10 % from the nominal value.

Although the flicker is harmful for electrical systems, the majority are designed to be insensitive to voltage fluctuations within some limits (maximum 3%). According to VDE-AR-N 4105, the generating unit should not create objectionable flicker for other customers. The standard for all grid connected system in terms of flicker regulations is IEC 61000-3-3 [41].

## **2.4 Anti-islanding requirements**

Islanding condition occur when a part of the grid is disconnected and PV inverter continues to operate with local load. For safety reasons, islanding is a major concern, especially for personnel who attempt to work on lines which they believe to be disconnected. If the reconnection is established, the voltage at the point where island occurred is not synchronized with the grid voltage causing disturbances in the system. In order to avoid these consequences, anti-islanding measures were issued in standards [42].

Anti-islanding methods are divided into [15]:

1. Passive methods:
  - Based on grid parameter monitoring
  - Do not affect the overall system, unless limits are strict and the inverter trips without being island mode:
    - Frequency limitations (magnitude change, rate of change, phase shift)
    - Voltage limitations
    - Power (change of active/reactive power, power factor)
    - Harmonic content changes
2. Active methods:
  - Disturbances are injected into the supply to detect from their behavior if the grid is still present:
    - Impedance measurement
    - Voltage variation
    - Frequency variation
    - Output power variation

Requirements for grid connected PV inverters involve using any passive or active method to detect islanding condition. If significant parameter changes are detected which could lead to transition from normal operation to islanding, the inverter will be shut down and shall not reconnect before voltage and frequency have been maintained within specified limits for at least 5 minutes. Afterwards, the inverter will automatically reconnect to the utility grid.

According to IEEE 1547, when unintentional islanding occurs, the DR interconnection system must detect the island and stop energizing the area Electric Power System (EPS) within 2s [32].

According to VDE-AR-N 4105, the method proposed for anti-islanding is the “Impedance measurement” method. The required disconnection time for the inverter is 5 seconds.



# Chapter 3 Voltage regulation strategies

*The chapter describes the voltage regulation methods proposed by the German GC and the LV network chosen for their study. Further on,  $\cos\phi(P)$  and  $Q(U)$  strategies are modeled and simulated. Their results are discussed and compared in order to find the best candidate of voltage regulation strategy for the LV network.*

## 3.1 Voltage regulation methods proposed by German GC VDE-AR-N 4105

The voltage and frequency levels in the utility system represent a fundamental criterion to determine the quality of the power delivered to customers. The voltage has to be controlled to remain within the prescribed limits; therefore devices such as on-load tap transformers, shunt capacitors and compensators are responsible with the voltage regulation process [24].

The massive integration of DG systems into distribution networks raises stability problems. It is expected that DGs will take part in the regulation process, as it has been revealed that operating with active and reactive power simultaneously result in benefit for the utilities as well as for customers. The purpose of controlling the reactive power consumption in the network is to support the voltage level in the grid during normal operation [43].

The voltage regulation methods proposed by the new German GC are:

- Fixed power factor:  $\cos\phi$  method
- Power factor characteristic:  $\cos\phi(P)$  method
- Reactive power / voltage characteristic:  $Q(U)$  method

Both  $\cos\phi(P)$  and  $Q(U)$  strategies are based on droop characteristic. The fixed  $\cos\phi$  method is suitable for systems where the active output generation is kept constant, otherwise, if the active output is fluctuating, it is recommended to use one of the droop-based regulation strategies. Furthermore, GCs encourage the use of load-flow calculations when determining the voltage change values.

This project will further focus only on the droop-based regulations strategies because the active generating output of the PV generators is fluctuating depending on the level of irradiation. In all the cases, the voltage changes will be determined using load-flow analysis.

## 3.2 LV network analysis

The increased active power generation due to high PV penetration leads to voltage rise in the network and can exceed the limit imposed by the GCs or can cause unexpected tripping of other grid connected PV systems. Therefore, the PV capacity is limited and further investments of transformer and lines upgrade are needed [44-48].

The focus of this project is on the voltage rise problem and, according to the new German GC VDE-AR-N 4105, the maximum voltage variation at CP after the connection of a distributed generator is maximum 3%. Therefore the PV capacity is limited by:

$$V_{CP} \leq 1.03V_n \quad (3.1)$$

$$\text{Transf.loading}_{\max} = 100\% \quad (3.2)$$

Where  $V_n$  is the voltage at the CP before the connection of the PV system.

Besides the above mentioned limitations, rural LV network are characterized by long distances between distribution transformer and consumers having large R/X ratios which are usually bigger than 1. This drawback results in limited reactive power flow along the cables [48-51].

The network configuration chosen to the analyzed is a European LV benchmark and it can be observed in Figure 3-1 [52].

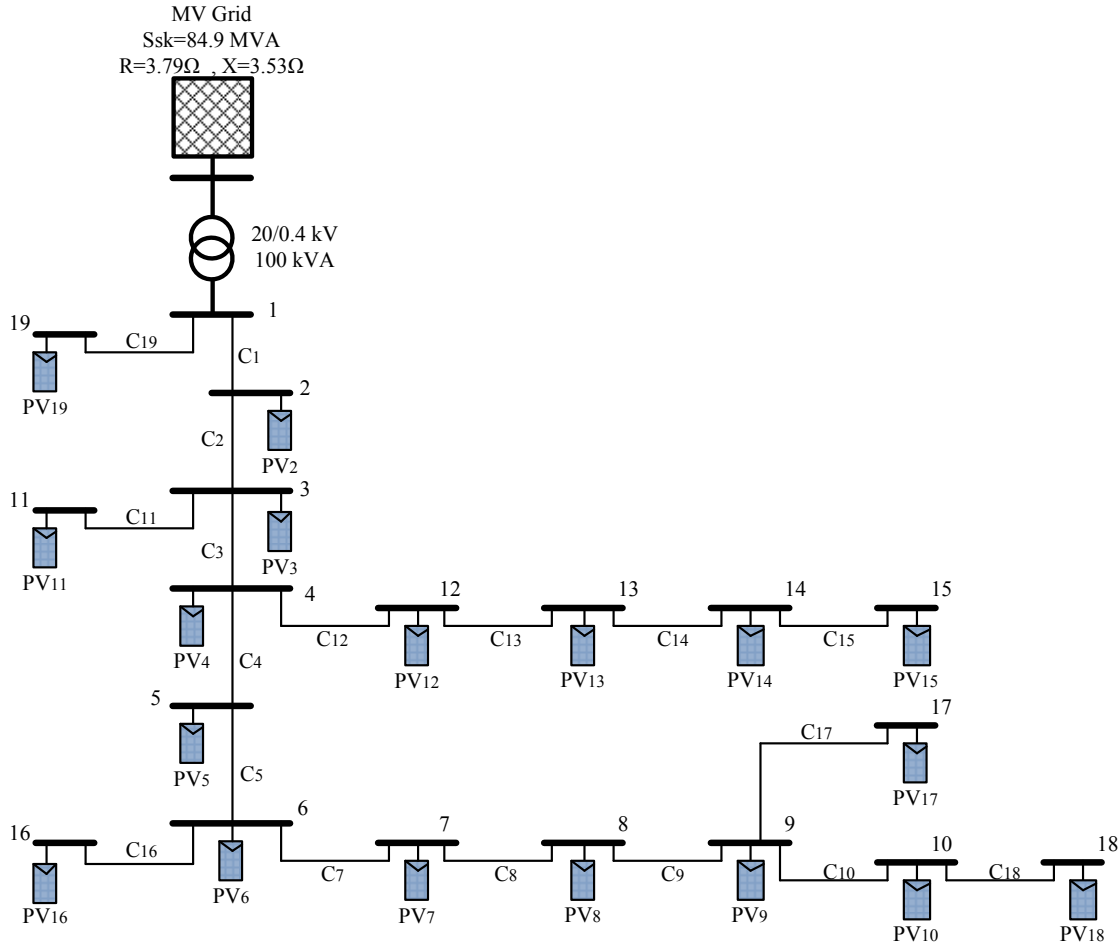


Figure 3-1 European network benchmark [52]

The network is composed of a 100 kVA 20/0.4 kV transformer, one main feeder and two sub-feeders. For simplification purposes the impedances of the cables used to connect the PV

system to the LV grid were assumed to be negligible, therefore, in the calculation process they were neglected. For simulation purposes, to observe the impact of PV generators over the LV network, 18 PV systems were analyzed, each having a peak installed power of 5 kW. The PV generators are three-phase connected and they operate with reactive power output corresponding to a minimum power factor of 0.9. The distance between the PV generators was chosen to be between 30m and 35m, depending on the LV topology. The complete data of the LV network was taken from [53] and it can be found in Table 3-1 [52].

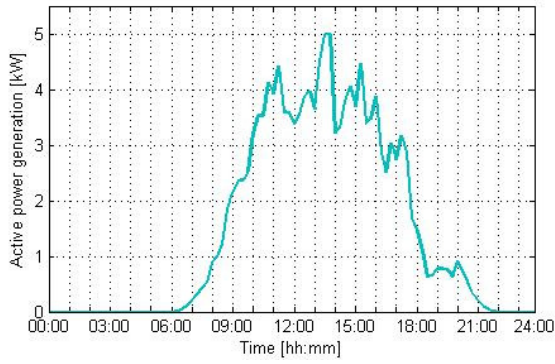
Table 3-1 Rural LV network specifications [52]

External Grid	SSK=84.9 MVA; R=3.79 $\Omega$ ; X=3.53 $\Omega$
Distribution transformer	S=100 kVA Dy5; 20/0.4 kV; ukr=4%; urr=2%
LV Branch Feeder conductor (C11, C15, C16, C17, C18, C19)	NAYY 4x70 mm <sup>2</sup> AL OLH; R=0.413 $\Omega$ /km; X=0.3 $\Omega$ /km; length=0.3 km
LV Branch Feeder conductor (C1, C2, C3, C4, C5, C7, C8, C9, C10, C12, C13, C14)	NAYY 4x70 mm <sup>2</sup> AL OLH; R=0.413 $\Omega$ /km; X=0.3 $\Omega$ /km; length=0.35 km

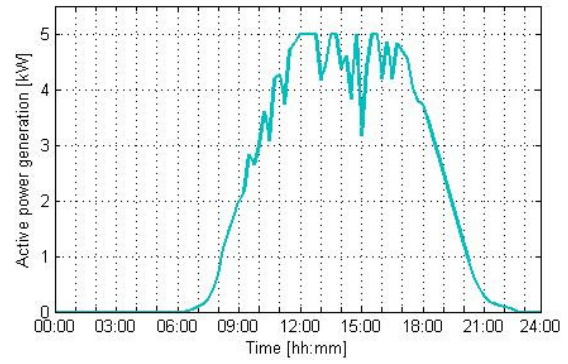
The overhead cables between individual systems have impedance which resulted in an R/X ratio of 1.37. Therefore, the active power has greater impact over the grid voltage and causes voltage rise during high PV generation period. In this situation, the probability of voltage violation is higher than in the other typical networks such as urban and suburban given the fact that the character of those networks is more inductive.

In order to determine the maximum PV capacity which can be installed in residential LV networks and how PV systems are influencing the grid, test studies were performed using the simulation software Power Factory from DigSILENT and MATLAB.

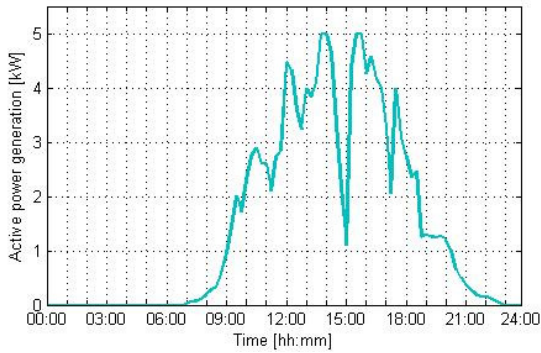
The considered input data in terms of active power production was chosen from a real generation profile [54]. The measurements have a resolution of 15 min and they record the active power generation of a residential PV system during a day with high irradiance in June 2007. For the network presented in Table 3-1, 9 active power generation profiles were developed using the data from [54]. Each generation profile was assigned to 2 PV systems. In Figure 3-2, the PV generation profiles for one day in June 2007 are shown.



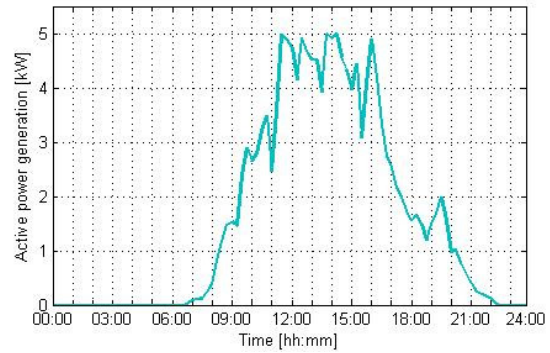
a) Profile 1 for PV2 & PV11 systems



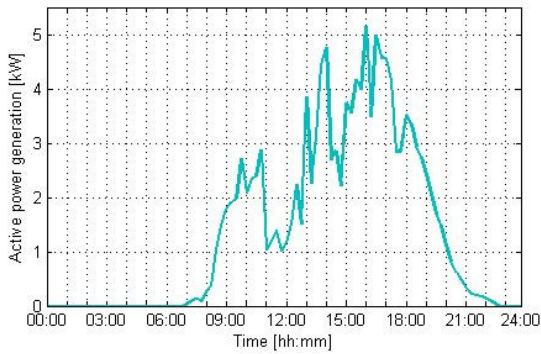
b) Profile 2 for PV3 & PV12 systems



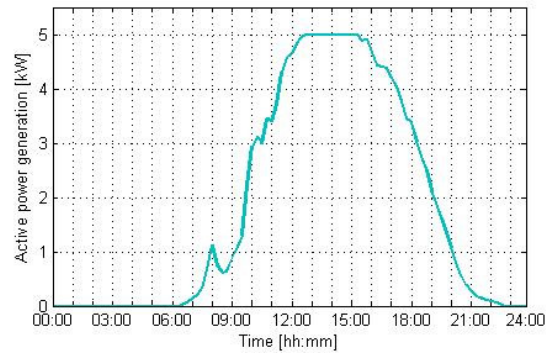
c) Profile 3 for PV4 & PV13 systems



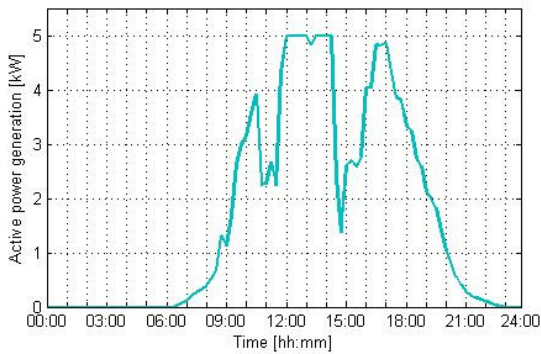
d) Profile 4 for PV5 & PV14 systems



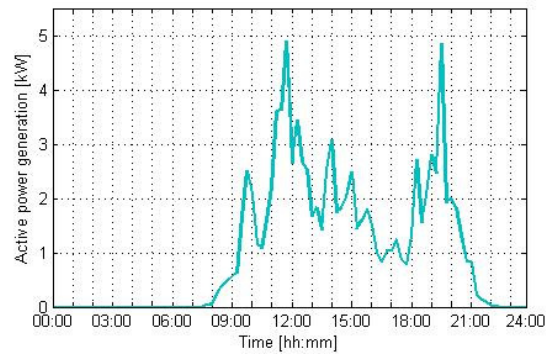
e) Profile 5 for PV6 & PV15 systems



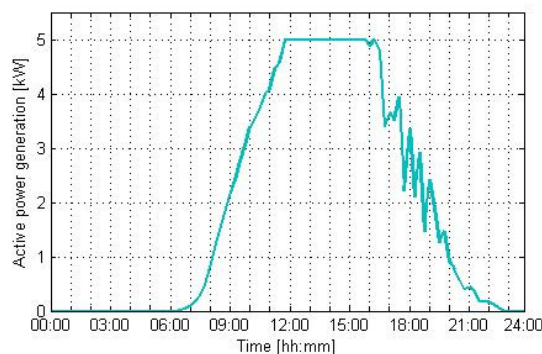
f) Profile 6 for PV7 & PV16 systems



g) Profile 7 for PV8 & PV17 systems



h) Profile 8 for PV9 & PV18 systems



i) Profile 9 for PV10 &amp; PV19 systems

Figure 3-2 Power generation profiles - June 2007 (a - i)

### 3.3 Load flow analysis

Load flow studies are performed to determine important features of power systems such as: the magnitude and angle of the voltage in each bus and the active and reactive power flow in each line. It also calculates the line losses and determines if the voltages remain within specified limits and whether transformers are overloaded [55].

In order to mitigate the voltage rise problem on the chosen LV network, successive load flow calculations are performed using the simulation software Power Factory from DigSILENT. This simulator uses Newton-Raphson method for load flow problem solving; therefore, this algorithm will be explained and later implemented using MATLAB software.

Basically, the Newton-Raphson method calculates two unknown variables using the known parameters and the power flow equations which include both types of variables and other known parameters. Depending on the bus type, the unknown variables which can be calculated based on the known variables are shown in Table 3-2.

Table 3-2 Known and unknown variables depending on bus type

	Known variables	Unknown variables
PQ bus	Active and reactive power (P, Q)	Voltage magnitude and angle ( V , $\delta$ )
PV bus	Active power and voltage magnitude (P,  V )	Reactive power and voltage angle (Q, $\delta$ )
Slack bus	Voltage magnitude and angle ( V , $\delta$ )	Active and reactive power (P, Q)

#### 3.3.1 Newton-Raphson method

Further, the Newton-Rapson algorithm will be explained step by step [56]:

### **Step 1: Reading of data**

The bus where the low-voltage side of the transformer is connected (CP1) was chosen to be the slack bus and the rest are PQ buses.

### **Step 2: Construct the admittance bus (Ybus)**

The  $Y_{bus}$  is the matrix which contains all the admittances in the network. The form of the matrix is the following:

$$Y_{bus} = \begin{pmatrix} Y_{11} & Y_{12} & \dots & Y_{1N} \\ Y_{21} & Y_{22} & \dots & Y_{2N} \\ \dots & \dots & \dots & \dots \\ Y_{N1} & Y_{N2} & \dots & Y_{NN} \end{pmatrix} = \frac{1}{Z_{bus}}, \quad N = 19 \quad (3.3)$$

Where:

- $Y_{ii}$  is the self-admittance (diagonal) and it is equal to the sum of the admittances of all the branches connected to the  $i^{th}$  node
- $Y_{ij}$  is the mutual admittance (off-diagonal) and is equal to the negative of the admittances of all the branches connected between  $i^{th}$  and  $j^{th}$  node

The impedance matrix  $Z_{bus}$  is calculated based on the cable specifications from Table 3-1. The values for all the elements of the  $Y_{bus}$  matrix can be found in Appendix A.

### **Step 3: Start values**

The start values refer to the initial conditions for the magnitude and angle of the voltages in all CPs. Usually, when there are no other specifications, the *flat start* values are consider: 1 p.u. and 0 degrees.

The reference values for the active power generation are taken from [54] and the reactive power reference is taken as 0.

### **Step 4: Number of iterations**

The number of iteration is set to 3.

### **Step 5: Calculation of injected power**

The active and reactive powers injected in all buses are calculated using the actual magnitude and phase angles:

$$P_i = \sum_{j=1}^{19} |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (3.4)$$

$$Q_i = -\sum_{j=1}^{19} |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) \quad (3.5)$$

A detailed description for calculating the above mentioned formulas is presented in Appendix B.

### **Step 6: Difference between specified and injected power**

The difference between the specified and the injected power values comes from the fact that the injected powers are computed based on guessed values of voltage magnitude and angle in the buses, whereas the specified ones are fixed reference values.

$$\Delta P_i = P_i^{ref} - P_i \quad (3.6)$$

$$\Delta Q_i = Q_i^{ref} - Q_i \quad (3.7)$$

### **Step 7: Maximum difference**

The power difference values is calculated and compared to a set tolerance value, in this case 0.0001. If the mismatch is less than the tolerance, proceed to step 11, otherwise continue with step 8.

### **Step 8: Jacobian matrix**

The Newton-Rapson method is responsible with the linearization of the power equations (3.6) and (3.7), therefore the Jacobian matrix is formed of partial derivatives that can be computed. The active and reactive power corrections are found in Step 6. In this way, the unknown variables, voltage magnitude and angle, can be calculated. The general form of the Jacobian matrix is the following [56, 57]:

$$\underbrace{\begin{pmatrix} \frac{\partial P_1}{\partial \delta_1} & \dots & \frac{\partial P_1}{\partial \delta_N} & \frac{\partial P_1}{\partial V_1} & \dots & \frac{\partial P_1}{\partial V_N} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_N}{\partial \delta_1} & \dots & \frac{\partial P_N}{\partial \delta_N} & \frac{\partial P_N}{\partial V_1} & \dots & \frac{\partial P_N}{\partial V_N} \\ \frac{\partial Q_1}{\partial \delta_1} & \dots & \frac{\partial Q_1}{\partial \delta_N} & \frac{\partial Q_1}{\partial V_1} & \dots & \frac{\partial Q_1}{\partial V_N} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_N}{\partial \delta_1} & \dots & \frac{\partial Q_N}{\partial \delta_N} & \frac{\partial Q_N}{\partial V_1} & \dots & \frac{\partial Q_N}{\partial V_N} \end{pmatrix}}_{Jacobian} \underbrace{\begin{pmatrix} \Delta \delta_1 \\ \vdots \\ \Delta \delta_N \\ \Delta V_1 \\ \vdots \\ \Delta V_N \end{pmatrix}}_{Corrections} = \underbrace{\begin{pmatrix} \Delta P_1 \\ \vdots \\ \Delta P_N \\ \Delta Q_1 \\ \vdots \\ \Delta Q_N \end{pmatrix}}_{Mismatches} \quad (3.8)$$

The form of the equation (3.8) can be simplified with the use of submatrixes:

$$\begin{pmatrix} H_{ik} & N'_{ik} \\ J_{ik} & L'_{ik} \end{pmatrix} \cdot \begin{pmatrix} \Delta \delta_i \\ \Delta V_i \end{pmatrix} = \begin{pmatrix} \Delta P_i \\ \Delta Q_i \end{pmatrix} \quad (3.9)$$

The elements of the submatrixes  $(H, J, N', L')$  are the partial derivatives from (3.8) which can be calculated taking into consideration also the bus type.

$$\left\{ \begin{array}{l} H_{ik} = \frac{\partial P_i}{\partial \delta_k} \quad i \neq \text{slack bus}, k \neq \text{slack bus} \\ N'_{ik} = \frac{\partial P_i}{\partial V_k} \quad i \neq \text{slack bus}, k \neq \text{slack bus or PV bus} \\ J_{ik} = \frac{\partial Q_i}{\partial \delta_k} \quad i \neq \text{slack bus or PV bus}, k \neq \text{slack bus} \\ L'_{ik} = \frac{\partial Q_i}{\partial V_k} \quad i \neq \text{slack bus or PV bus} \quad k \neq \text{slack bus or PV bus} \end{array} \right. \quad (3.10)$$

The LV network analyzed in this project does not contain PV buses, therefore, only the derivatives for the slack bus are not computed. The mismatches for the slack bus are not considered since  $\Delta P_1$  and  $\Delta Q_1$  are undefined when  $P_1$  and  $Q_1$  are not scheduled and the correction for  $\Delta \delta_1$  and  $\Delta V_1$  are both 0. In consequence, the dimensions of the submatrixes  $H, J, N', L'$  are  $(N-1) \times (N-1)$  where N is the total number of buses in the network and in this case is equal to 19.

In order to simplify the expression of the  $N'_{ik}$  and  $L'_{ik}$  submatrixes, their elements will be multiplied with a voltage magnitude without influencing the result [57]. Therefore the correction will become  $\Delta V_i / V_i$  and equation (3.9) can be rewritten in the following form:

$$\begin{pmatrix} H_{ik} & N_{ik} \\ J_{ik} & L_{ik} \end{pmatrix} \cdot \begin{pmatrix} \Delta \delta_i \\ \Delta V_i / V_i \end{pmatrix} = \begin{pmatrix} \Delta P_i \\ \Delta Q_i \end{pmatrix} \quad (3.11)$$

The elements of the Jacobian matrix can now be calculated based on equations (3.4) and (3.5).

- when  $i \neq k$ :

$$\left\{ \begin{array}{l} H_{ik} = \frac{\partial P_i}{\partial \delta_k} = V_i V_k (G_{ik} \sin(\delta_{ik}) - B_{ik} \cos(\delta_{ik})) \\ N_{ik} = V_k N'_{ik} = V_k \frac{\partial P_i}{\partial V_k} = V_i V_k (G_{ik} \cos(\delta_{ik}) + B_{ik} \sin(\delta_{ik})) \\ J_{ik} = \frac{\partial Q_i}{\partial \delta_k} = -V_i V_k (G_{ik} \cos(\delta_{ik}) + B_{ik} \sin(\delta_{ik})) \\ L_{ik} = V_k L'_{ik} = V_k \frac{\partial Q_i}{\partial V_k} = V_i V_k (G_{ik} \sin(\delta_{ik}) - B_{ik} \cos(\delta_{ik})) \end{array} \right. \quad (3.12)$$



- when  $i = k$ :

$$\begin{cases} H_{ii} = -Q_i - B_{ii}V_i^2 \\ N_{ii} = P_i + G_{ii}V_i^2 \\ J_{ii} = P_i - G_{ii}V_i^2 \\ L_{ii} = Q_i - B_{ii}V_i^2 \end{cases} \quad (3.13)$$

A more detailed description of how the Jacobian matrix is formed and how its elements are computed can be found in [57].

#### **Step 9: Calculation of $\Delta V$ and $\Delta \delta$**

Using the power mismatches calculated at Step 6 and the elements of the Jacobian matrix computed at Step 8, the corrections can be found using the following formula:

$$\begin{pmatrix} \Delta \delta_i \\ \Delta V_i / V_i \end{pmatrix} = \begin{pmatrix} H_{ik} & N_{ik} \\ J_{ik} & L_{ik} \end{pmatrix}^{-1} \cdot \begin{pmatrix} \Delta P_i \\ \Delta Q_i \end{pmatrix} \quad (3.14)$$

#### **Step 10: New voltage magnitude and angle**

Using the calculated corrections in Step 9, the new voltages can be computed using equations (3.15) and (3.16).

$$V_i = V_i (1 + \Delta V_i / V_i) \quad i \neq \text{slack bus} \quad (3.15)$$

$$\delta_i = \delta_i + \Delta \delta_i \quad i \neq \text{slack bus} \quad (3.16)$$

#### **Step 11: Power flow and power production**

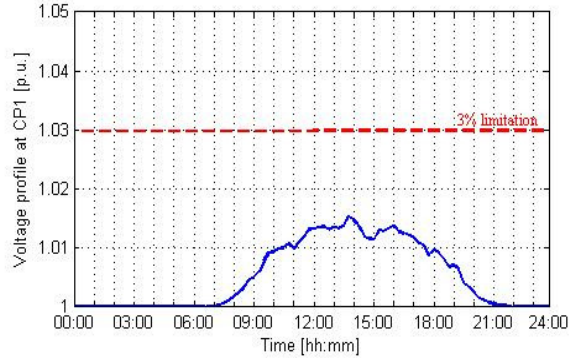
The active and reactive power flows and the net power production in all busses can be calculated with the known voltage magnitude and angle values. Furthermore, the total network losses can also be computed.

### **3.3.2 Load flow results**

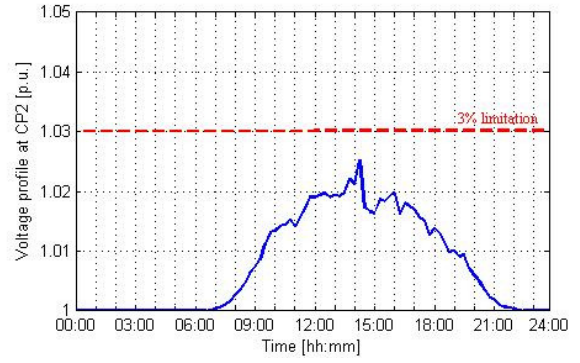
The first load flow analysis on the chosen LV network must be performed with the following conditions: maximum active power generation and no reactive power consumption. The purpose of this study is to examine the maximum voltage levels in the network and based on these values, a reactive power compensation strategy can be proposed. Furthermore, based on the measured values, the droop characteristics can be developed for both regulation methods proposed by the German GC VDE-AR-N 4105.

To emphasize the voltage increase due to PV power generation, a study case with zero load demand was considered. The voltage value at the slack bus before the connection of the PV systems is chosen 1 p.u.. In Figure 3-3 the network voltage levels at all CPs are presented. As

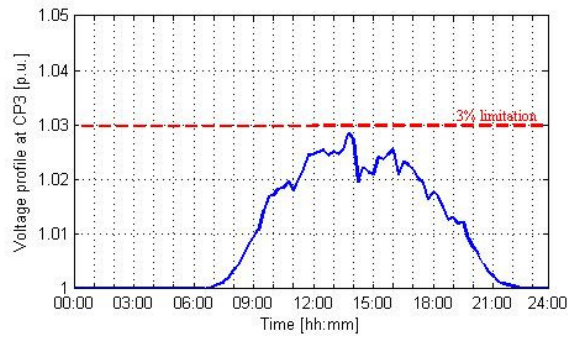
expected, the network experience voltage rise above the 3% limit with the maximum rise at the end of the feeder.



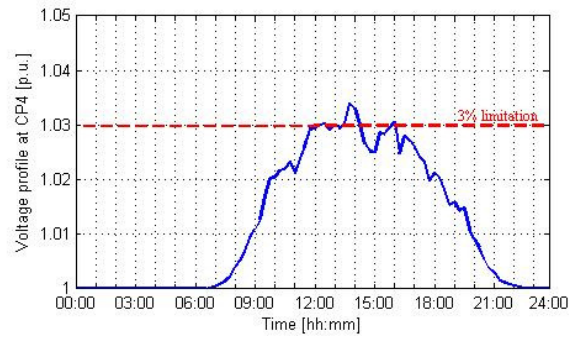
a) Voltage level at CP1



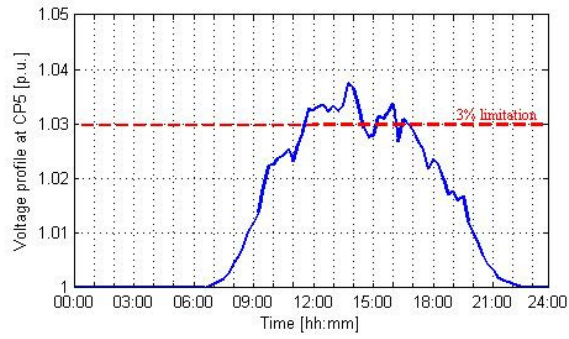
b) Voltage level at CP2



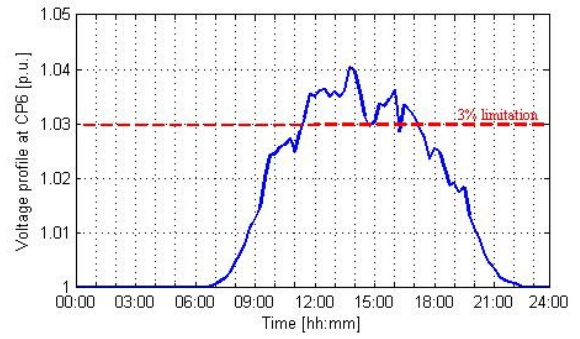
c) Voltage level at CP3



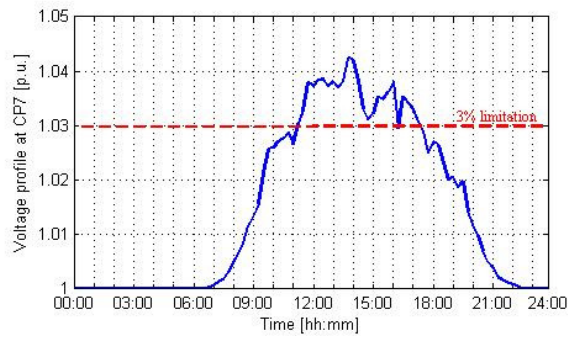
d) Voltage level at CP4



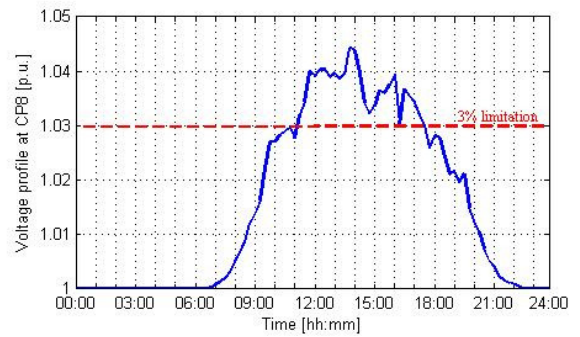
e) Voltage level at CP5



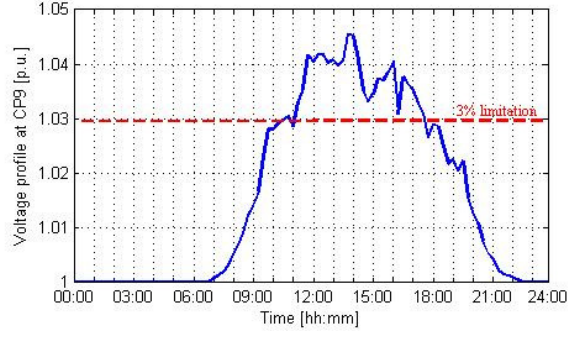
f) Voltage level at CP6



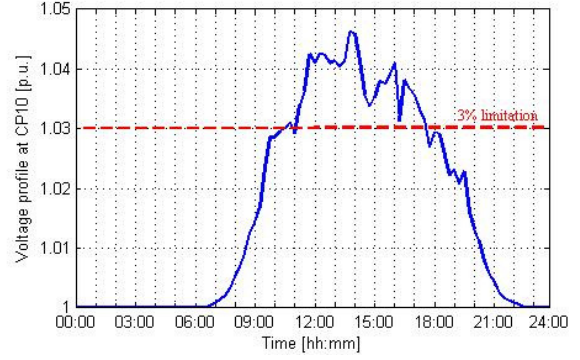
g) Voltage level at CP7



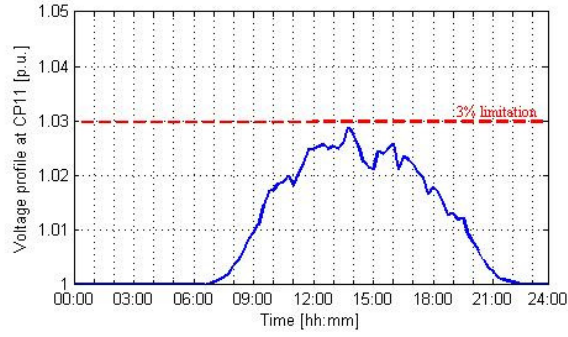
h) Voltage level at CP8



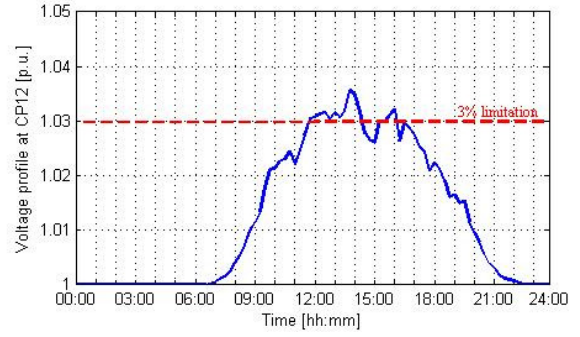
i) Voltage level at CP9



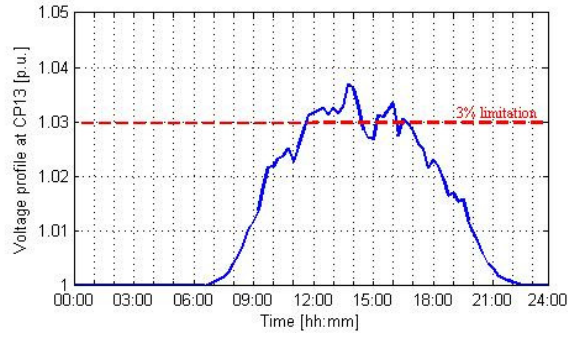
j) Voltage level at CP10



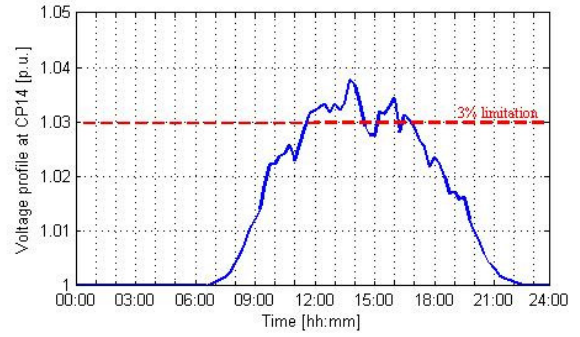
k) Voltage level at CP11



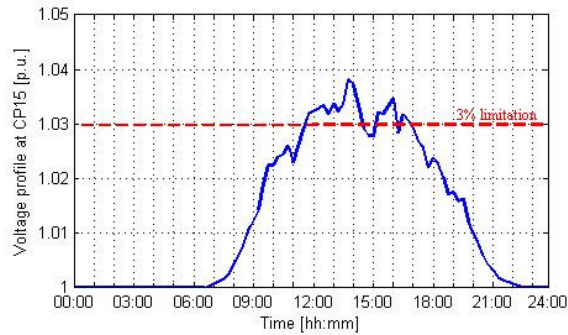
l) Voltage level at CP12



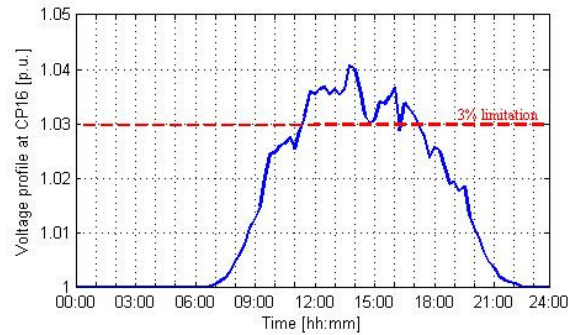
m) Voltage level at CP13



n) Voltage level at CP14



o) Voltage level at CP15



p) Voltage level at CP16



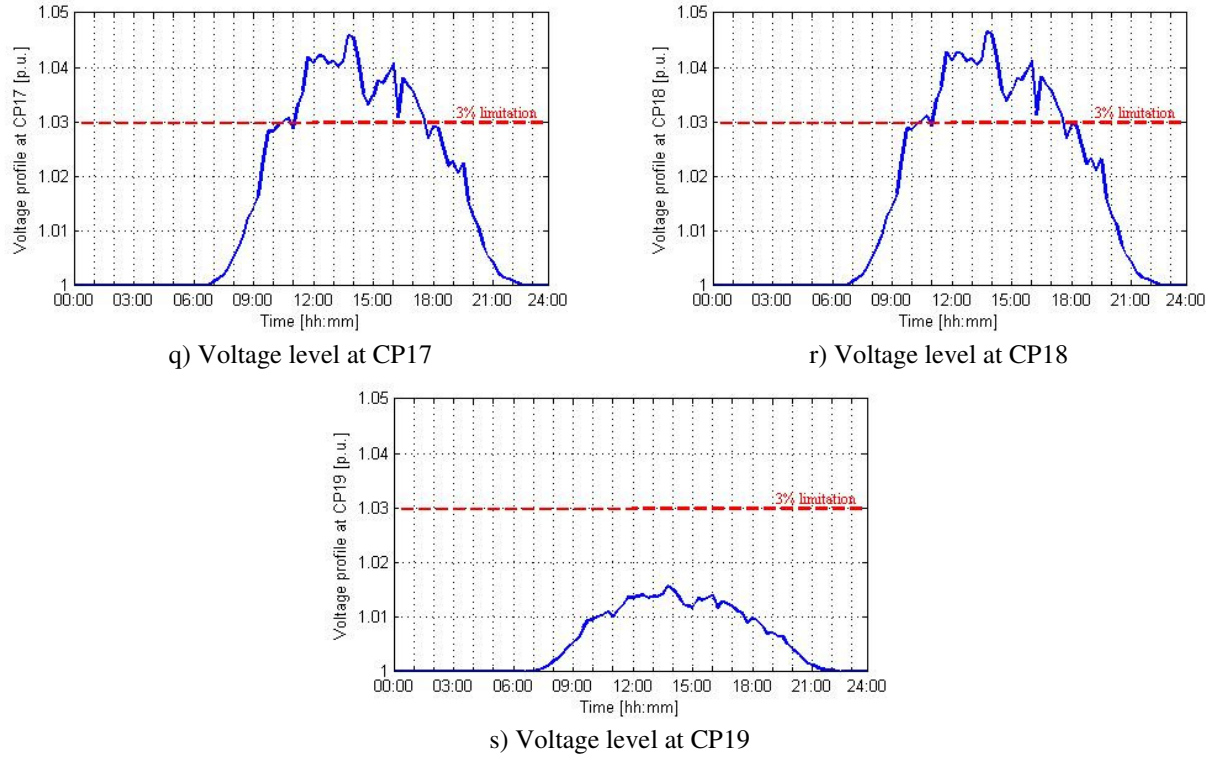


Figure 3-3 Voltage levels at all CPs of the network after performing the load flow analysis (a - s)

In order for the whole system to be inbounded to the 3% voltage limit and to avoid power curtailment, PV generators have to adopt voltage regulation methods.

The transformer loading also calculated after performing the load flow analysis for one day in June 2007 can be seen in Figure 3-4. As it can be observed, the loading level does not exceed 100%.

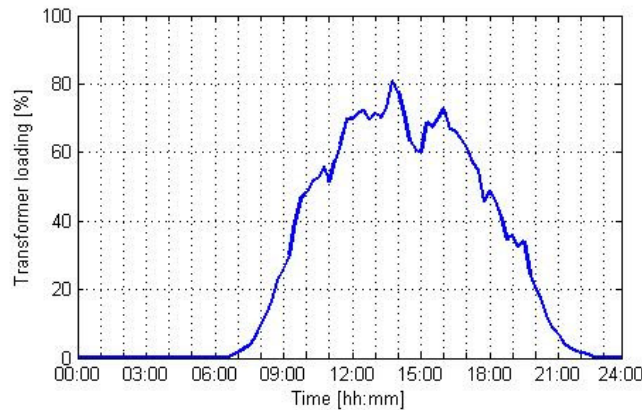


Figure 3-4 Transformer loading when no voltage regulation methods are applied

The source code developed using DigSILENT simulator for the load flow analysis can be found in Appendix C.

### 3.4 Cosφ(P) method

The first voltage regulation method proposed by the German GC is calculating the reactive power reference depending on the active power generated by the PVs (Figure 3-5). When the power production is low, the risk of overvoltage in the network is small as well. When the power generation increase reaches half of the PV nominal power, the power factor is decreasing towards 0.9 and reactive power is absorbed. The method does not use grid voltage information and is only assuming that high power generation matches the voltage increase.

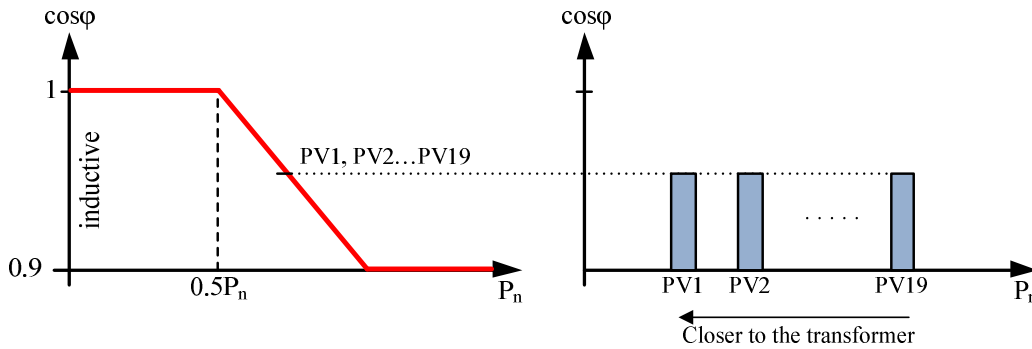


Figure 3-5 Droop characteristic for cosφ (P) method

The main drawback of this method is the possibility of reactive power consumption even though the voltage at the CP is in admissible range. Furthermore, this method does not take into consideration the impedance of the cables and the PV system located nearest to the transformer can absorb the same amount of reactive power as the PV system located at the end of the feeder if they both have the same active power generation.

In this case the reactive power reference can be expressed as:

$$Q = \tan(a \cos \varphi) \cdot P \quad (3.17)$$

The maximum reactive power the PV inverter can absorb at the rated power of 5kW is:

$$Q_{max} = \tan(a \cos(0.9)) \cdot P_n = 2.42 \text{ kVar} \quad (3.18)$$

The flow chart presented in Figure 3-6 shows the implementation of the cosφ(P) algorithm on the chosen LV network.

The first step consists of assigning the active power reference value ( $P_i^{ref}$ ). The data will be assigned each 15 minutes during a day; therefore a total of 96 assignments will be performed. Next, the algorithm checks the value of the active power generation value to assign its corresponding cosφ value and calculate the reactive power consumption. If the  $P_i^{ref}$  value is less than half the rated power ( $P_n = 5kW$ ), the system works at unitary PF and no reactive power is consumed. If the power reference is higher than the nominal value, the system absorbs the

maximum amount of reactive power (  $Q_{max} = 2.42kVar$  ). For any other values of  $P_i^{ref}$  a corresponding value for PF is assigned according to Table 3-3 and the reactive power reference  $Q_i^{ref}$  is calculated. The algorithm stops when the number of iterations set by user is reached.

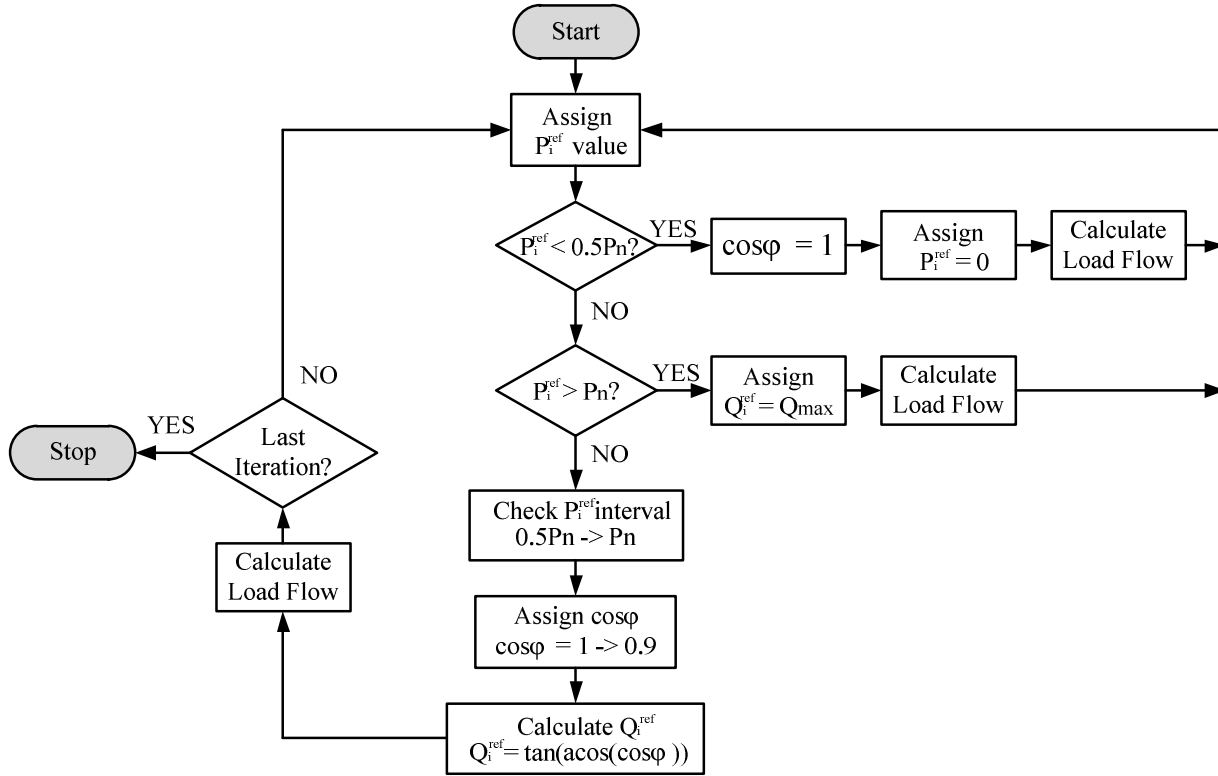


Figure 3-6 Flow chart with the implementation of the  $\cos\phi(P)$  method

Table 3-3  $\cos\phi$  values assigned corresponding to  $P_i^{ref}$  values when  $P_i^{ref} \in [2.5;5]kW$

$P_i^{ref}$ interval (kW)	[2.5, 2.75]	(2.75, 3]	(3, 3.25]	(3.25, 3.5]	(3.5, 3.75]
$\cos\phi$	0.99	0.98	0.97	0.96	0.95
$P_i^{ref}$ interval (kW)	(3.75, 4]	(4, 4.25]	(4.25, 4.5]	(4.5, 4.75]	(4.75, 5]
$\cos\phi$	0.94	0.93	0.92	0.91	0.9

The source code developed using DigSILENT simulator to implement the  $\cos\phi(P)$  method can be found in Appendix D.

### 3.5 Q(U) method

The second strategy of voltage regulation proposed by the German GC, presented in Figure 3-7, is calculating the reactive power reference of each PV system depending on the voltage magnitude measured at its corresponding CP. The benefit of this method compared to  $\cos\phi(P)$  is that it uses local voltage information in the regulation process which means the reactive power consumption will be proportional to the voltage level.

The main drawback of this regulation method is the improper use of the inverter available capacity. It is likely the voltage magnitude at the CPs near the transformer to be within limits, therefore the corresponding PV systems will not participate in the regulation process, making the task much difficult for the other PV inverters. Furthermore, the probability that the inverters situated further away from the transformer will work at full capacity or at a capacity higher than the inverters located near the transformer. Because each PV system performs a local regulation process, the inverters with available capacity cannot help the inverters working at full capacity; therefore, in terms of reliability, the inverters located at the end of the feeder will experience problems earlier.

As stated in the German GC, the droop curve for the Q(U) method is provided by the network operator. Therefore, the droop characteristic specific for the LV network studied in this project must be designed. Based on the results of the first load flow analysis, for the maximum voltage value, the corresponding reactive power absorption value can be assigned. As it can be seen from Figure 3-7, this value can be taken as 1.05 p.u. because when there is no reactive power absorption in the network, the maximum voltage magnitude does not exceed 1.05 p.u.. The start value for absorbing reactive power is chosen to be 1.02 p.u.. Using these values, the droop characteristic can be achieved and the Q(U) regulation method can be implemented (Figure 3-8) [53].

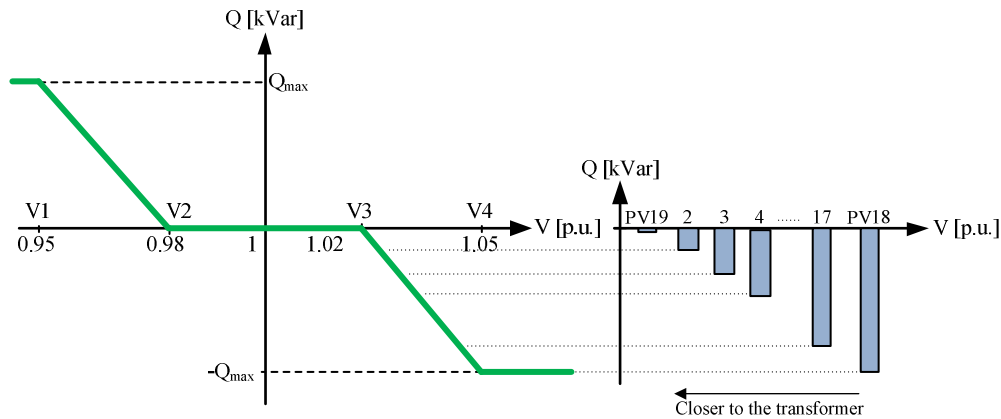


Figure 3-7 Droop characteristic for Q(U) method

The voltage variation is calculated using the following formula:

$$\zeta = \frac{V_{meas} - V_3}{V_3} \cdot 34 [\%], \quad \zeta \in [0,1] \quad (3.19)$$

The reactive power reference is calculated using the value of the voltage variation found in (3.19):

$$Q_i^{ref} = \zeta \cdot Q_{max} \quad (3.20)$$

The flow chart shown in Figure 3-8 presents the implementation of the Q(U) method. For this purpose the DigSilent Power Factory software was used and for each iteration, two load flow analysis are performed. First, the effect of active power generation on the voltage magnitude is investigated. Based on the measured voltage value ( $V_{meas}$ ), an individual reactive power is assigned to each PV ( $Q_i^{ref}$ ) and a new load flow analysis is performed in order to check if the problem has been suppressed.

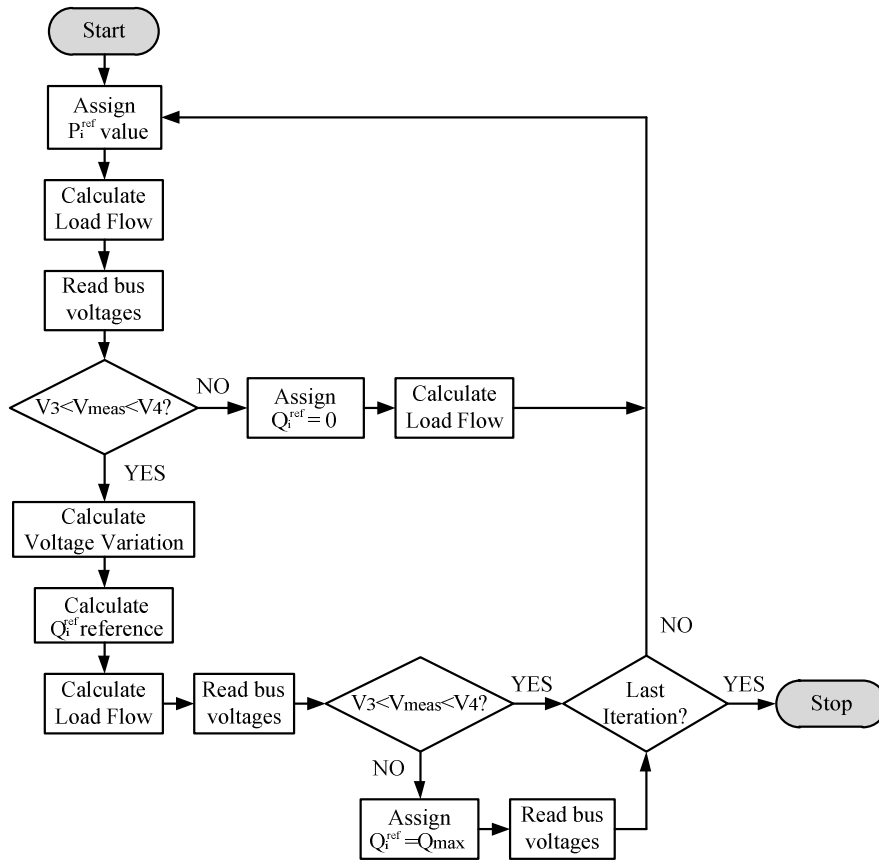


Figure 3-8 Flow chart with the implementation of the Q(U) method

The algorithm for Q(U) method can be summarized by the equation system from (3.21). It can be mentioned that for the LV network studied in this project, the only concern is the voltage rise problem and PV systems are required only to absorb reactive power, therefore only the corresponding part from the equation system was considered for implementation.

The source code developed using DigSILENT simulator to implement the Q(U) method can be found in Appendix E.



$$Q_i^{ref} = \left\{ \begin{array}{ll} Q_{max}; & V_{meas} > V_1 \\ \frac{V_{meas} - V_3}{V_3} \cdot 100 \cdot Q_{max}; & V_1 < V_{meas} < V_2 \\ 0; & V_2 < V_{meas} < V_3 \\ \frac{V_{meas} - V_1}{V_1} \cdot 100 \cdot (-Q_{max}); & V_3 < V_{meas} < V_4 \\ -Q_{max}; & V_{meas} > V_4 \end{array} \right\} \quad (3.21)$$

### 3.6 Study case results

The performance of the above described methods is investigated based on voltage level, reactive power flow and the transformer loading level. First, the behavior of the PV systems closer to the transformer is investigated. It is expected that these systems will experience less voltage rise at their CPs. When the selected voltage regulation strategies are implemented, each PV system consume a reactive power value corresponding to its active power generation ( $\cos\phi(P)$ ) or the local voltage magnitude ( $Q(U)$ ).

In Figure 3-9a) the voltage profile of the closest system to the transformer (PV19) is shown. As it can be observed the highest voltage level at the CP is around 1.015p.u.. In Figure 3-9b), the generation profile of the PV19 generator is presented together with the levels of reactive power consumed using both regulation methods. The reason there is no reactive power absorption for  $Q(U)$  strategy is because the droop-characteristic, defined in Figure 3-7, states that the inverter will start consuming reactive power only when the voltage reaches the value of 1.02 p.u. For this PV system the voltage remains inside the dead band of the droop curve (0.98p.u. – 1.02p.u.). On the other hand, it can be observed that the  $\cos\phi(P)$  algorithm consumes large amounts of reactive power, proportional to the active generation levels, even though no voltage regulation is needed. Although the voltage is between limits, the high amount of reactive absorption leads to a decrease in voltage level to an approximate value of 1.005 p.u..

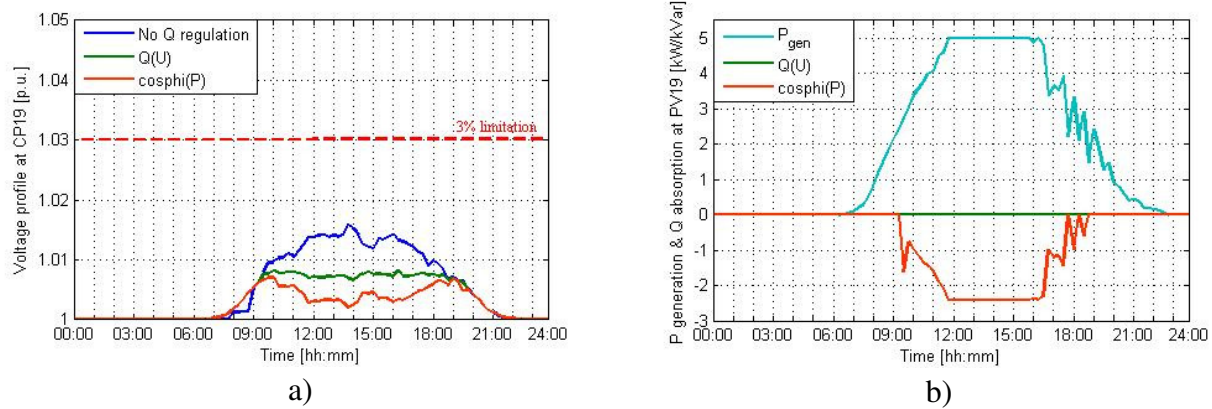


Figure 3-9 PV19 system analysis a) Voltage levels with and without regulation methods b) Active power generation and reactive power consumed using regulation methods

The reason the voltage at the CP19 when using the Q(U) algorithm is lower compared to the voltage when no regulation is applied in the network is due to the influence of the reactive power absorbed by the rest of the network and the high impedance of the transformer.

Figure 3-10 presents the analysis results of the second PV system closest to the transformer – PV2. As it can be noticed, the only difference compared to the previously analyzed PV system is the fact that the voltage at the CP slightly increases above 1.02p.u. and, for a short period of time, the Q(U) method is absorbing reactive power.

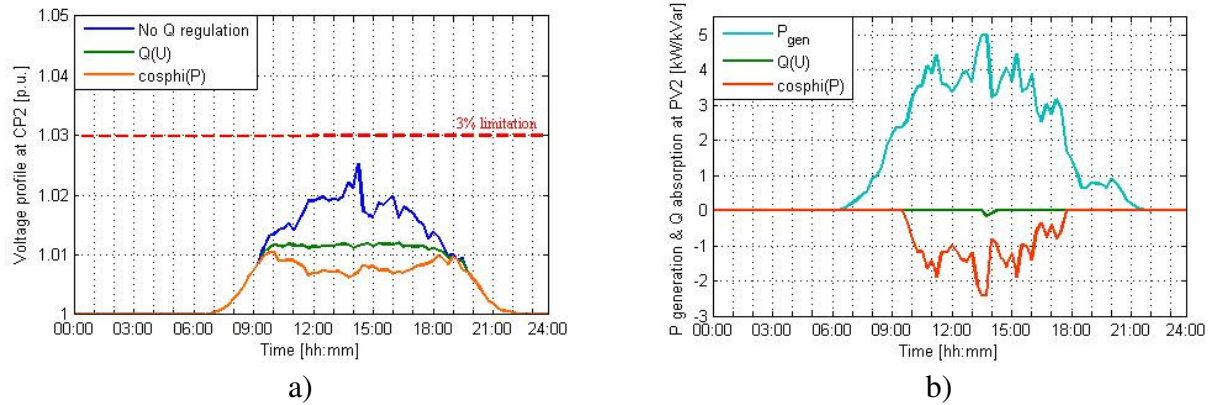


Figure 3-10 PV2 system analysis a) Voltage levels with and without regulation methods b)

Active power generation and reactive power consumed using regulation methods

For PV19 system, the active power generation profile is different from the previously discussed one, but the high amounts of reactive power absorption when using  $\cos\phi(P)$  algorithm is present in this case also. This fact leads again to having the lowest voltage values at the CP when considering  $\cos\phi(P)$  strategy.

As expected, the CPs near the transformer did not experience voltage rise above the 3% limit. Further on, the PV systems situated at the end of the main feeder and the ones located at the end of the two sub-feeders will be analyzed.

Figure 3-11 describes the simulation results for the PV system located at the end of the main feeder – PV16.

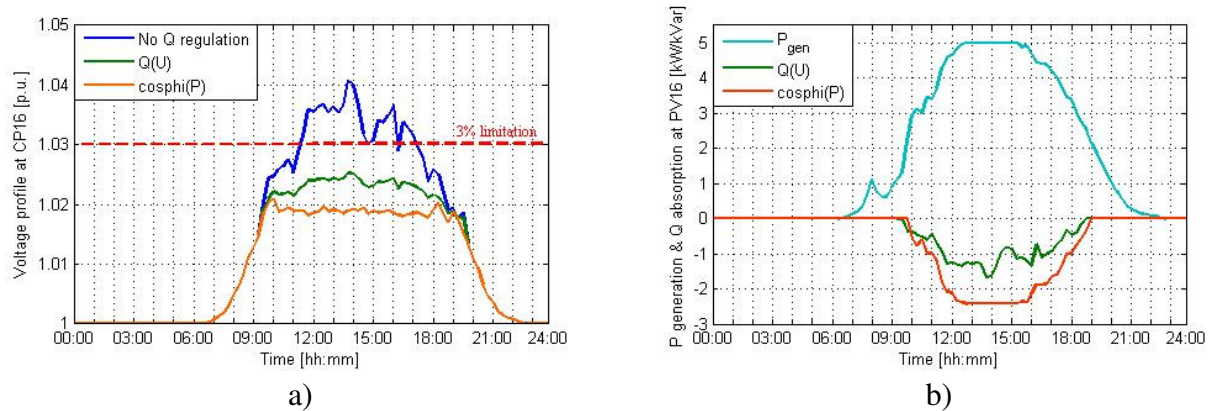


Figure 3-11 PV16 system analysis a) Voltage levels with and without regulation methods b)

Active power generation and reactive power consumed using regulation methods

The voltage level after performing the first load flow analysis reaches 1.04 p.u., therefore voltage regulation is mandatory to lower the voltage below the imposed limit. Both  $\cos\phi(P)$  and  $Q(U)$  strategies perform successfully the regulation process with the same difference in terms of reactive power consumption: the amount absorbed with  $\cos\phi(P)$  is significantly higher than using  $Q(U)$ .

The analysis of the simulation results continue with the PV system located at the end of the first sub-feeder - PV15. As well as the previous analyzed system, the voltage level at the CP violates the 3% limit and after the regulation process the voltage is reduced and maintained in the specific range (Figure 3-12).

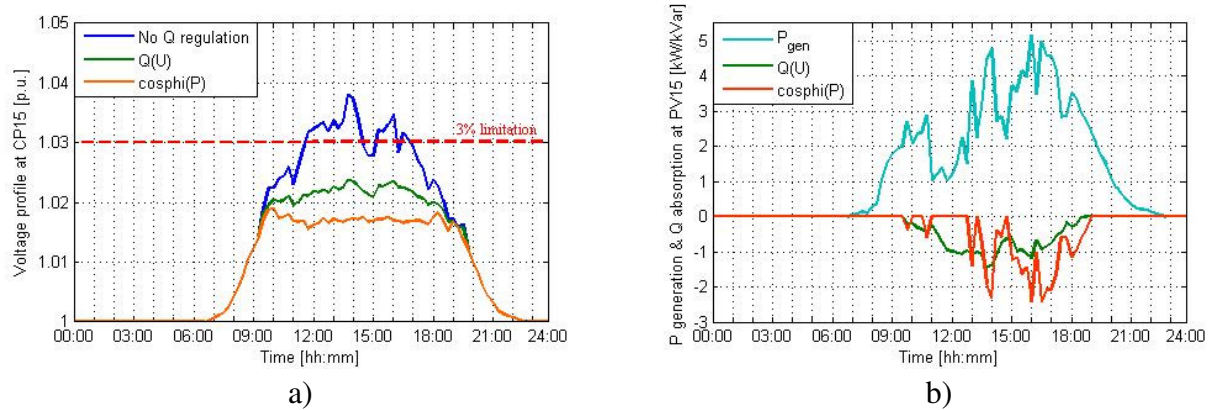


Figure 3-12 PV15 system analysis a) Voltage levels with and without regulation methods b) Active power generation and reactive power consumed using regulation methods

Finally, the PV system situated at the end of the second sub-feeder and furthest away from the transformer is discussed – PV18 (Figure 3-13). The highest voltage level in the network, approximately 1.046, is reached at the CP of this system. The interesting part is that in this case the roles are reversed and the  $Q(U)$  method consumes more reactive power than  $\cos\phi(P)$  in the first part of the day until around 15:00. The reason this happened is the low levels of active power generation.

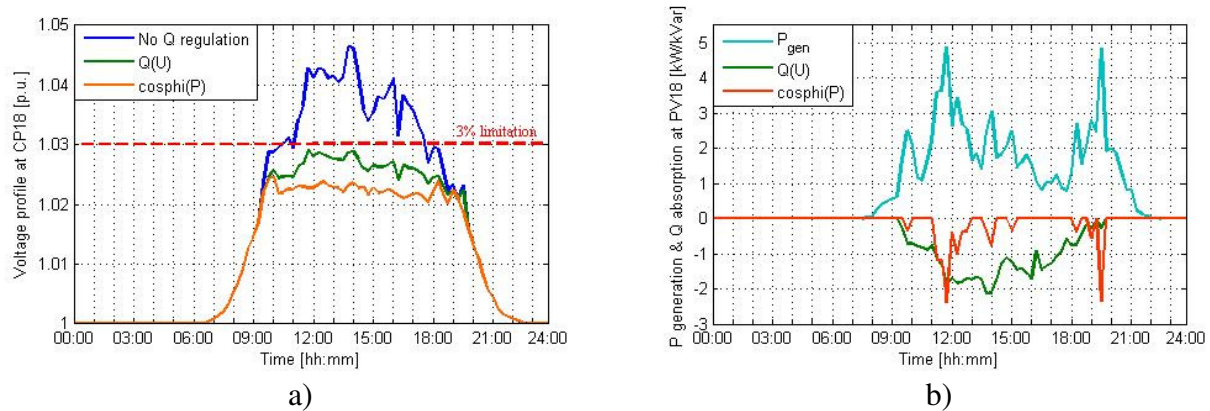


Figure 3-13 PV18 system analysis a) Voltage levels with and without regulation methods b) Active power generation and reactive power consumed using regulation methods

In Figure 3-14, the transformer loading for the analyzed strategies is shown. Without the reactive power regulation from the PV systems, the maximum transformer loading is 81%. The Q(U) method minimizes the reactive power absorption and increases the loading of the transformer to a maximum value of 85.5%. On the other hand, the  $\cos\phi(P)$  method limits the further PV capacity achievement due to the high amounts of reactive power consumption which lead to a 91% loading of the transformer.

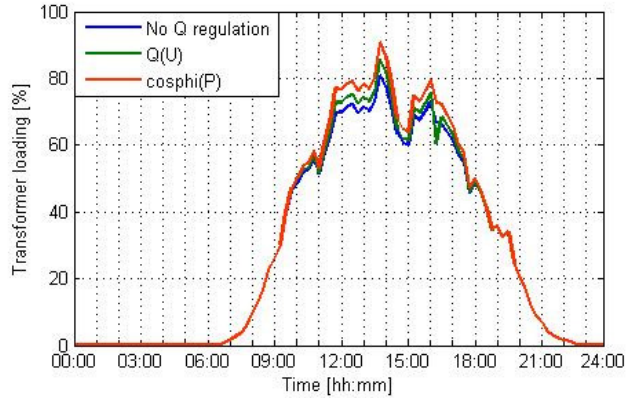


Figure 3-14 Transformer loading for the analyzed strategies

### 3.7 Discussions

The performance of both  $\cos\phi(P)$  and Q(U) regulation methods was evaluated on the chosen European LV network based on their ability to maintain the voltage between specified limits.

The purpose of having more active power generation profiles for the PV systems is to emphasize the effect of the  $\cos\phi(P)$  method. If all PV generators had the same profile, the amount of reactive power consumed using  $\cos\phi(P)$  would have been the same for all the inverters.

The simulation results show that both methods have achieved their regulation purpose. Although the voltage values using the  $\cos\phi(P)$  are closer to 1 p.u. compared to Q(U) method, the consequence of having a lower voltage is a higher reactive power consumption. As long as the voltage does not exceed the 3% limit, the value is not an issue, therefore the fact that the voltage level is lower using  $\cos\phi(P)$  cannot be seen as an advantage because it does not have any effect on the network.

The difference between the two strategies in terms of reactive power is prominent as both strategies calculate the reactive power consumption in two different ways. Because  $\cos\phi(P)$  method does not consider any feedback from the network nor the voltage sensitivity, all the inverters in the network can consume the same amount of reactive power, regardless of their position and the voltage levels. On the other hand, Q(U) method takes into consideration the above mentioned issues and improves the inverter capacity use. The inverters that do not experience voltage rise over the limit are not as stressed as the other inverters and the reactive

power consumption is therefore decreased. From the point of view of reactive power absorption, it can be stated that Q(U) method is better, but improvements can be made so that all inverters can participate in the regulation process with their available capacity.

From the above mentioned, another conclusion can be drawn in terms of reliability. Because of the higher levels of reactive power consumed by all the inverters with  $\cos\phi(P)$  method, the amount of inverters that can experience problems is bigger than in case of using Q(U) strategy; thus leading to a lower life-time of the inverters.

The last performance criterion to evaluate the two control strategies is the level of transformer loading. The simulation results shown that the transformer loading was most increased when using the  $\cos\phi(P)$ . It is normal because the higher stress on the transformer is the consequence of the larger amounts of reactive power absorption.

Both methods proposed by the new German GC VDE-AR-N 4105 were implemented on a LV network and analyzed from different points of view. All the results and discussions point in the same direction: the Q(U) algorithm is the best candidate when considering voltage regulation in a LV network with minimum reactive power consumption.





# Chapter 4 Improved voltage regulation strategies

*The chapter describes an optimization algorithm for voltage regulation in LV network in order to improve the classical methods proposed by the German GC. The implementation of the optimized  $Q(U)$  algorithm is explained in detail and simulation results are discussed and compared with the classical  $Q(U)$  algorithm which was chosen as best candidate based on the results from the previous chapter.*

## 4.1 Optimized $Q(U)$ method

The main objectives when talking about networks are to find optimal solutions to problems that minimize the costs. The optimization problem treated in this chapter refers to the reactive power dispatch problem with the focus on developing an algorithm with the following purposes:

- Maintain the voltages at the CPs below the specified limit
- Minimize the reactive power consumption of the overall network, hence minimize the losses in the line
- Use the available capacity of all the PV inverters to avoid stressing the ones at the end of the feeder
- Use advanced communication protocols to gather information from all the PV systems on a centralized controller which would calculate the optimal reactive power reference for each PV system

### 4.1.1 Standard optimization problem

*Optimization is a mathematical process in which a search is activated that aims at a best value of an objective function that is optimal [58].* In general, an optimization algorithm has a specific objective function to be minimized while satisfying some predefined equality and inequality constraints.

The objective functions are formed based on a problem definition. In general, there are various features in a network that can be considered problems which can be optimized, for example: minimization of the total generating cost, reduction of active transmission losses, security and stability of the power system [59, 60]. Each of these problems can be define to form the objective function of an optimization algorithm. The standard form of the objective function is  $F(x)$  where  $F$  is a scalar function and  $x$  is the vector of the design variables containing both state and control variables. The state variables describe any unique state of the power system, whereas the control variables can be modified to satisfy predefined conditions.

For any optimization problem, the equality constraints are expressed using the form  $g(x)=0$  where  $g$  is a function assumed to be continuous and at least twice differentiable [61]. The most common equality constraints for power systems refer to the nonlinear load flow equations. These constraint functions contain the limits for the state variables.

The inequality constraint function has the form  $h(x) \leq 0$ . Usually, these functions define some specific bounds such as: voltage levels at the CP in a network, transmission line flow limit, reactive power capabilities of inverters etc.

Therefore, the standard form of the optimization problem can be expressed as:

$$\min F(x) \tag{4.1}$$

Subject to:

$$g(x) = 0 \tag{4.2}$$

$$h(x) \leq 0 \tag{4.3}$$

#### **4.1.2 Problem formulation process for the LV network**

In this subchapter, the problem formulation process will be presented step by step based on [62]:

##### **Step 1: Problem Statement**

Maintain the voltage levels at all the CPs of the LV network between limits imposed by the German GC considering in the same time the optimization of the reactive power dispatch.

##### **Step 2: Data and Information Collection**

- the number of PV systems in the network is 18
- the considered CPs are beginning from the LV-side of the transformer and the total number is 19 (1 slack bus and 18 PQ buses)
- the influence of the transformer impedance is not taken into consideration (Figure 4-1)
- active power generation profile of all PV generators are predefined
- inverter capabilities in terms of active and reactive power are set
- parameters for cables are predefined



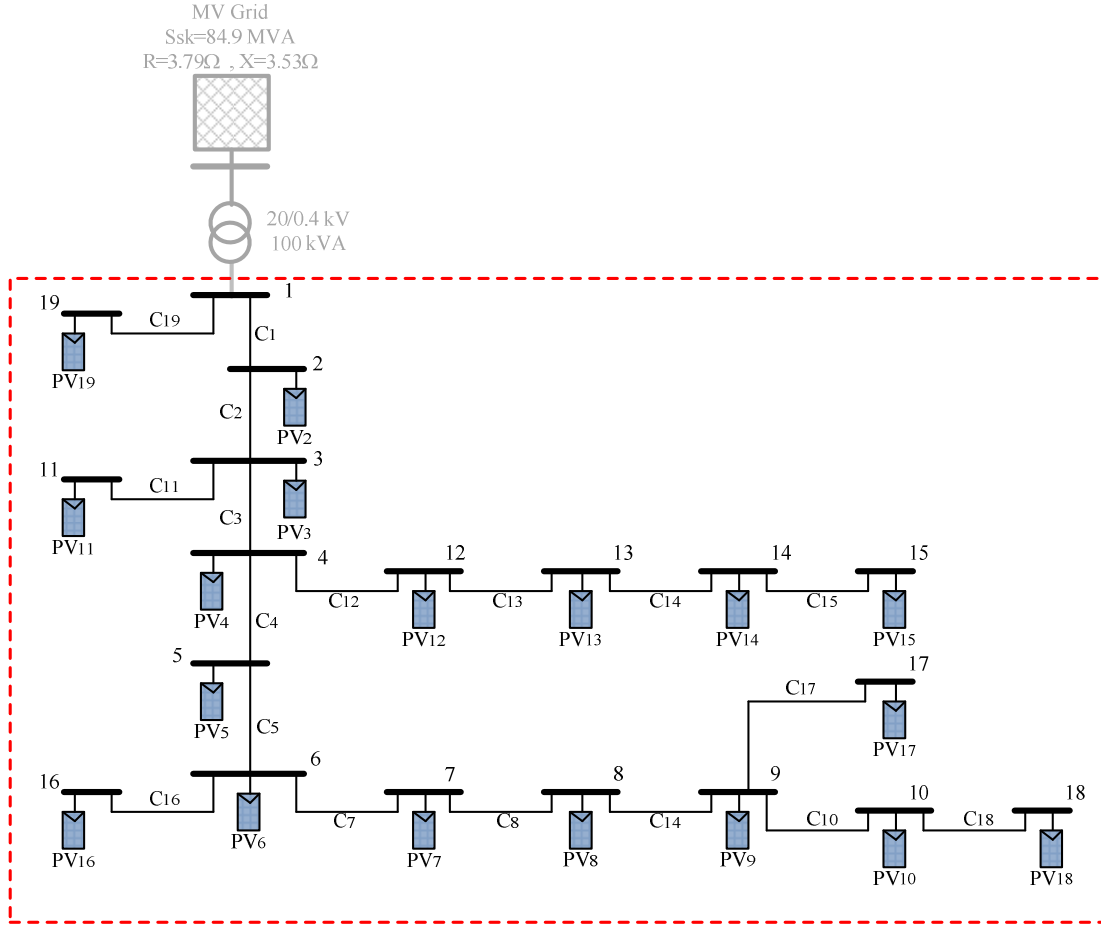


Figure 4-1 LV network under study with the area of interest highlighted

### **Step 3: Identification/Definition of the design variables**

The state variables consist of the voltage magnitude ( $V_i$ ) and angle ( $\delta_i$ ) for each bus in the LV network. The reactive power references ( $Q_i^{ref}$ ) of all PV systems are defined as the control variables. Both set of variables have the following vector form:

$$X_1 = [V_1, V_2, \dots, V_{19}] \quad (4.4)$$

$$X_2 = [\delta_1, \delta_2, \dots, \delta_{19}] \quad (4.5)$$

$$U = [Q_1^{ref}, Q_2^{ref}, \dots, Q_{19}^{ref}] \quad (4.6)$$

The design variable vector contains all the variables of the system, therefore its form will be:

$$x_{opt} = [V_i, \delta_i, Q_i^{ref}] \quad \text{where } i = \overline{1:19} \quad (4.7)$$

#### **Step 4: Identification of Criterion to be optimized**

Using the problem statement defined in Step1, the objective function can be formulated as follows:

$$\min f(x) = \sum (Q_i^{ref})^2, i = \overline{2:19} \quad (4.8)$$

#### **Step 5: Identification of Criterion to be optimized**

##### Step 5.1: Identification of Equality Constraints

As stated before, the power flow equations are used as equality constraints:

$$g_1 = P_i^{ref} - V_i \sum_{j=1}^{19} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0, i = \overline{2:19} \quad (4.9)$$

$$g_2 = Q_i^{ref} - V_i \sum_{j=1}^{19} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0, i = \overline{2:19} \quad (4.10)$$

Where  $V_i, V_j$  are the voltages at i and j buses,  $i = \overline{2:19}, j = \overline{1:19}$ .  $P_i^{ref}, Q_i^{ref}$  are the active and reactive power injected at bus i.  $G_{ij}, B_{ij}$  are the conductance and susceptance between bus i and j and  $\theta_{ij}$  is the voltage angle difference between bus i and j.

The equality constraint for the slack bus refers to the reactive power reference, voltage magnitude and angle:

$$\begin{cases} Q_1^{ref} = 0 \\ V_1 = 1 \text{ p.u.} \\ \delta_1 = 0 \end{cases} \Rightarrow g_3 = \begin{cases} Q_1^{ref} = 0 \\ V_1 - 1 = 0 \\ \delta_1 = 0 \end{cases} \quad (4.11)$$

##### Step 5.2: Identification of Inequality Constraints

First inequality constraint expresses the limits for voltage magnitude for all PQ buses in the network:

$$0.97 \text{ p.u.} \leq V_i \leq 1.03 \text{ p.u.} \Rightarrow h_1 = \begin{cases} 0.97 - V_i \leq 0 \\ V_i - 1.03 \leq 0 \end{cases}, i = \overline{2,19} \quad (4.12)$$

Moreover, the reactive power capabilities of the PV inverters are limited:

$$(P_i^{ref})^2 + (Q_i^{ref})^2 \leq S_i^2 \Rightarrow h_2 = (P_i^{ref})^2 + (Q_i^{ref})^2 - S_i^2 \leq 0, i = \overline{2,19} \quad (4.13)$$

It should be mentioned that a minimization of line losses is also achieved with the load flow equations taken as constraints and the use of *fmincon* function.

### Step 6: Initial Conditions

The initial condition for voltage magnitude and angle are the output values of the first load flow performed for the LV network and zero for the reactive power references.

$$x_{init} = [V_{i_{load\_flow}}, \delta_{i_{load\_flow}}, Q_{i_{init}}^{ref}] \quad \text{where } Q_{i_{init}}^{ref} = 0, i = \overline{1:19} \quad (4.14)$$

## 4.2 Implementation of optimized Q(U) method

The flow chart presented in Figure 4-2 describes the implementation of the optimized Q(U) strategy.

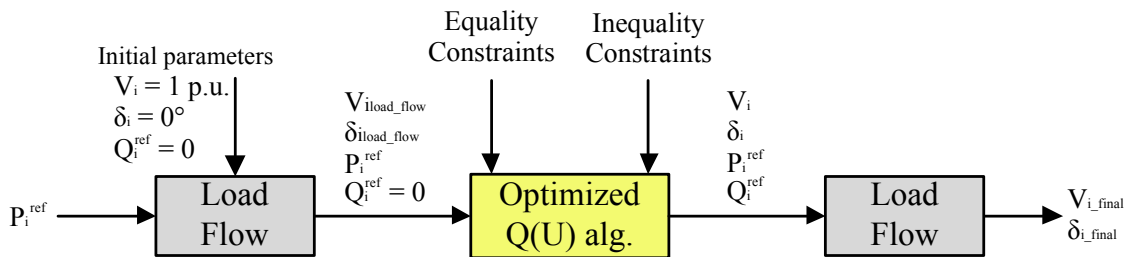


Figure 4-2 Flow chart with the implementation of the optimized Q(U) method

The first step consists of performing a load flow analysis with the *flat start* conditions for voltage magnitude ( $V_i = 1 p.u.$ ) and angle ( $\delta_i = 0^\circ$ ), the set active power generation  $P_i^{ref}$  and  $Q_i^{ref} = 0$ . Afterwards, the optimized Q(U) algorithm takes as reference the output values of the load flow for voltage magnitude and angle. Considering also the equality and inequality constraints, a feasible solution will be obtained for the defined objective function. The output values of the algorithm will be given as reference to the inverters and another load flow analysis will be performed in order to check if the voltage is maintained between limits.

The source code developed using MATLAB to implement the optimized Q(U) method can be found in Appendix F.

## 4.3 Study case results

Further on, the simulation results of the optimized Q(U) strategy will be presented and compared with the results obtained when Q(U) method was analyzed on the LV network.

In Figure 4-3a) the voltage profile and power levels of the closest system to the transformer (PV19) is shown. In Figure 4-3b), the generation profile of the PV19 generator is presented together with the levels of reactive power consumed using both regulation methods. The voltage profile when using the optimized Q(U) method is similar to the one when no regulation methods are applied because the influence of the transformer was not considered when the algorithm was designed. Only very small amounts of reactive power are absorbed in

this case because the PV19 system tries to take part in the regulation process, but the distance between this system and the first one which experience voltage rise above the limit at the CP is the highest.

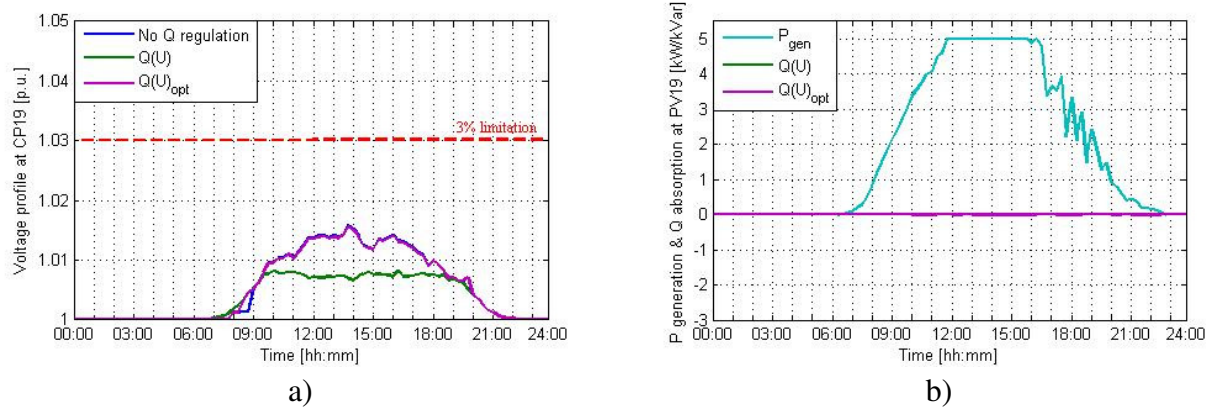


Figure 4-3 PV19 system analysis a) Voltage levels with and without regulation methods b) Active power generation and reactive power consumed using regulation methods

Similar results are shown in Figure 4-4 for PV2 system compared with PV19 system because the difference between them is the length of the cables. PV19 system is connected directly to the rest of the system, therefore it takes part in the regulation process with slightly higher amounts of reactive power absorption compared with the previous system, but they are still low compared to the other systems.

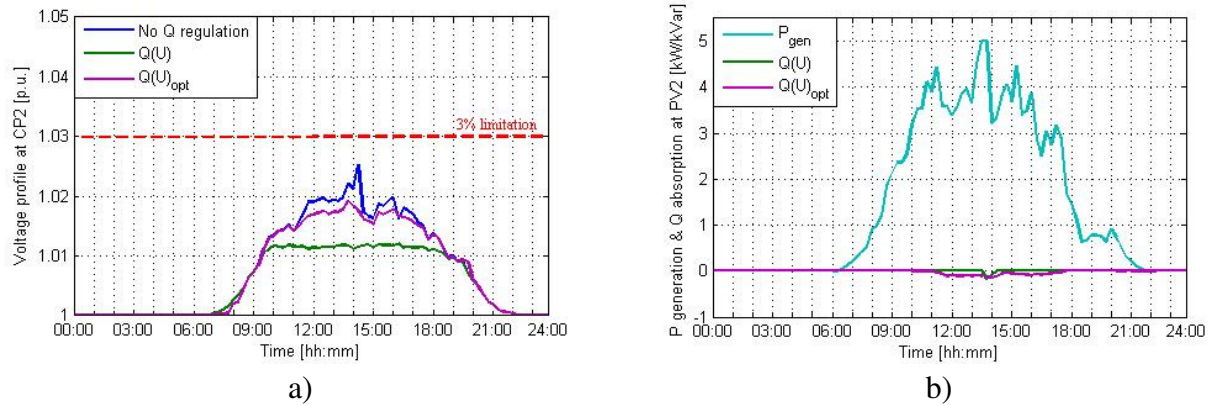


Figure 4-4 PV2 system analysis a) Voltage levels with and without regulation methods b) Active power generation and reactive power consumed using regulation methods

In order to see the improvements brought by the optimized Q(U) algorithm the systems located at the end of the main feeder and the two sub-feeders will be presented further on.

Figure 4-5 describes the simulation results for the PV system located at the end of the main feeder – PV16. Although there is a difference between the voltages after performing the regulation strategies, both perform successfully the regulation process, but the reactive power amount absorbed with the optimized Q(U) algorithm is lower than using Q(U).

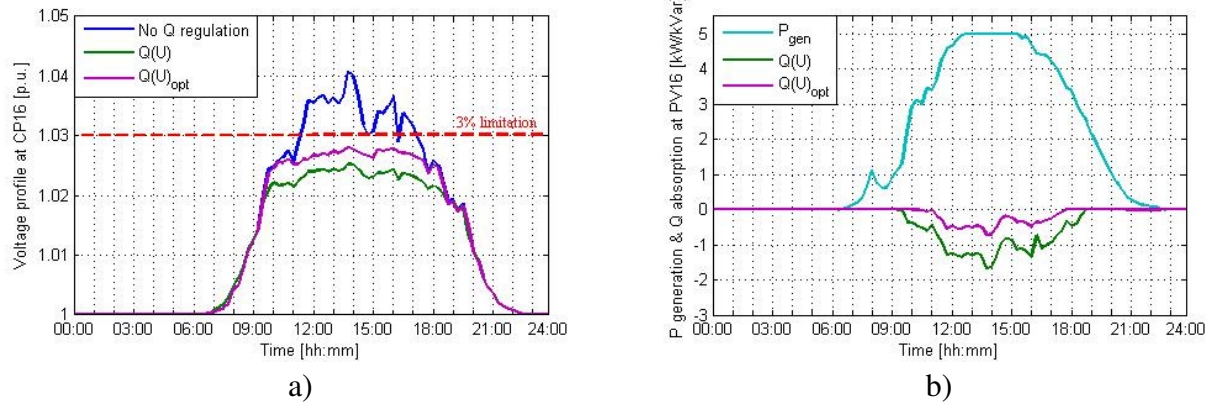


Figure 4-5 PV16 system analysis a) Voltage levels with and without regulation methods b) Active power generation and reactive power consumed using regulation methods

The analysis of the simulation results continue with the PV systems located at the end of the two sub-feeders - PV15 and PV18 (Figure 4-6 and Figure 4-7).

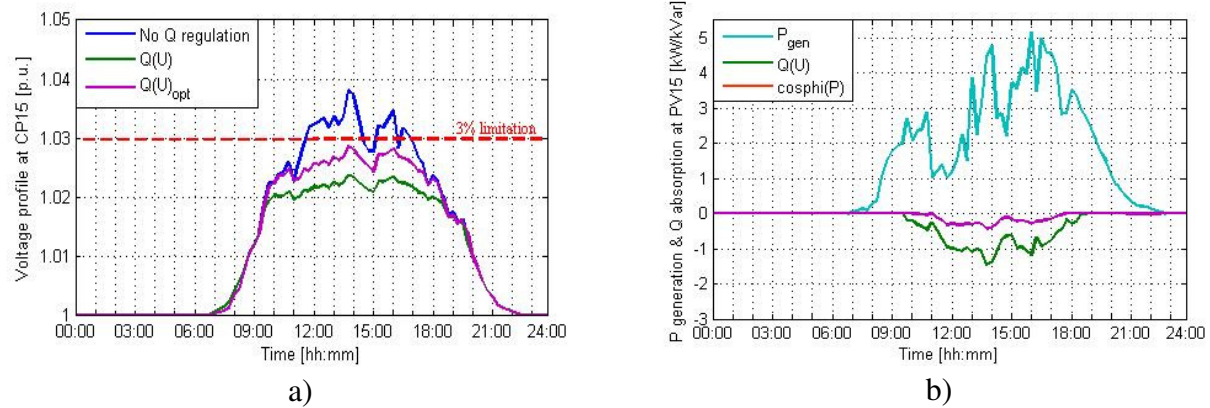


Figure 4-6 PV15 system analysis a) Voltage levels with and without regulation methods b) Active power generation and reactive power consumed using regulation methods

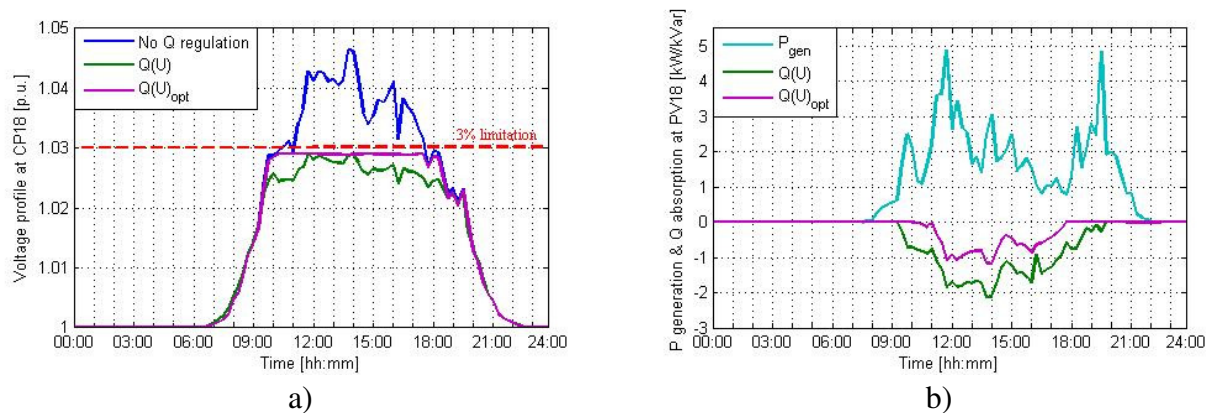


Figure 4-7 PV18 system analysis a) Voltage levels with and without regulation methods b) Active power generation and reactive power consumed using regulation methods

It can be noticed that the Q(U) algorithm absorbs unnecessary amounts of reactive power to perform the voltage regulation process. Lower levels of reactive power are possible when using the optimized Q(U) algorithm because these references are calculated based on the information gathered from all the PV systems in the network and it also considers the impedance of the cables between them.

The limitation of the voltage profile from Figure 4-7a) when using the optimized Q(U) method is performed by the inequality constraint ( $h_1$ ) which is also responsible for keeping the voltage at a constant value of 1.029 p.u. between 10:00 and 18:00.

Figure 4-8 presents the total active power losses before and after performing the Q(U) optimized algorithm.

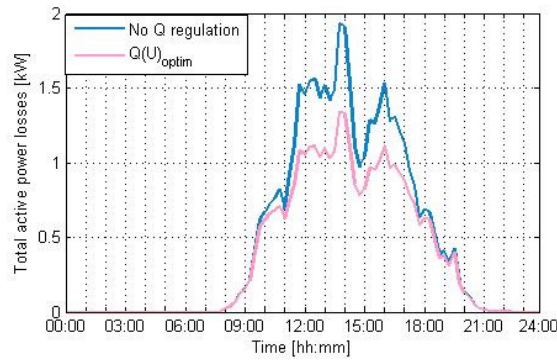


Figure 4-8 Total active power losses in the network

Besides the optimization of the reactive power reference, the proposed algorithm presents the benefit of minimizing the line losses. This is achieved because the optimization algorithm uses the load flow equations as equality constraints and performs the balancing of the power transfer in the network.

Due to the fact that the optimized Q(U) method is absorbing less reactive power than the Q(U) method, it can be stated that the transformer does not exceed the 100% loading in this case also. In addition, the optimized Q(U) method presents the advantage of less stressing the transformer.

## 4.4 Discussions

The best candidate from the regulation strategies proposed by the German GC, Q(U) was compared with the optimized algorithm. Their performance was evaluated based on their ability to maintain the voltage within limits and to minimize the reactive power absorption.

The main difference between the two strategies is the fact that while for the first one, each PV inverter absorbs a calculated value of reactive power corresponding to its local voltage magnitude, for the second strategy, the amount of reactive power values are computed based on all the PCC voltages of the network. In consequence, the optimized Q(U) algorithm makes the LV network more flexible in terms of connecting more PV systems.



Even though the voltage levels using the optimized Q(U) method are higher, but within limits compared to the voltage using the Q(U) algorithm, the benefit of the optimized method is the minimization of the reactive power absorption while the PV generators maintain their operation in MPPT.

Other benefits of the optimized Q(U) method over the classical Q(U) are the minimization of the line losses and lower transformer loading.

Both methods were implemented on a LV network and analyzed from different points of view. All the results and discussions conclude that the optimized Q(U) algorithm has improved the classical Q(U) method proposed by the new German GC VDE-AR-N 4105.





# Chapter 5      Voltage regulation strategies using the communication concept

*The chapter presents an overview of the communication series IEC 61850 and a general description of the information model. Further on, the experimental setup is described along with the implementation and validation of the communication concept.*

## **5.1 Overview of communication protocols IEC 61850**

### **5.1.1 Purpose**

The rapid growth of PV penetration lead to the necessity of developing a modernized electricity delivery system. The technology referred to as Smart Grid aims to enhance the existing distributed systems and the operation of all its interconnected elements in terms of reliability, efficiency and costs [8]. The most important characteristic of this concept is the two-way flow of electricity and information which were developed to provide reliable and high-quality electric power to comply with customer demands. This process implies changing the control and dealing with a two-way data information exchange system which will enable the accommodation of DG without affecting the efficiency of the power flow. The key element for successful implementation of the Smart Grid is designing a system architecture that complies with all the requirements [63].

The communication between the interconnected IEDs within a substation is enabled by the IEC 61850 standard. The communication is possible by means of defining standard object models for the IEDs and all the functions within a Substation Automation System (SAS). The idea of developing an international standard came due to the existence of a wide variety of inverters and communication techniques that needed other equipment to be compatible among each other.

The goal of this coordinate control is to increase the efficiency of managing operations and maintenance with minimal human intervention. This development was based on the intelligent functionalities of the inverters which have the capabilities of being controlled from external devices. The additional smart function along with the communication capability makes the inverters an important component of the distributed system. Besides the benefit of interoperability between inverters from different vendors, there is the “plug’n play” function. This means that the inverters are self-describing devices and whenever they are connected, their description and capabilities can be discovered with no need for datasheets.

## 5.1.2 Parts

Figure 5-1 presents all the parts that compose the communication standard IEC 61850 and their relationship among each other [64].

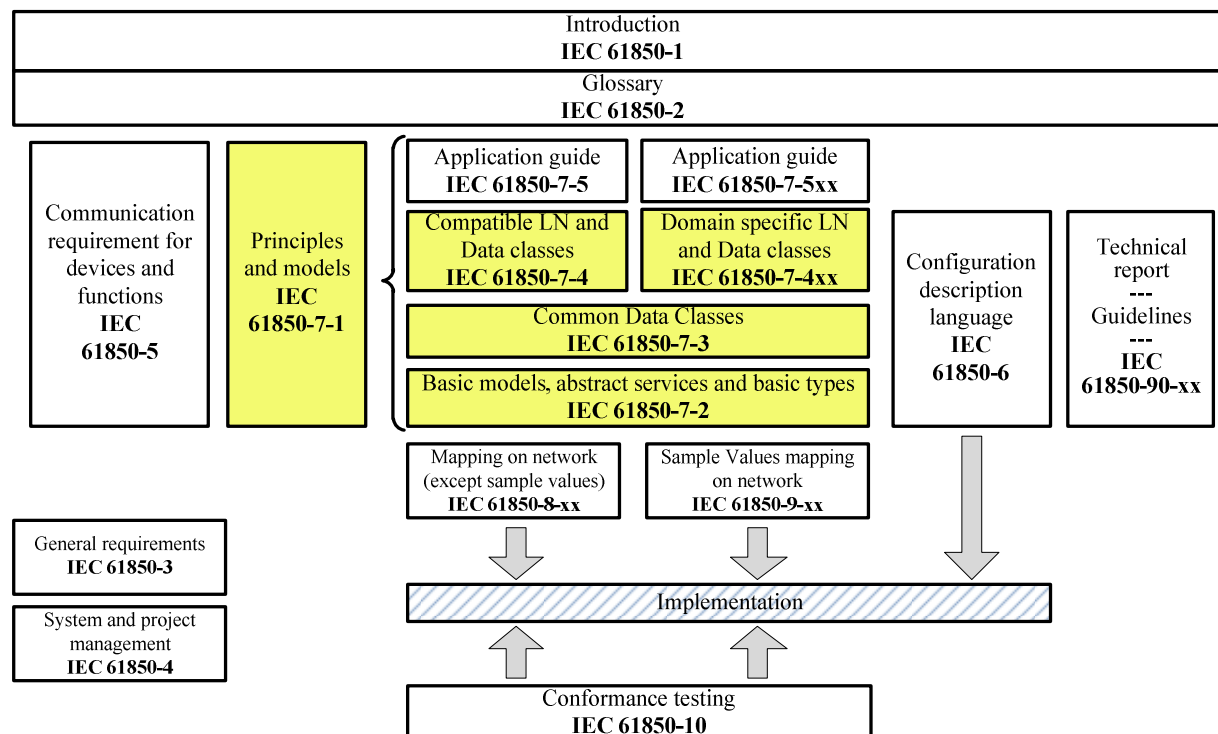


Figure 5-1 Relations between IEC 61850 series [64]

Although there are 10 sets of documents, the most important content and also which will be the focus of this chapter is comprised in 7-x series [65]:

- IEC 61850-7-1: Principles and models [64]
- IEC 61850-7-2: Abstract Communication Service Interface [66]
- IEC 61850-7-3: Common Data Classes (CDCs) [67]
- IEC 61850-7-4: Compatible logical node classes and data classes [68]
- IEC 61850-7-420: Distributed energy resources (DER) logical nodes [69]

The main function in SASs is the ability to model the information in devices and the communication services necessary to access and modify the respective data. The 7-xx series describes how to standardize the communication functions among the devices in a SAS. Part 7-2 presents how to access the functions to model the information of IEDs and the services for information exchange. Part 7-3 lists the commonly used information composed by the common data classes and attribute types of the Logical Nodes (LN) and the data classes. Specific information models about data classes are found in part 7-4. LDs and LNs are the fundamental components used to describe and model real systems and their functionalities. The scope of part 7-420 is to model the LNs specific to Distributed Energy Resources (DER) applications [64, 65].

### 5.1.3 Modeling concept

#### Information model

The subchapter presents the modeling approach of a circuit breaker to understand how to define the information of a real device to the corresponding virtual world of IEC 61850. In order to properly exchange data, a well-defined information model of the circuit breaker is necessary. The IEC 61850 encourages an easier approach of decomposing the functions into smaller entities to describe the data model and the services to exchange information.

The main entity is called Logical Device and it is formed by several defined and modeled LNs. An important feature to know is the fact that a LD is always implemented in only one IED which means that it will not contain LNs from other devices.

The general structure of the information model of a LN is presented in Figure 5-2. The semantic of a LN is composed of data and data attributes (DAs) organized in a hierarchical structure [64].

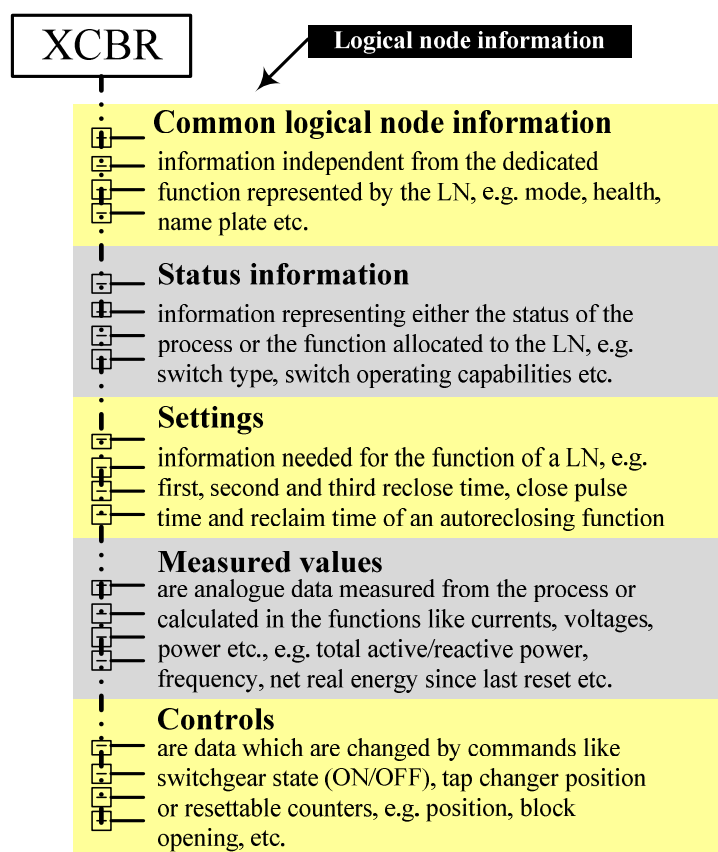


Figure 5-2 Logical nodes information categories [64]

The second entity is the LN which, in this case, is the circuit breaker with the corresponding class XCBR defined in part 7-4. Depending on the functionalities of a device, the defined LN contains the information model with the corresponding data, DAs and the services of data exchange.

For example, the position Pos of the circuit breaker can be defined as data consisting of DAs gathered into three sets: status (or measured/metered values, or settings), substitution and configuration, description and extension. An example of DA is Pos.stVal and it represents the position of the circuit breaker (intermediary-state, on, off or bad-state). The position Pos is integrated in the “controls” category which means it can access the control service. It is important to understand that the control services are not like the DAs and they are available only when the command is executed.

A more detailed description of the circuit breaker which contains more examples for the DAs and the service parameters can be found in Figure 5-3.

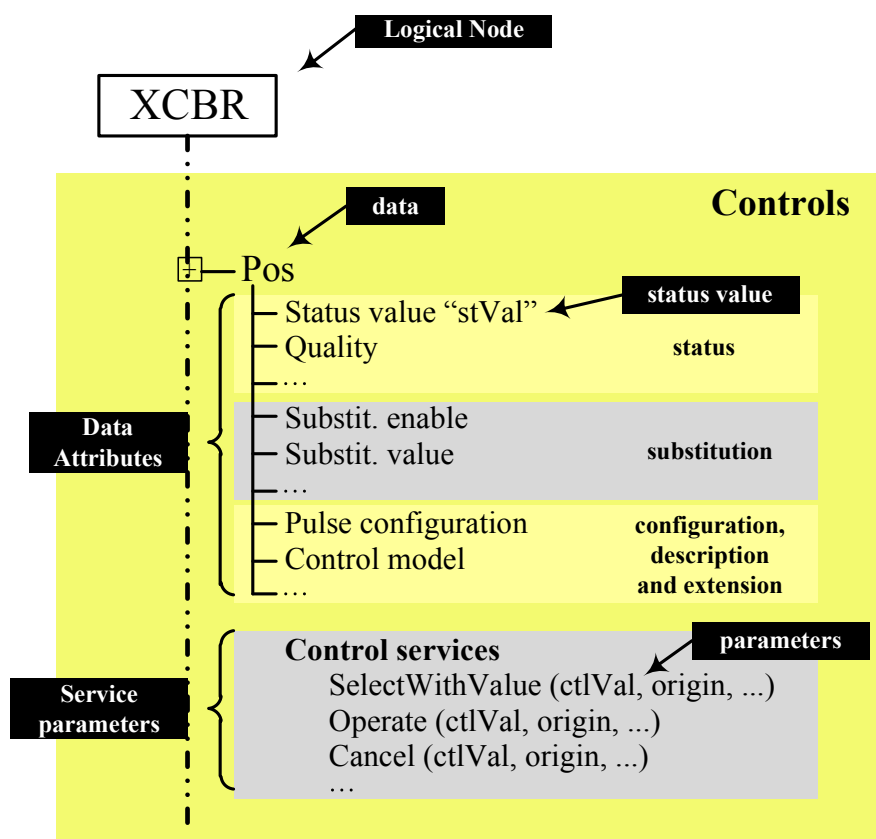


Figure 5-3 Information model for the circuit breaker [64]

The DAs are defined by reserved attribute name and type. All the attribute names have specific semantic which are available in IEC 681850-7-3. In Table 5-1, an example of attribute name and type along with the corresponding semantics are shown.

Table 5-1 Data information example – attribute name, type and semantic [64]

Attribute name	Attribute type	Semantics
stVal	CODED ENUM	Status value of the data
ctlModel	CtlModels	Configuration information about the control model

The data model and the services for information exchange configured in the LNs is the main feature to achieve interoperability in SASs. Therefore, it is very important to properly configure each set of data of the considered devices.

The IEC 61850 series are based on the object oriented approach which means it considers the use of data objects (DOs) that consists of data structures and fields together with their interactions. For each data, a corresponding reference is formed to provide the path to access the information. The object oriented approach is detailed in Figure 5-4 using the circuit breaker as example.

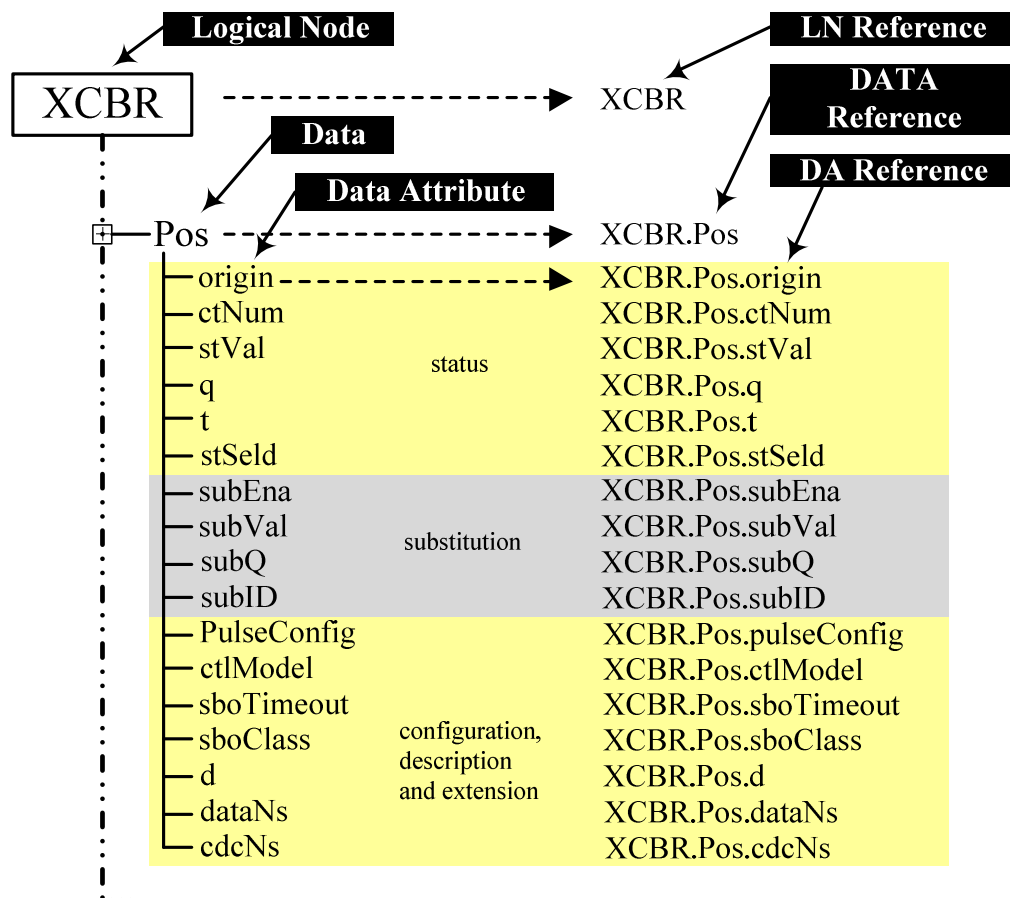


Figure 5-4 XCBR class tree information model [64]

In this way, the information exchange services can access the DAs from the hierarchical tree. For example, XCBR.Pos.ctlModel defines the control service configured to report when the circuit breaker changes its state (status information -> XCBR.Pos.stVal).

### Services model

The services used for information exchange between IEDs or between an IED and a control center of a power utility are presented in Figure 5-5 and categorized in IEC 61850-7-2.

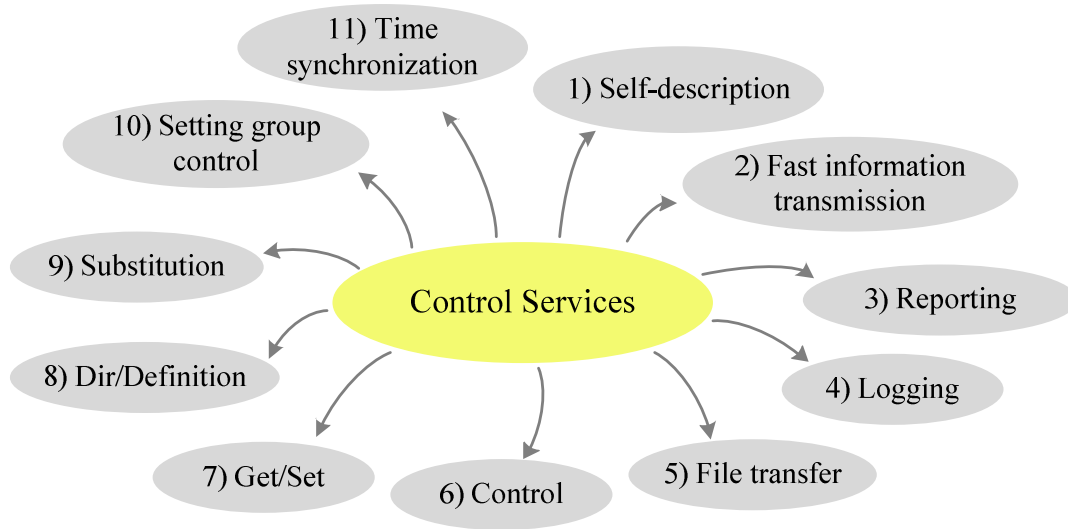


Figure 5-5 Control services provided by IEC 61850-7-2 [64]

The management of the IEC 61850 services from Figure 5-5 is explained as follows [64]:

- 1) Self-description - retrieve data model of a device using GetDirectory service
- 2) Information exchange provided by:
  - Generic Object Oriented Substation Events (GOOSE) - fast and reliable transmission of time critical information (e.g. status change, trips etc.)
  - Sample Value (SV) – fast transmission of synchronized stream of sample values (the response time is 3 ms)
- 3) Report any set of data (DAs) – e.g. report of status value or a periodical event (cyclic or event triggered operation)
- 4) Logging and retrieving sets of data (DAs) – the local storage of events or other historical data (cyclic or event triggered operation)
- 5) File transfer: for configuration, disturbance recording or historical data
- 6) Control – describes the services to control (e.g. devices or parameter setting groups)
- 7) Get/Set – read/write data and data set values, such as the value of a DA
- 8) Dir/Definition – to retrieve directory information of data and its definition
- 9) Substitution – used to replace a data value with a fixed one
- 10) Setting group control – handling and setting of a consistent set of values
- 11) Time/Time synchronization – accurate time is provided to services that need synchronization

Figure 5-6 presents the hierarchically management of the services corresponding to each information model level (server, LD and LN).

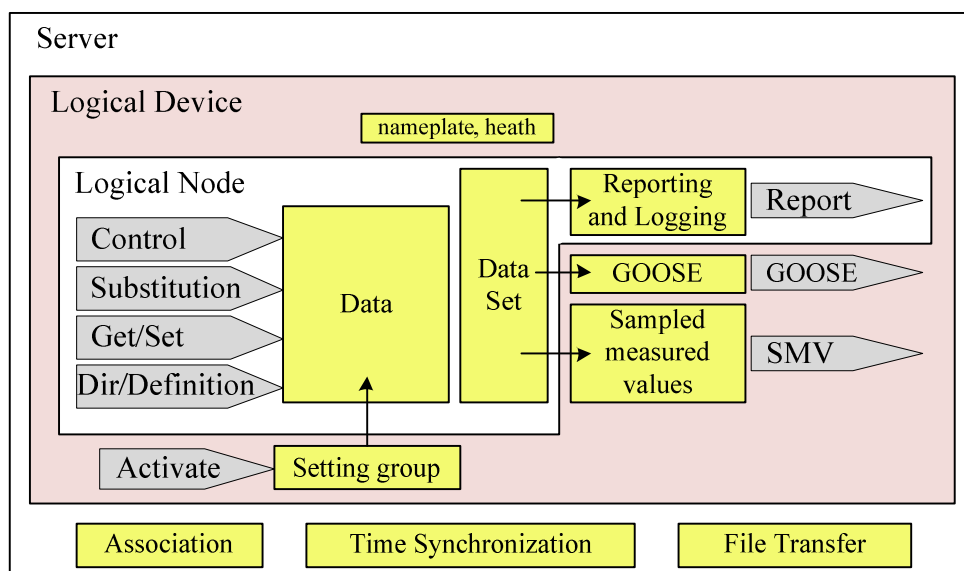


Figure 5-6 Data services specific to hierarchy levels [64]

At LN level, the services implemented have the ability to control the data in a device. Besides the control, there are other services that operate on data such as: substitution, Get/Set and Dir/Definition using the GetDataDirectory and GetDataDefinition functions. Inside the LN, data can be grouped into data sets that can use the reporting or logging services to be immediately reported or stored for later use.

At LD level, the additional services are GOOSE, SV and setting group. The LNs are grouped in the LD based on their common features to easier implement the services among them. One of the most important features at LD level is the self-description as all the information of the device can be accessed from its configuration without the need for datasheets.

At server level, the services offer mechanisms to connect the devices as well as maintaining it, the accurate time for the synchronization of other services, for example SV. Also the file transfer service is available at this level which means the possibility to exchange data blocks such as programs.

### Communication services mapping

In order to implement the information exchange model, the LDs are mapped to the specific communication services presented in Figure 5-7. GOOSE and SV bypass the TCP/IP protocol to transmit fast information. For example, if the status of a device has changed, a GOOSE message can be send. The device will continue sending the message with a long cycle time in case there are recently activated other devices that depend on the transmitted information. The Manufacturing Message Specification (MMS) protocol provides specific functions such as information modeling methods and services necessary to reach interoperability between IEDs. The Simple Network Time Protocol (SNTP) is used to synchronize the IEDs within one network. The last protocol, SV is used to transmit fast and synchronized set of information in the form of

sampled values. Further details about specific communication service mapping (SCSM) can be found in IEC 61850-8-1 and IEC 61850-9-2 [70, 71].

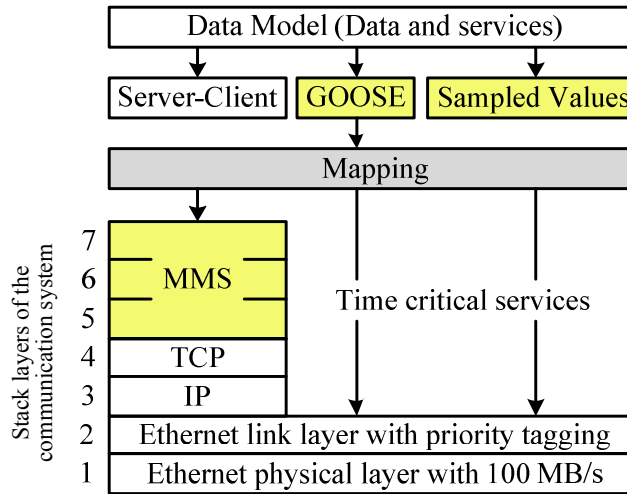


Figure 5-7 Data model mapped to specific communication services [71]

Throughout this chapter, the general functions to implement the communication concept were explained using as example a circuit breaker. Figure 5-8 presents the summary of the process which it can be divided into three main steps [64]:

- Information model – consisting of the defined LNs and data
- Information exchange – executed by specific control services
- Mapping to communication services

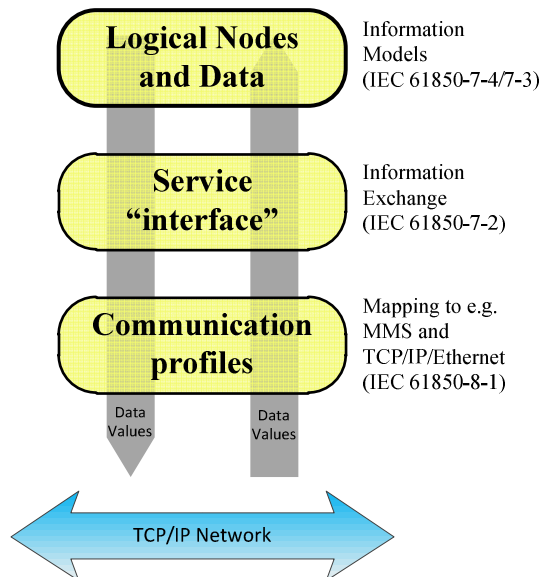


Figure 5-8 Implementation summary [64]



### 5.1.4 Server/Client architecture

A server/client model, shown in Figure 5-9, provides a bi-directional information exchange between the client, which sends a request, and the server, which sends the reply. This type of architecture is useful when more clients, in our case the PV systems in the network, need to send the information to a centralized server and wait for the reply with the necessary instructions to be processed. After sending the request, the client will be blocked until it receives the reply from the server [65].

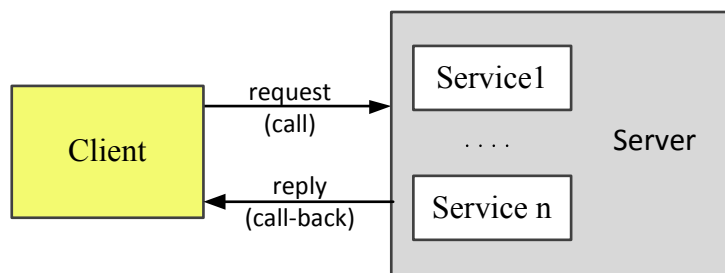


Figure 5-9 General Server/Client Architecture

The TCP protocol is used to transmit the information between server and client; therefore the IP addresses must also be included. The integration of a server/client application is possible with the use of the Protocol Integration Stack (PIS). PIS uses the configured file of an IED made using a System Configuration description Language (SCL) to map the IEC 61850 objects to the server/client application.

### 5.1.5 Server/Client modeling

The mapping mechanism between a user application and the IEC 61850 stack is done by the Application Programming Interface (API), as shown in Figure 5-10 [72].

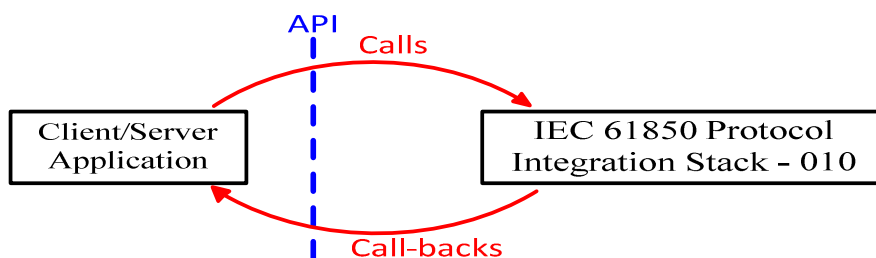


Figure 5-10 Mapping of the user application to IEC 61850 [72]

The information model of a server or client is configured separately in a SCL file which, besides the data and DAs, contains also the IP addresses. The SCL file uses Private Elements that are used to link the server/client application objects with the IEC 61850 DAs. Server/client application objects are part of the user application and they can be read, written and updated by the call-back functions.

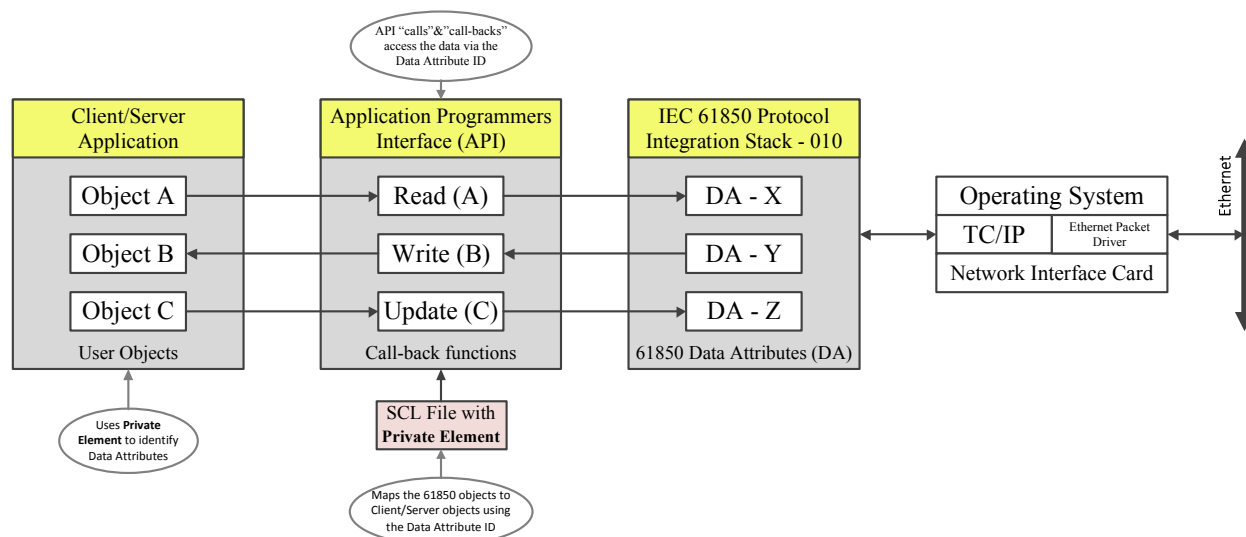


Figure 5-11 Context diagram [72]

Figure 5-12 presents the basic functions used for data exchange between PIS-010 and client/server application.

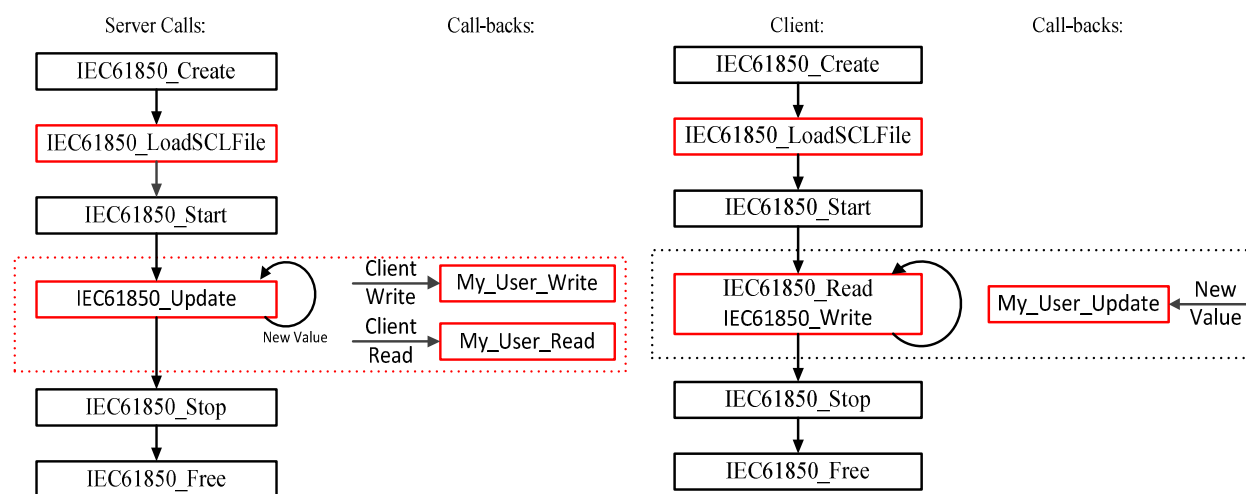


Figure 5-12 Server/client management – API functions [72]

The call and call-back functions for client and server are [72]:

- IEC61850\_Create – used to create a client or server object
- IEC61850\_LoadSCLFile – load the SCL file to get the configuration of server or client
- IEC61850\_Start – start the server or client
- IEC61850\_Read – read the value of a specified DA
- IEC61850\_Write – write the value to a specified DA
- IEC61850\_Update – update the value of a specified DA
- IEC61850\_Stop – stop the server or client

- IEC61850\_Free – delete a server or client object created
- Using the above mentioned functions, the server and client source codes can be created.

## 5.2 Implementation of the IEC 61850 concept

The diagram for implementing the IEC 61850 concept on the LV network chosen in Chapter 3 is presented in Figure 5-13. The theory presented in the previous subchapter is used to configure the IEDs which are in this case the PV inverters. Each PV system will send its voltage information to the control server which will calculate and send back to the inverters the optimal reactive power reference using the improved Q(U) algorithm described in Chapter 4. Additional functions for inverters such as reset, trip check, start and stop are implemented locally by each inverter.

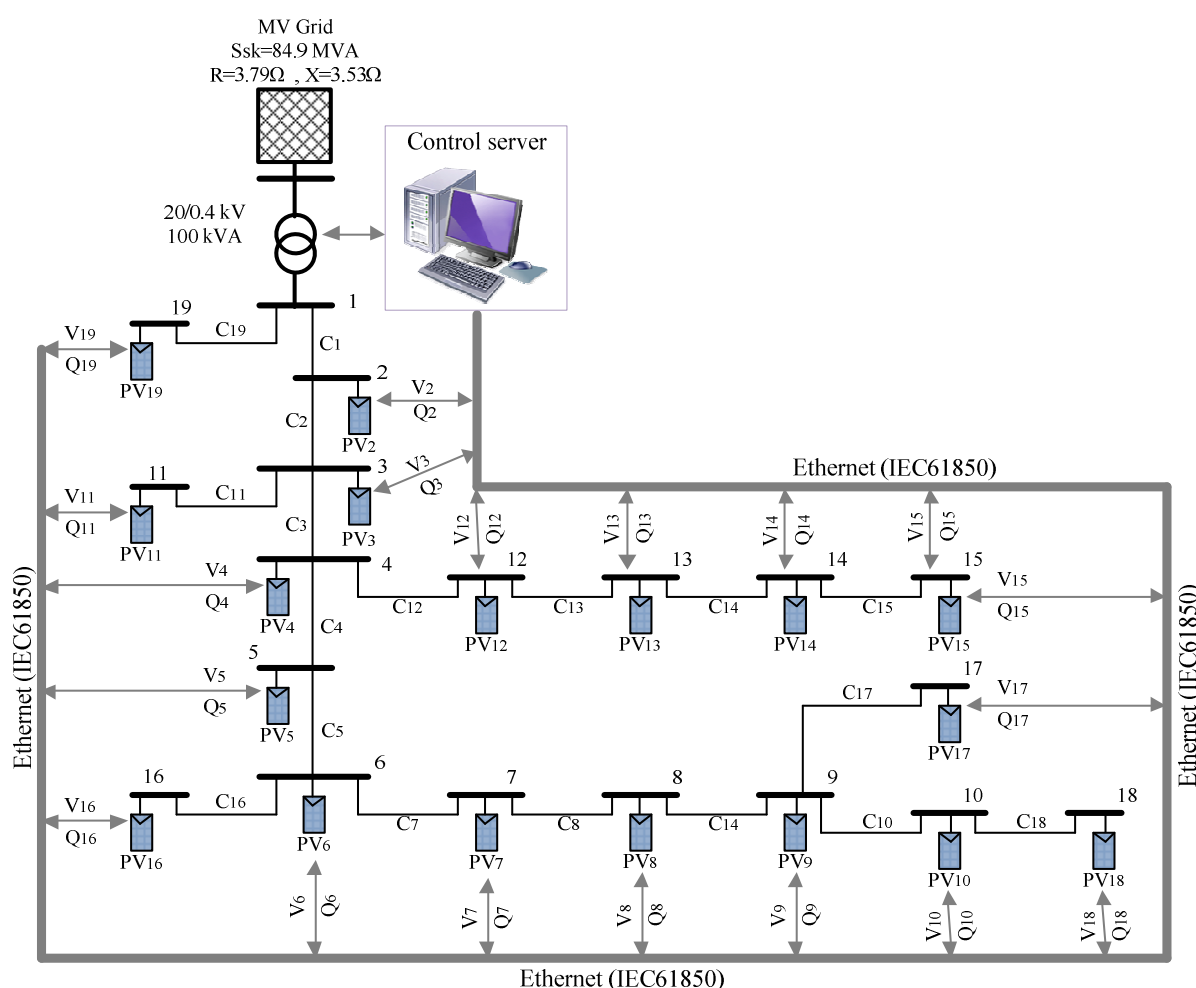


Figure 5-13 LV network with the IEC 61850 communication concept

Each of the 18 PV systems from Figure 5-13 has the configuration presented in Figure 5-14.

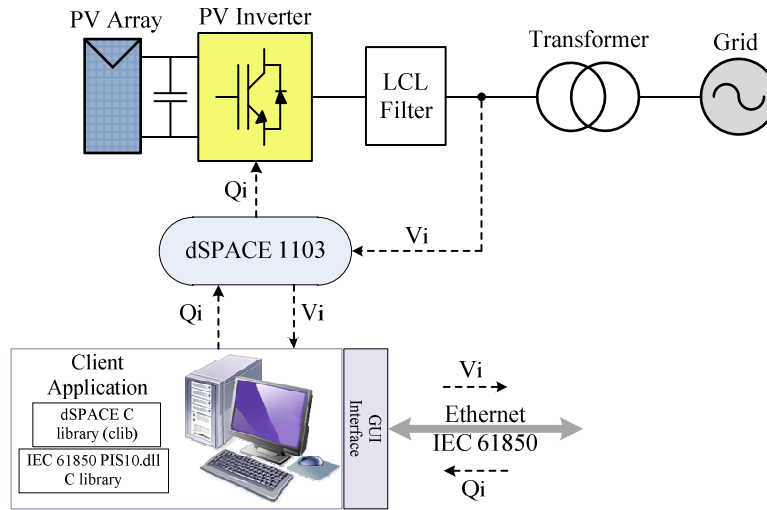


Figure 5-14 PV system configuration

Further on in this chapter, the way data from dSPACE can be accessed and modified will be presented. The configuration of the IEDs will be explained and the source code for server/client application will be developed. Using this data, it will be possible to transmit the voltage information at the CPs of the PV systems and to receive reactive power reference values for the PV inverters using Ethernet.

### 5.2.1 C Interface Library (CLIB)

CLIB is a library composed of a set of basic functions and used to access the memory of the dSPACE processor [73]. In other words, it accesses the registers with the necessary information about the signals and parameters to be transmitted to and from the central server. CLIB offers also the possibility of creating an interface; therefore eliminating the need for Control Desk.

A host application does not access the dSPACE hardware directly; it uses functions to call the DSP Device Driver which controls the communication with the hardware.

The main steps for an application are [73]:

#### Step 1. Register an application

Each application must be first registered with the DSP Device Driver. Up to 50 applications can be registered with the current version of CLIB (CLIB 4) with the following syntax:

```
DS_register_host_app("app_name");
```

The *app\_name* parameter can be changed by user with the desired name of the application.

### Step 2. Select and access a board

First, a parameter is required to specify which processor board to access. In this case, the controller board of the dSPACE from the laboratory setup is DS1103, therefore *board\_name* = DS1103.

In order to access a board, its index must be retrieved from the DSP Device Driver using the following function:

```
DS_board_index("board_name",&board_index);
```

Further information about the selected board, such as name or type, can be found using the *board\_index* parameter and the function:

```
DS_board_spec(board_index,&board);
```

The parameter *board* will contain the information and to retrieve, for example, the name or the type of the board, the following syntax is used: *board.board\_name* or *board.board\_type*.

### Step 3. Allocate a board resource

Allocation of resources refers to a certain amount of the board memory which can be controlled by the DSP Device Driver and within this section applications can allocate a separate block of memory.

```
DS_alloc_mem(board_index,required_size,&memory_address);
```

The value of *required\_size* parameter contains the number of required bytes or words to be allocated for the current application.

### Step 4. Free a board resource

After the work with the allocated memory block is finished, it is necessary to free the memory for other applications to use it. The parameters for the functions are the board index and the start address to free the memory block.

```
DS_free_mem(board_index,&memory_address);
```

### Step 5. Unregister application

If errors are found in the source code and before exiting, each application should be unregistered in order to free all the internal resources allocated for that application.

```
DS_unregister_host_app();
```

The above functions were used when the application necessary for this project was developed along with some additional basic functions to access, read and write specific parameters from the dSPACE. The additional functions used are:

1) Get parameter/signal address

To access the signals and parameters from the MATLAB model of the PV system presented in Figure 5-14 that will be used later, their addresses have to be retrieved and stored for all time use.

*DS\_get\_var\_addr(board\_index,"Specific\_signal",&Address\_Signal);*

In other words, the function *DS\_get\_var\_addr* reads the signal or parameter from the MATLAB model *Specific\_signal* and retrieves and stores its address into *Address\_Signal*.

2) Read parameter/signal value

Using the parameter/signal address retrieved with the previous function, the value corresponding to the respective address can be read.

*DS\_read\_64(board\_index,Address\_Signal,count,&Value\_Signal);*

Therefore, a block of *count* 64-bit values is read from the board memory starting at the given address *Address\_Signal* and transferred to the buffer referenced by *Value\_Signal*.

3) Write parameter value

This function is specific only to parameters, as signals cannot be written only read.

*DS\_write\_64(board\_index,Address\_Signal,count,&Value\_Signal);*

The *count* values referenced by *Value\_Signal* is written to the board memory at the specific address given by the parameter *Address\_Signal*.

The entire source code developed for the application referred to in Figure 5-14 is available in Appendix G.

## **5.2.2 IEC 61850 – IED configuration**

To configure the information model of an IED containing the specific data and the desired services, a configuration tool was necessary. The chosen tool is ICD Designer provided by SystemCORP. Using this tool, the LDs, LNs, data objects with the corresponding DAs and services were configured in a SCL file. Furthermore, the SCL file contains the IP addresses of the server and client applications. The SystemCorp ICD Designer user manual for IED configuration can be found in [74].

The following functions were assigned to the IED model [75]:

- DC link voltage measurement
- DC current measurement
- Inverter reset
- Inverter trip
- Inverter set active power reference
- Inverter set reactive power reference
- Phase A voltage measurement

- Phase B measurement

Further, the corresponding LNs for the above mentioned functions are chosen from the predefined list available in the IEC 61850 standard. Three LNs are considered:

- MMDC: for the DC measurements with DOs that correspond to “measured values” from the MV Common Data Class (CDC) [68]. The DC voltage and current are analogue signals and they are configured as DAs.
- MMXU: for the AC measurements with DOs for “phase to ground/neutral related measured value” from the WYE CDC [68].
- ZINV: - one set of DOs for the trip and reset function of the inverter available in the “single point status” (SPS) CDC.  
- one set of DOs for the P and Q references defined in the “analogue setting” (ASG) CDC [69].

The semantic of the above chosen LNs is explained in Table 5-2.

Table 5-2 Semantic of analyzed LNs [75]

LN	DO	CDC	Explanation	DA	Type or Value
MMDC	Vol	MV	DC voltage	mag	Analogue value
	Amp	MV	DC current	mag	Analogue value
MMXU	PhV1	WYE	Phase to ground AC voltage	cVal.mag	Analogue value
	A2	WYE	Phase current	cVal.mag	Analogue value
ZINV	Stdbyl	SPS	Inverter stand-by status	stVal	Boolean
	Stdbyl2	SPS	Inverter stand-by status	stVal	Boolean
	OutVSet	ASG	Active power set-point	setMag	INT32
	OutWSet	ASG	Reactive power set-point	setMag	INT32

The main drawback when using the tool to configure the IED is the fact that not all the LNs predefined in IEC 61850 are provided by the ICD Designer. For example, the LNs MMDC and ZINV are not available in the configuration tool, thus some additional assignments have to be made.

The LNs that are not provided by the configuration tool can be replaced by others with common functionalities and similar semantics from the CDCs. In this case, the MMDC LN was replaced by the “generic process I/O” (GGIO) LN with the corresponding DOs for DC voltage and current measurements (AnIn1 and AnIn2).

The ZINV LN was replaced by the “generic automatic process control” (GAPC) LN with the corresponding DOs (StrVal1 and StrVal2) for the inverter trip and reset functions.

The semantic containing the above mentioned changes regarding the LNs are available in Table 5-3.

Table 5-3 Modified semantic of LNs [75]

LN	DO	CDC	Explanation	DA	Type or Value
GGIO	AnIn1	MV	DC voltage	mag	Analogue value
	AnIn2	MV	DC current	mag	Analogue value
MMXU	PhV1	WYE	Phase to ground AC voltage	cVal.mag	Analogue value
	A2	WYE	Phase current	cVal.mag	Analogue value
GAPC	SPCSO1	SPC	Inverter stand-by status	stVal	Boolean
	SPCSO2	SPC	Inverter stand-by status	stVal	Boolean
	StrVal1	ASG	Active power set-point	setMag	INT32
	StrVal2	ASG	Reactive power set-point	setMag	INT32

After the information model is defined, the next step consists of the actual configuration process using the ICD Designer based on SCL XML language. The following steps are considered:

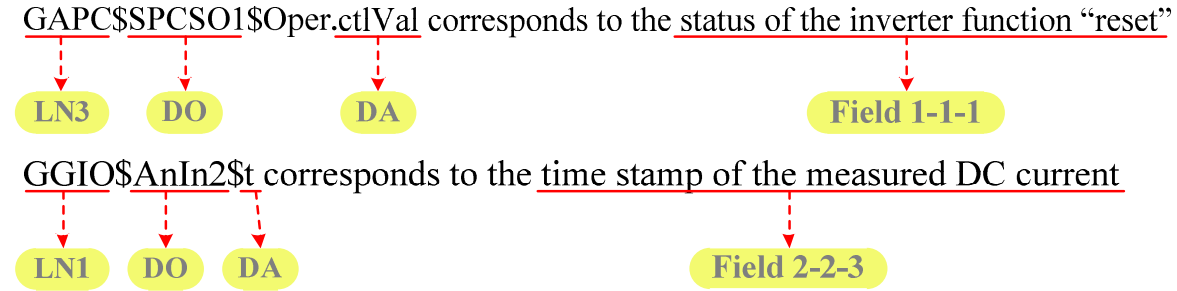
- 1) Each LN is configured with the corresponding DOs and DAs from Table 5-3.
- 2) Field attributes are assigned and used to identify the mapping between the user DOs and IEC 61850 DAs. The meaning and content of the field attributed are shown in Table 5-4.
- 3) The desired services for the information exchange have to be configured. The ICD Designer tool provides the configuration for the get/set service. To implement other services such as: reporting, logging, GOOSE or SMV, the logical node zero (LLN0) is used.
- 4) For each service a corresponding dataset is defined in LLN0. The datasets include the DAs with the following features: common functionalities and same functional constraints (FC). Two datasets were created; one for all the measurements and one for the trip function of the inverter.
- 5) Two control blocks are created in the LLN0: one unbuffered report control block for the measurement dataset and one GOOSE control block for the inverter trip dataset.
- 6) The IP was configured for the control services to function

Table 5-4 Field attributes related to DAs (API mapping) [75]

Values	Field 1 [Inverter functions]		Field 2 [Measurements]	Field 3 [Values]
	Descriptions:			
1	Reset inverter	Voltage	Inverter functions	Status value
2	Trip inverter	Current	DC measurements	Quality
3	Set P ref		AC measurements	Time stamp
4	Set Q ref		-	



Some examples are explained to understand how to interpret the hierarchical model of field attribution using Table 5-3 and Table 5-4:



The configured services of the IED are:

- URCB for measurements
- GOOSE to transmit the inverter trip signal
- Get/Set to transmit the inverter enable signal and to set the P,Q references

## 5.3 Experimental application of IEC 61850 standard

### 5.3.1 Laboratory setup

The experimental setup structure used in the laboratory is presented in Figure 5-15.

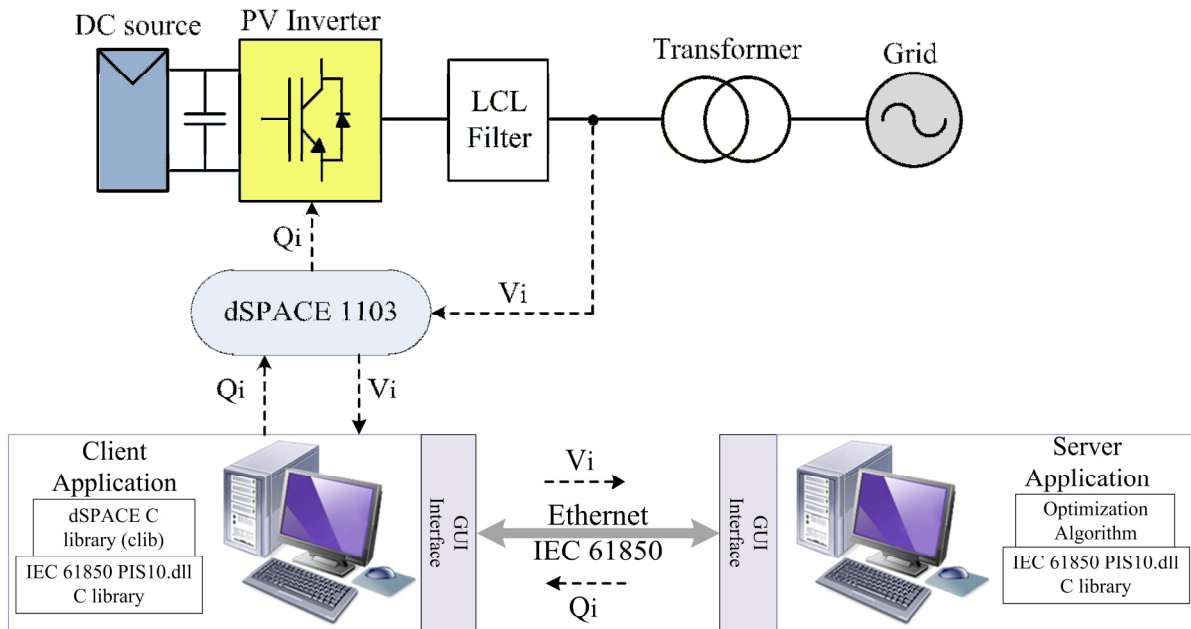


Figure 5-15 Description of laboratory setup

The main components of the system are:

- DC source
- Inverter (VLT Danfoss Drive – 2.3 kW/400V)
- LCL filter
- Transformer (1:1)
- Grid
- Measurement boxes for current and voltage (LEM modules)
- dSPACE 1103 control system
- CLIB 4

The control of the PV inverter is made through the Interface and Protection Card (IPC2) of the dSPACE system. The PC connected to the dSPACE holds the CLIB which can access the desired parameters. Additional functions for the inverter were implemented in the CLIB application. First, a grid check will be performed, which consists of reading the value from dSPACE of the grid voltage magnitude. If the value is within a specific range the application will proceed, otherwise it will wait for the grid. Next, a function to reset the PLL is made and one to check whenever the inverter has tripped. In case of trip, the inverter will be reset with the corresponding function. If no problems occurred so far, the application continues with the inverter start function. Signals and parameters are read from the dSPACE processor board using the CLIB functions. In this case, the grid voltage/ current/ power and DC voltage/ current/ power are read to gather information to monitor the PV system.

First step in implementing the communication protocol was to send a parameter value from the server to the client application. In order to visualize the effects of the transmitted information, both client and server have a console application. The parameter is first read in the server application when the value is given in the console and then transmitted to the client. When the value reaches the client, the console application will take over and using a write function will write the parameter to the dSPACE at the desired address.

### 5.3.2 CLIB validation

Figure 5-16 presents the console application of the implemented CLIB source code.

```

C:\Student\Ana\TestAppCLIB\Debug\TestAppCLIB.exe
CLIB test application
1 → Board type = DS1103
2 → PLL was reset
3 → Grid check...
Grid on. Continue...
Grid voltage is 319.178655 U.
4 → Inverter checking...
Trip check...
Inverter interface problem. Check hardware!
5 → Inverter was reset
Trip check...
No trip detected
6 → Inverter is OFF. Please start the inverter
Inverter is ON!
Trip check...
No trip detected
PU system monitoring
7 → Udc348.732688
Idc0.003884
Urms221.315763
Irms0.157420
Previous DC voltage reference was 350.000000
8 → Write the new DC voltage reference =
400
New DC voltage value is 400.000000
Trip check...
No trip detected
9 → PU system monitoring
Udc399.502841
Idc0.003607
Urms222.227227
Irms0.167702
Trip check...
No trip detected
10 → Inverter is OFF!
End of application

```

Figure 5-16 Console application for CLIB source code

The CLIB application steps from Figure 5-16 are:

- 1) The processor board type is read, in this case is DC1103
- 2) The function to reset the PLL is called
- 3) The value of the grid voltage magnitude is checked to see if the grid is on. If on the application will continue with a display of the voltage value, otherwise it will wait for the grid for a period of time and close the application.
- 4) The trip check function is called here and also in other parts of this application. This is one of the most important functions because whenever the application reads a trip it will stop the inverter if it is enabled and perform the rest of the check functions before enabling it again.
- 5) The inverter is reset.
- 6) The status of the inverter is checked and enabled if no malfunctions are encountered.
- 7) The values of the grid voltage/current and DC voltage/current are read for a PV system monitoring. Only the sample of the signal read at that instance is displayed. For a continuous monitoring of the signals, a read loop can be implemented.
- 8) The initial DC voltage reference is read to be 350V. Next, the application allows the user to insert the desired new voltage reference and in this case is 400V. To check if the value was written at its corresponding address, the application calls the value at the address and displays it. As it can be seen in the console application, the new value of 400 V was successfully written.
- 9) The PV system monitoring is performed again with the new DC voltage value.
- 10) The inverter is stopped at the end of the application.

Another way to validate the CLIB application is to run the Control Desk in parallel. In Figure 5-17, the ControlDesk screen shot is presented. As it can be seen, the PLL is reset, there is no trip detected as the inverter was reset and the DC voltage reference of 400V was written to the dSPACE.

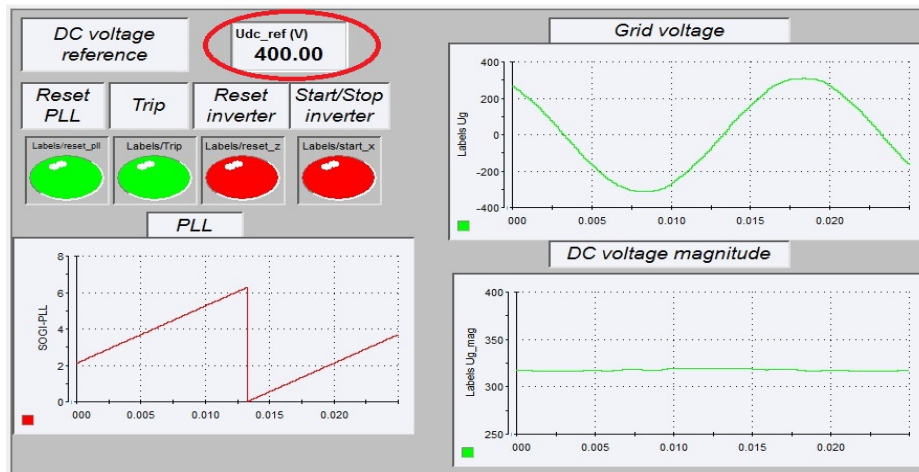


Figure 5-17 ControlDesk validation of CLIB application

### 5.3.3 ICD validation

The console application for both server and client is presented in Figure 5-18. This application only sends a parameter value from the server to the client using the exchange information services provided by IEC 61850: get/set and report control block services. The purpose of this simple application is to validate the data and services configuration of the IED. The communication between server and client is a success; therefore further DAs and services can be configured for multiple data transmission.

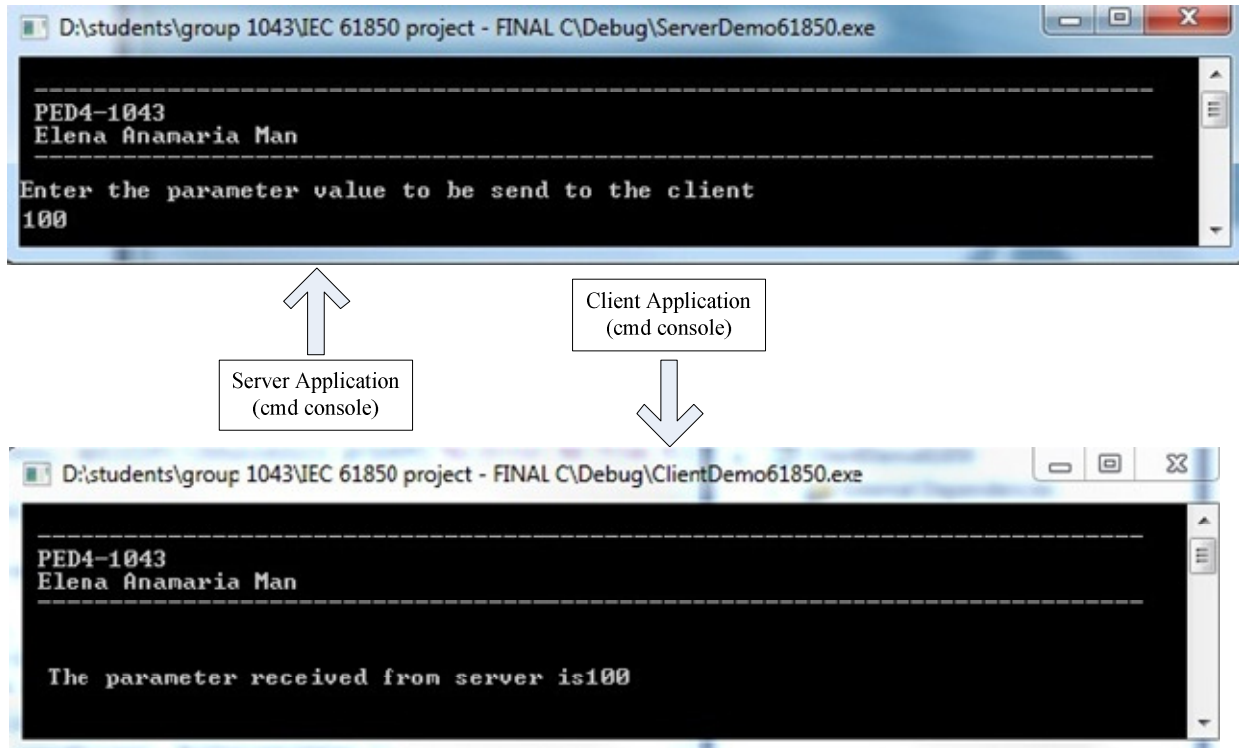


Figure 5-18 Server/Client application



# Chapter 6      Conclusions and future work

## 6.1 Conclusions

The focus of this report was on the voltage regulation methods for PV systems with ancillary services. The objectives were to model and implement the strategies proposed by the new German GC VDE-AR-N 4105 on a European LV benchmark grid. The performance of the two strategies was assessed in order to choose the best candidate in terms of maintaining the voltage at the CP between limits and to minimize the reactive power consumption. Results showed that both methods can keep the voltage at the CP below the 3% limit, but using the  $\cos\phi(P)$  strategy, more than needed reactive power was absorbed compared to  $Q(U)$ . The simulation results of Chapter 3 concluded that the  $Q(U)$  strategy followed best the requirements in terms of voltage stability and reactive power consumption.

The next objective was to develop an improved voltage regulation strategy able to dispatch the minimum amount of reactive power at each PV inverter to optimize the existing solution encouraged by the system operators. The method considers all the voltages at the CP of each grid connected PV system in the network and calculates the minimum absorption of reactive power. To develop such optimized control strategy, communication infrastructure is needed in order for the central controller to transmit the calculated values of reactive power for each PV inverter which participates in the voltage regulation process. The aim of the optimized algorithm was to use the IEC 61850 communication concept. The simulation results of the optimized  $Q(U)$  algorithm were presented and discussed. In conclusion, this algorithm presents the following improvements to the network: a better usage of the PV inverter capacity which leads to increased PV capacity in the network, lower transformer loading and lower network losses.

To experimentally test the communication concept on the laboratory setup, several applications were developed. The information model of the PV inverter was configured using a SCL file. To access the information from dSPACE, a CLIB application was necessary which was joint with the source code from IEC61850 to transmit or receive information. The CLIB application can run in parallel with the Control Desk, therefore it was used to validate the results and to see if the proper values were read/written from/to dSPACE.

## **6.2 Future work**

Because not all the goals of this project were accomplished, several tasks can be considered as future work:

- Graphical User Interface (GUI) can be developed for the CLIB application to facilitate the access to the functions.
- Only parameters from server to client were transmitted in the project, therefore it should be implemented and tested the client-server information exchange also.
- The optimization algorithm should be implemented on a central server and the communication should be tested on more than one PV inverter to assess the performance of the entire network.
- The European benchmark can be replaced with an actual network to analyze the voltage regulation methods.



## References

- [1] A. Timbus, "Grid Monitoring and Advanced Control of Distributed Power Generation Systems," 2007.
- [2] M. Rashid, *Power Electronics Handbook- Devices, Circuits and Applications*. 2011.
- [3] European Photovoltaic Industry Association, "Market Report 2011," 2012.
- [4] X. Yaosuo, D. Kurthakoti, G. Gerd, L. Mihalache, S. Sindhu and M. Madhav, "Towards Next Generation Photovoltaic Inverters," 2010.
- [5] European Photovoltaic Industry Association, "Solar generation 6. solar photovoltaic electricity empowering the world," 2011.
- [6] Electric Power Research Institute, "Solar Photovoltaics: Status, Costs, and Trends," 2009.
- [7] K. Budenbender, M. Braun, T. Stetz and P. Strauss, "Multifunctional PV systems offering additional functionalities and improving grid integration," vol. Volume 7, Number 2 (2011) Pages 109-128, 2011.
- [8] ABB, "IEC 61850: Special report," 2010.
- [9] A. Mohd, E. Ortjohann, A. Schmelter, N. Hamsic and D. Morton, "Challenges in integrating distributed energy storage systems into future smart grid," in *Industrial Electronics, 2008. ISIE 2008. IEEE International Symposium On*, 2008, pp. 1627-1632.
- [10] IMS Research Organization, "The World Market for PV Inverters 2011 Report," 2011.
- [11] IEA International Energy Agency, "Snapshot of international electricity utility activities; survey report of selected IEA countries between 1992 and 2010," .
- [12] A. S. Khalifa, "Control and Interfacing of Three Phase Grid Connected Photovoltaic Systems," 2010.
- [13] R. Teodorescu, P. Rodriguez, V. Benda, D. Sera and T. Kerekes, "Industrial/PhD course in photovoltaic power systems - in theory and practice," in Aalborg, Denmark, 2010, .
- [14] R. Teodorescu, M. Liserre and P. Rodriguez, *Grid Converters for Photovoltaic and Wind Power Systems*. 2011.
- [15] S. Evju, "Fundamentals of Grid Connected Photo-Voltaic Power Electronic Converter Design," 2007.

- [16] F. Blaabjerg, Zhe Chen and S. B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *Power Electronics, IEEE Transactions On*, vol. 19, pp. 1184-1194, 2004.
- [17] T. Kerekes, "Analysis and Modeling of Transformerless Photovoltaic Inverter Systems," 2009.
- [18] DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik im DIN und VDE, "Entwurf DIN VDE 0126-1-1 (VDE 0126 Teil 1-1)," 2005.
- [19] VDE-AR-N 4105, "Generators connected to the low-voltage distribution network - Technical requirements for the connection to and parallel operation with low-voltage distribution networks," 2011.
- [20] M. C. Benhabib, J. M. A. Myrzik and J. L. Duarte, "Harmonic effects caused by large scale PV installations in LV network," in *Electrical Power Quality and Utilisation, 2007. EPQU 2007. 9th International Conference On*, 2007, pp. 1-6.
- [21] F. Shahnian, A. Ghosh, G. Ledwich and F. Zare, "Voltage unbalance reduction in low voltage distribution networks with rooftop PVs," in *Universities Power Engineering Conference (AUPEC), 2010 20th Australasian*, 2010, pp. 1-5.
- [22] F. Shahnian, R. Majumder, A. Ghosh, G. Ledwich and F. Zare, "Sensitivity analysis of voltage imbalance in distribution networks with rooftop PVs," in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, pp. 1-8.
- [23] Prof. Dr. Ingo Stadler, "Study about international standards for the connection of small distributed generators to the power grid," 2011.
- [24] E. Paal, Z. Weitzl and C. S. Choi, "Grid management functions built in PV inverters for distributed power generation," in *Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference On*, 2011, pp. 2637-2644.
- [25] N. R. Ullah, T. Thiringer and D. Karlsson, "Voltage and Transient Stability Support by Wind Farms Complying With the E.ON Netz Grid Code," *Power Systems, IEEE Transactions On*, vol. 22, pp. 1647-1656, 2007.
- [26] R. A. Walling and K. Clark, "Grid support functions implemented in utility-scale PV systems," in *Transmission and Distribution Conference and Exposition, 2010 IEEE PES*, 2010, pp. 1-5.
- [27] Hernan Miranda, "State of the Art on: Grid Interactive Wind Converters," 2008.
- [28] EPIA (European Photovoltaic Industry Association), WIP, FIEC (the European Construction Industry Federation), AIE (the European Association of Electrical Contractors),

UIA-ARES (International Union of Architects)., "Recommendations for unified technical regulations for grid-connected PV systems," 2009.

[29] T. Degner, G. Arnold, M. Braun, D. Geibel, W. Heckmann and R. Brundlinger, "Utility-scale PV systems: grid connection requirements, test procedures and European harmonisation," 2009.

[30] CIGRE WG14.31, "CUSTOM POWER - STATE OF THE ART," 2000.

[31] E. Fuchs and M. Masoum, *Power Quality in Power Systems and Electrical Machines*. 2008.

[32] IEEE Standards Coordinating Committee 21 on Fuel Cells Photovoltaics, Dispersed Generation and Energy Storage, "IEEE standard 1547.2 for interconnecting distributed resources with electric power systems," 2008.

[33] A. Baghini, "Handbook of power quality," Wiley, 2008.

[34] M. Tsili, C. Patsiouras and S. Papathanassiou, "Grid code requirements for large wind farms: A review of technical regulations and available wind turbine technologies," .

[35] Commission of the European Communities - Directorate General Joint Research Centre (JRC) - Institute for Energy, "Research, methodologies and technologies for the effective development of pan-european key grid infrastructures to support the achievement of a reliable, competitive and sustainable electricity supply." 2009.

[36] Copper Development Association, "Voltage disturbances standard EN 50160," 2004.

[37] E. Acha, V. G. Agelidis, O. Anaya-Lara and T. Miller, *Power Electronic Control in Electrical Systems*. Oxford, UK: 2002.

[38] E. J. Coster, "Distribution Grid Operation Including Distributed Generation," 2010.

[39] P. Lyons, "Experimental Investigation and Evaluation of Future Active Distribution Networks," 2009.

[40] PV Upscale Report and Intelligent Energy Europe, "Utilities experience and perception of PV distributed generation," 2008.

[41] W. Christiansen and D. T. Johnsen, "Analysis of requirements in selected grid codes," 2006.

[42] A. Kotsopoulos, J. L. Duarte, M. A. M. Hendrix and P. J. M. Heskes, "Islanding behaviour of grid-connected PV inverters operating under different control schemes," in *Power Electronics Specialists Conference, 2002. Pesc 02. 2002 IEEE 33rd Annual*, 2002, pp. 1506-1511 vol.3.

- [43] A. D. T. Le, M. A. Kashem, M. Negnevitsky and G. Ledwich, "Control strategy of distributed generation for voltage support in distribution systems," in *Power Electronics, Drives and Energy Systems, 2006. PEDES '06. International Conference On*, 2006, pp. 1-6.
- [44] G. Kerber, R. Witzmann and H. Sappl, "Voltage limitation by autonomous reactive power control of grid connected photovoltaic inverters," in *Compatibility and Power Electronics, 2009. CPE '09*. 2009, pp. 129-133.
- [45] E. Demirok, P. Casado González, K. H. B. Frederiksen, D. Sera, P. Rodriguez and R. Teodorescu, "Local Reactive Power Control Methods for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Grids," *Photovoltaics, IEEE Journal Of*, vol. 1, pp. 174-182, 2011.
- [46] A. Canova, L. Giaccone, F. Spertino and M. Tartaglia, "Electrical impact of photovoltaic plant in distributed network," in *Industry Applications Conference, 2007. 42nd IAS Annual Meeting. Conference Record of the 2007 IEEE*, 2007, pp. 1450-1455.
- [47] N. Grass, G. Kerber, R. Witzmann, M. Sebeck and R. Keck, "Increasing Grid Transmission Capacity and Power Quality by new Solar Inverter Concept and Inbuilt Data Communication," *Telecommunication - Energy Special Conference (TELESCON), 2009 4th International Conference On*, pp. 1-5, 2009.
- [48] L. Herman, B. Blazic and I. Papic, "Voltage profile support in LV distribution networks with distributed generation," in *Universities Power Engineering Conference (UPEC), 2009 Proceedings of the 44th International*, 2009, pp. 1-5.
- [49] T. Stetz, W. Yan and W. Braun, "Voltage Control in distribution systems with high level PV penetration (Improving absorption capacity for PV systems by reactive power supply)," vol. 25th European PV Solar Energy Conference and Exhibition, 6th - 10th September 2010, Valencia, Spain, 2010.
- [50] E. Demirok, D. Sera, R. Teodorescu, P. Rodriguez and U. Borup, "Clustered PV inverters in LV networks: An overview of impacts and comparison of voltage control strategies," in *Electrical Power & Energy Conference (EPEC), 2009 IEEE*, 2009, pp. 1-6.
- [51] G. Kerber, "Statistische analyse von NS-Verteilungsnetzen und modellierung von referenznetzen," 2208.
- [52] Cigre Task Force C6.04.02, "Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources," 2011.
- [53] M. Braun, T. Stetz, T. Reimann, B. Valov and G. Arnold, "Optimal reactive power supply in distribution networks; Technological and economic assessment for PV systems," vol. 24th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, 2009.
- [54] D. EnergiMidt Entreprise A/S, "The SOL-300 project – A 300 roof-top project," 1998-2001.

- [55] J. R. Pillai, "Lecture 5: Load flow studies," .
- [56] L. Soder, "EG2030 Power Systems, advanced course - Load flow study and sensitivity analysis of power systems," .
- [57] J. Grainger J and W. D. Stevenson, Eds., *Power System Analysis*. 1994.
- [58] J. A. Momoh, "Electric power distribution, automation, protection and control," 2007.
- [59] H. Glavitsch and R. Bacher, "OPTIMAL POWER FLOW ALGORITHMS," .
- [60] C. E. Bănceanu and I. Vrânceanu, "Coordinated Control of Wind Turbines," 2011.
- [61] E. Lund, "Optimization course 2011 - Lecture 1," Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark.
- [62] J. S. Arora, "Introduction to Optimum Design, Second Edition; ISBN: 0-12-064155-0," 2004.
- [63] V. K. Sood, D. Fischer, J. M. Eklund and T. Brown, "Developing a communication infrastructure for the smart grid," in *Electrical Power & Energy Conference (EPEC), 2009 IEEE*, 2009, pp. 1-7.
- [64] IEC61850, "Communication networks and systems for power utility automation - Part 7-1: Basic communication structure - Principles and models," 2011.
- [65] C. Ozansoy, "Modelling and Object Oriented Implementation of IEC 61850; The New International Standard on Substation Communications and Automation," 2010.
- [66] IEC61850, "Communication networks and systems for power utility automation - Part 7-2: Basic information and communication structure - Abstract communication service interface (ACSI)," 2011.
- [67] IEC61850, "Communication networks and systems for power utility automation - Part 7-3: Basic communication structure - Common data classes," 2011.
- [68] IEC61850, "Communication networks and systems for power utility automation - Part 7-4: Basic communication structure - Compatible logical node classes and data object classes," 2011.
- [69] IEC61850, "Communication networks and systems for power utility automation - Part 7-420: Basic communication structure - Distributed energy resources logical nodes," 2011.
- [70] IEC61850, "Communication networks and systems for power utility automation - Part 8-1: Specific communication service mapping (SCSM) - Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3," 2011.

[71] IEC61850, "Communication networks and systems for power utility automation - Part 9-2: Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3," 2011.

[72] SystemCORP, "IEC 61850 Protocol API User Manual - Protocol Integration Stack," 2009.

[73] dSPACE GmbH, "C Interface Library," 2011.

[74] SystemCORP, "IEC 61850 Intelligent Electronic Device (IED) Capability Description (ICD) - SystemCorp ICD Designer User Manual," 2010.

[75] C. I. Ciontea and R. N. Beres, "Photovoltaic Power Plant prepared for smart grid," Aalborg University, 2012.

# Appendix A

Admittance matrix  $Y_{bus} = G_{bus} + jB_{bus}$  :

- Conductance matrix ( $G_{bus}$ )

156.9898	-72.4568	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-84.533
-72.4568	144.9136	-72.4568	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	-72.4568	229.4466	-72.4568	0	0	0	0	0	0	-84.533	0	0	0	0	0	0	0	0	0
0	0	-72.4568	217.3704	-72.4568	0	0	0	0	0	0	-72.4568	0	0	0	0	0	0	0	0
0	0	0	-72.4568	144.9136	-72.4568	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	-72.4568	229.4466	-72.4568	0	0	0	0	0	0	0	0	0	-84.533	0	0	0
0	0	0	0	0	-72.4568	144.9136	-72.4568	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	-72.4568	144.9136	-72.4568	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	-72.4568	229.4466	-72.4568	0	0	0	0	0	0	0	-84.533	0	0
0	0	0	0	0	0	0	0	-72.4568	156.9898	0	0	0	0	0	0	0	0	-84.533	0
0	0	-84.533	0	0	0	0	0	0	0	84.53295	0	0	0	0	0	0	0	0	0
0	0	0	-72.4568	0	0	0	0	0	0	0	144.9136	-72.4568	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	-72.4568	144.9136	-72.4568	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	-72.4568	156.9898	-84.533	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	-84.533	84.53295	0	0	0	0	0
0	0	0	0	0	-84.533	0	0	0	0	0	0	0	0	0	84.53295	0	0	0	0
0	0	0	0	0	0	0	0	-84.533	0	0	0	0	0	0	0	84.53295	0	0	0
0	0	0	0	0	0	0	0	0	-84.533	0	0	0	0	0	0	0	84.53295	0	0
-84.533	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	84.53295	0

- Susceptance matrix ( $B_{bus}$ )

-114.036	52.63207	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	61.40408
52.63207	-105.264	52.63207	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	52.63207	-166.668	52.63207	0	0	0	0	0	0	61.40408	0	0	0	0	0	0	0	0	0
0	0	52.63207	-157.896	52.63207	0	0	0	0	0	0	52.63207	0	0	0	0	0	0	0	0
0	0	0	52.63207	-105.264	52.63207	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	52.63207	-166.668	52.63207	0	0	0	0	0	0	0	0	61.40408	0	0	0	0
0	0	0	0	0	52.63207	-105.264	52.63207	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	-105.264	52.63207	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	-105.264	52.63207	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	52.63207	-166.668	52.63207	0	0	0	0	0	61.40408	0	0	0
0	0	0	0	0	0	0	0	0	52.63207	-114.036	0	0	0	0	0	0	61.40408	0	0
0	0	61.40408	0	0	0	0	0	0	0	-61.4041	0	0	0	0	0	0	0	0	0
0	0	0	52.63207	0	0	0	0	0	0	0	-105.264	52.63207	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	52.63207	-105.264	52.63207	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	52.63207	-114.036	61.40408	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	61.40408	-61.4041	0	0	0	0	0
0	0	0	0	0	0	61.40408	0	0	0	0	0	0	0	0	-61.4041	0	0	0	0
0	0	0	0	0	0	0	0	0	61.40408	0	0	0	0	0	0	-61.4041	0	0	0
0	0	0	0	0	0	0	0	0	0	61.40408	0	0	0	0	0	0	-61.4041	0	0
61.40408	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-61.4041

## Appendix B

Figure B-1 shows a general representation of each bus in the network presented in Figure 3-1. Further on, the load flow equations will be determined and the first step consists of applying Kirchoff's current law for the LV network in order to obtain the load flow equations.

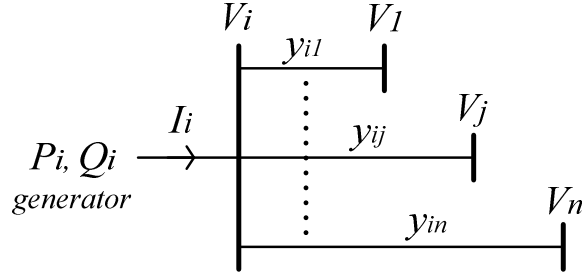


Figure B-1 A typical bus of a power system

The general formula of the current  $I_i$  injected to bus  $i$  from the PV generators is:

$$I_i = y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \dots + y_{in}(V_i - V_n) \quad (\text{B.1})$$

$$I_i = (y_{i1} + y_{i2} + \dots + y_{in})V_i - y_{i1}V_1 - y_{i2}V_2 - \dots - y_{in}V_n \quad (\text{B.2})$$

$$I_i = V_i \sum_{j=1}^{19} y_{ij} - \sum_{j=1}^{19} y_{ij} V_j, \quad i = \overline{2, 19}, \quad i \neq j \quad (\text{B.3})$$

Denoting  $\sum_{j=1}^{19} y_{ij} = Y_{ii}$  and  $-y_{ij} = Y_{ij}$ ,  $i \neq j$ , it results:

$$I_i = V_i Y_{ii} + \sum_{j=1}^{19} Y_{ij} V_j \quad (\text{B.4})$$

The active and reactive power formula at bus  $i$  is:

$$S_i = P_i + jQ_i = V_i I_i^* \quad (\text{B.5})$$

Therefore, from (B.4) and (B.5) it results:

$$I_i = \frac{P_i - jQ_i}{V_i^*} = V_i Y_{ii} + \sum_{j=1}^{19} Y_{ij} V_j \quad (\text{B.6})$$

Denote:

$$V_i = |V_i| e^{j\delta_i} \quad (\text{B.7})$$

$$Y_{ij} = |Y_{ij}| e^{j\theta_{ij}} \quad (\text{B.8})$$



Substituting (B.7) and (B.8) in (B.6), it results that the polar form of the active and reactive power is:

$$P_i = \text{Re}\{S_i\} = \sum_{j=1}^{19} |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (\text{B.9})$$

$$Q_i = \text{Im}\{S_i\} = -\sum_{j=1}^{19} |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) \quad (\text{B.10})$$

## Appendix C

### Source code for load flow analysis:

```
object LDF, oPV, oTerm, oTrafo, oFeeder;
set sPV, sTerm, sTrafo, sFeeder;
int ierr,i;
double p2,p3,p4,p5,p6,p7,p8,p9,p10;
string s,s1,s2;

!!!!!!!!!!!!This part opens a connection with Excel and read values from it!!!
! open a DDE connection to Sheet1 : #ITERATION 1
s = sprintf('%s%s', ExcelPath, 'Excel.exe');
ierr = ddeOpen(s, 'Excel', 'System');
if (.not.ierr) {
    ! ok, excel can be opened. Now close and connect to a specific sheet
    ddeClose();
    ierr = ddeOpen('', 'Excel', 'Sheet1');
}
!!Connecting to the next row
i = ddeRequest('R79C2',s,p2); ! get the contents of a cell
! if (i=1) printf('%f', p2); ! i=1 means a number

i = ddeRequest('R79C6',s,p3); ! get the contents of a cell
! if (i=1) printf('%f', p3); ! i=1 means a number

i = ddeRequest('R79C9',s,p4); ! get the contents of a cell
! if (i=1) printf('%f', p4); ! i=1 means a number

i = ddeRequest('R79C12',s,p5); ! get the contents of a cell
! if (i=1) printf('%f', p5); ! i=1 means a number

i = ddeRequest('R79C15',s,p6); ! get the contents of a cell
! if (i=1) printf('%f', p6); ! i=1 means a number

i = ddeRequest('R79C18',s,p7); ! get the contents of a cell
! if (i=1) printf('%f', p7); ! i=1 means a number

i = ddeRequest('R79C21',s,p8); ! get the contents of a cell
! if (i=1) printf('%f', p8); ! i=1 means a number

i = ddeRequest('R79C24',s,p9); ! get the contents of a cell
! if (i=1) printf('%f', p9); ! i=1 means a number

i = ddeRequest('R79C27',s,p10); ! get the contents of a cell
! if (i=1) printf('%f', p10); ! i=1 means a number
```

```
!This part assigns a P value to the PV -> do this for all PVs
! Further only PV19 is taken as example

LDF=GetCaseCommand('ComLdf'); !to calculate the load flow

sPV = AllRelevant('PV19*.ElmLod'); !select here for which PV to assign value
oPV=sPV.First(); !takes the first one
oPV:plini=p10; !active power reference for all PV
oPV:qlini=0; !reactive power reference for all PV

!Perform a load flow!!!!
LDF.Execute();

!VOLTAGE MAGNITUDE AT CP -> do this for all PVs
!Only CP19 is defined as example

sTerm = AllRelevant('R19*.ElmTerm');
oTerm = sTerm.First();
printf('%f',oTerm:m:u);

!Transformer loading

sTrafo=AllRelevant('*.ElmTr2');
oTrafo=sTrafo.First();
printf('%f',oTrafo:c:loading);
```

## Appendix D

### Source code for $\cos\phi(P)$ method:

```
object LDF, oPV, oTerm, oTrafo, oFeeder;
set sPV, sTerm, sTrafo, sFeeder;
int ierr,i;
double PF19,p2,p3,p4,p5,p6,p7,p8,p9,p10,Q19;
string s,s1,s2;

!!!!!!!This part opens a connection with Excel and read values from it!!!
! open a DDE connection to Sheet1 : #ITERATION 1
s = sprintf('%s%s', ExcelPath, 'Excel.exe');
ierr = ddeOpen(s, 'Excel', 'System');
if (.not.ierr) {
    ! ok, excel can be opened. Now close and connect to a specific sheet
    ddeClose();
    ierr = ddeOpen('', 'Excel', 'Sheet1');
}
!!Connecting to the next row
i = ddeRequest('R55C2',s,p2); ! get the contents of a cell
if (i=1) printf('%f', p2); ! i=1 means a number

i = ddeRequest('R55C6',s,p3); ! get the contents of a cell
if (i=1) printf('%f', p3); ! i=1 means a number

i = ddeRequest('R55C9',s,p4); ! get the contents of a cell
if (i=1) printf('%f', p4); ! i=1 means a number

i = ddeRequest('R55C12',s,p5); ! get the contents of a cell
if (i=1) printf('%f', p5); ! i=1 means a number

i = ddeRequest('R55C15',s,p6); ! get the contents of a cell
if (i=1) printf('%f', p6); ! i=1 means a number

i = ddeRequest('R55C18',s,p7); ! get the contents of a cell
if (i=1) printf('%f', p7); ! i=1 means a number

i = ddeRequest('R55C21',s,p8); ! get the contents of a cell
if (i=1) printf('%f', p8); ! i=1 means a number

i = ddeRequest('R55C24',s,p9); ! get the contents of a cell
if (i=1) printf('%f', p9); ! i=1 means a number

i = ddeRequest('R55C27',s,p10); ! get the contents of a cell
if (i=1) printf('%f', p10); ! i=1 means a number
```

---

```

! Calculate the power factor and reactive power -> do this for all PVs
! Further only PV19 is taken as example

if (-2.5>p10>-2.75) {
PF19=0.99;
}
if (-2.75>p10>-3) {
PF19=0.98;
}
if (-3>p10>-3.25) {
PF19=0.97;
}
if (-3.25>p10>-3.5) {
PF19=0.96;
}
if (-3.5>p10>-3.75) {
PF19=0.95;
}
if (-3.75>p10>-4) {
PF19=0.94;
}
if (-4>p10>-4.25) {
PF19=0.93;
}
if (-4.25>p10>-4.5) {
PF19=0.92;
}
if (-4.5>p10>-4.75) {
PF19=0.91;
}
if (-4.75>p10>-5) {
PF19=0.90;
}
if (p10<-5) {
p10=-5;
}
if (p10>-2.5) {
Q19 = 0;
}
else {
Q19=tan(acos(PF19))*(-p10);
}
printf('%f',Q19);

!This part assigns a P value to the PV -> do this for all PVs
! Further only PV19 is taken as example
LDF=GetCaseCommand('ComLdf'); !calculate the load flow

sPV = AllRelevant('PV19*.ElmLod'); !select here for which PV to assign value
oPV=sPV.First(); !takes the first one
oPV:plini=p10; !active power reference for all PV
oPV:qlini=Q19; !reactive power reference for all PV

!Perform a load flow!!!!
LDF.Execute();

```

---

```
!VOLTAGE MAGNITUDE AT CP -> do this for all PVs
!Only CP19 is defined as example
sTerm = AllRelevant('R19*.ElmTerm');
oTerm = sTerm.First();
printf('%f',oTerm:m:u);

!Transformer loading
sTrafo=AllRelevant('*.ElmTr2');
oTrafo=sTrafo.First();
printf('%f',oTrafo:c:loading);
```

# Appendix E

## Source code for Q(U) method:

```

object LDF, oPV, oTerm, oTrafo, oFeeder;
set sPV, sTerm, sTrafo, sFeeder;
int ierr,i;
double
p2,p3,p4,p5,p6,p7,p8,p9,p10,PF,Q2,Q3,Q4,Q5,Q6,Q7,Q8,Q9,Q10,Q11,Q12,Q13,Q14,Q1
5,Q16,Q17,Q18,Q19,Er,Vmes,Vbase;
string s,s1,s2;

!!!!!!!This part opens a connection with Excel and read values from it!!!
! open a DDE connection to Sheet1 : #ITERATION 1
s = sprintf('%s%s', ExcelPath, 'Excel.exe');
ierr = ddeOpen(s, 'Excel', 'System');
if (.not.ierr) {
    ! ok, excel can be opened. Now close and connect to a specific sheet
    ddeClose();
    ierr = ddeOpen('', 'Excel', 'Sheet1');
}
!!Connecting to the next row
i = ddeRequest('R59C2',s,p2); ! get the contents of a cel
if (i=1) printf('%f', p2); ! i=1 means a number

i = ddeRequest('R59C6',s,p3); ! get the contents of a cel
if (i=1) printf('%f', p3); ! i=1 means a number

i = ddeRequest('R59C9',s,p4); ! get the contents of a cel
if (i=1) printf('%f', p4); ! i=1 means a number

i = ddeRequest('R59C12',s,p5); ! get the contents of a cel
if (i=1) printf('%f', p5); ! i=1 means a number

i = ddeRequest('R59C15',s,p6); ! get the contents of a cel
if (i=1) printf('%f', p6); ! i=1 means a number

i = ddeRequest('R59C18',s,p7); ! get the contents of a cel
if (i=1) printf('%f', p7); ! i=1 means a number

i = ddeRequest('R59C21',s,p8); ! get the contents of a cel
if (i=1) printf('%f', p8); ! i=1 means a number

i = ddeRequest('R59C24',s,p9); ! get the contents of a cel
if (i=1) printf('%f', p9); ! i=1 means a number

i = ddeRequest('R59C27',s,p10); ! get the contents of a cel
if (i=1) printf('%f', p10); ! i=1 means a number

```

```
!This part assigns a P value to the PV -> do this for all PVs
! Further only PV19 is taken as example

LDF=GetCaseCommand('ComLdf'); !calculate the load flow

sPV = AllRelevant('PV19*.ElmLod'); !select here for which PV to assign value
oPV=sPV.First(); !takes the first one
oPV:plini=p10; !active power reference for all PV
oPV:qlini=0; !reactive power reference for all PV

!Perform load flow
LDF.Execute();

! Read voltage at CP and calculate reactive power -> do this for all PVs
! Further only PV19 is taken as example

sTerm = AllRelevant('R19*.ElmTerm');
oTerm = sTerm.First();
Vmes=oTerm:m:u;
Vbase=1.02;
if (1.02<oTerm:m:u<1.05) {
    Er=(Vmes-Vbase)/Vbase)*34;
    Q19=Er*2.42;
}
    else {
        Q19=0;
    }
if (oTerm:m:u>1.05) {
    Q19=2.42;
}
printf('%f',oTerm:m:u);

LDF=GetCaseCommand('ComLdf'); !calculate the load flow

! Assign reactive power reference to PVs -> do this for all PVs
! Further only PV19 is taken as example
sPV = AllRelevant('PV19*.ElmLod'); !select here for which PV to assign value
oPV=sPV.First(); !takes the first one
oPV:plini=p10; !active power reference for all PV
oPV:qlini=Q19; !reactive power reference for all PV
!Perform load flow
LDF.Execute();

! Read measured reactive power & voltage at CPs -> do this for all PVs
! Further only PV19 is taken as example
sTerm = AllRelevant('R19*.ElmTerm');
oTerm = sTerm.First();
printf('%f',oTerm:m:u);
printf('%f',Q19);

! Read transformer loading value
sTrafo=AllRelevant('*.ElmTr2');
oTrafo=sTrafo.First();
printf('%f',oTrafo:c:loading);
printf('%f',oTrafo:m:Qsum:buslv);
```



# Appendix F

## Source code for optimized Q(U) method:

- Parameters initialization

```

%% Parameters initialization for the electric system
tole=1e-4;
deg=180/pi;
rad=1/deg ;
Sbase=100000;
Vbase=400;
Zbase=1.6;
Ybase=0.625;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% All variables are expressed in p.u.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Type=1 means slack-bus, Type=2 means PQ-bus, Type=3 means PU-bus
%Bus Types
bt1 = 1;
bt2 = 2;
bt3 = 2;
bt4 = 2;
bt5 = 2;
bt6 = 2;
bt7 = 2;
bt8 = 2;
bt9 = 2;
bt10 = 2;
bt11 = 2;
bt12 = 2;
bt13 = 2;
bt14 = 2;
bt15 = 2;
bt16 = 2;
bt17 = 2;
bt18 = 2;
bt19 = 2;
%voltage magnitude & angle at buses
V1=1; % voltage magnitute in p.u. at buses
ang1=0/deg; % angle in radians
%Assign Pgen and Qgen in each node
PG1=0/100; QG1=0/100;
PG2=-P2/100; QG2=0/100;
PG3=-P3/100; QG3=0/100;
PG4=-P4/100; QG4=0/100;
PG5=-P5/100; QG5=0/100;
PG6=-P6/100; QG6=0/100;
PG7=-P7/100; QG7=0/100;
PG8=-P8/100; QG8=0/100;
PG9=-P9/100; QG9=0/100;
PG10=-P10/100; QG10=0/100;
PG11=-P2/100; QG11=0/100;
PG12=-P3/100; QG12=0/100;
PG13=-P4/100; QG13=0/100;

```

```

PG14=-P5/100;          QG14=0/100;
PG15=-P6/100;          QG15=0/100;
PG16=-P7/100;          QG16=0/100;
PG17=-P8/100;          QG17=0/100;
PG18=-P9/100;          QG18=0/100;
PG19=-P10/100;         QG19=0/100;
%%%%%%%%%%
% Bus Data
%%%%%%%%%%
BUSDATA= [
%      1      2      3      4      5      6
%      Node  Type      V      Angle  Pgen  Qgen
%      1      bt1      V2      angl  PG1   QG1
%      2      bt2      V1      angl  PG2   QG2
%      3      bt3      V1      angl  PG3   QG3
%      4      bt4      V1      angl  PG4   QG4
%      5      bt5      V1      angl  PG5   QG5
%      6      bt6      V1      angl  PG6   QG6
%      7      bt7      V1      angl  PG7   QG7
%      8      bt8      V1      angl  PG8   QG8
%      9      bt9      V1      angl  PG9   QG9
%     10      bt10     V1      angl  PG10  QG10
%     11      bt11     V1      angl  PG11  QG11
%     12      bt12     V1      angl  PG12  QG12
%     13      bt13     V1      angl  PG13  QG13
%     14      bt14     V1      angl  PG14  QG14
%     15      bt15     V1      angl  PG15  QG15
%     16      bt16     V1      angl  PG16  QG16
%     17      bt17     V1      angl  PG17  QG17
%     18      bt18     V1      angl  PG18  QG18
%     19      bt19     V1      angl  PG19  QG19];
%%%%%%%%%%
% Line Data
%%%%%%%%%%
R35 = 0.014455;          %% resistance for 35m cable
X35 = 0.0105;            %% reactance for 35m cable
R30 = 0.01239;           %% resistance for 30m cable
X30 = 0.009;             %% reactance for 30m cable
R12=R35/Zbase;           X12=X35/Zbase;           % 35m cable
R119=R30/Zbase;          X119=X30/Zbase;          % 30m cable
R23=R35/Zbase;           X23=X35/Zbase;           % 35m cable
R34=R35/Zbase;           X34=X35/Zbase;           % 35m cable
R311=R30/Zbase;          X311=X30/Zbase;          % 30m cable
R45=R35/Zbase;           X45=X35/Zbase;           % 35m cable
R412=R35/Zbase;          X412=X35/Zbase;          % 35m cable
R56=R35/Zbase;           X56=X35/Zbase;           % 35m cable
R67=R35/Zbase;           X67=X35/Zbase;           % 35m cable
R616=R30/Zbase;          X616=X30/Zbase;          % 30m cable
R78=R35/Zbase;           X78=X35/Zbase;           % 35m cable
R89=R35/Zbase;           X89=X35/Zbase;           % for 35m cable
R910=R35/Zbase;          X910=X35/Zbase;          % 35m cable
R917=R30/Zbase;          X917=X30/Zbase;          % 30m cable
R1018=R30/Zbase;         X1018=X30/Zbase;         % 30m cable
R1213=R35/Zbase;         X1213=X35/Zbase;         % 35m cable
R1314=R35/Zbase;         X1314=X35/Zbase;         % 35m cable
R1415=R30/Zbase;         X1415=X30/Zbase;         % 30m cable

```

```

LINEDATA = [
% Line   from   to       R       X
    1     1     2       R12      X12
    2     1    19       R119     X119
    3     2     3       R23      X23
    4     3     4       R34      X34
    5     3    11       R311     X311
    6     4     5       R45      X45
    7     4    12       R412     X412
    8     5     6       R56      X56
    9     6     7       R67      X67
   10     6    16       R616     X616
   11     7     8       R78      X78
   12     8     9       R89      X89
   13     9    10       R910     X910
   14     9    17       R917     X917
   15    10    18       R1018    X1018
   16    12    13       R1213    X1213
   17    13    14       R1314    X1314
   18    14    15       R1415    X1415];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%% Rated power for each PV system %%%%%

nl = size(BUSDATA,1);
S = zeros(1,nl);
for N = 1:nl
    if BUSDATA(N,2) ~= 1
        S(1,N) = 5.55/100;
    else
        S(1,N) = 0/100;
    end
end

```

### ● Admittance matrix

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Bus and Line Numbers
[busnumber, busproperty] = size(BUSDATA);
[linenumber, lineproperty] = size(LINEDATA);
YBUS = zeros(busnumber);

%Adding line impedances and capacitances
for N = 1:linenumber
    %For digonal elements
    YBUS(LINEDATA(N,2),LINEDATA(N,2)) = YBUS(LINEDATA(N,2),LINEDATA(N,2))+...
        1 / (LINEDATA(N,4)+1j*LINEDATA(N,5));

    YBUS(LINEDATA(N,3),LINEDATA(N,3)) = YBUS(LINEDATA(N,3),LINEDATA(N,3))+...
        1 / (LINEDATA(N,4)+1j*LINEDATA(N,5));

    %For off-digonal elements
    YBUS(LINEDATA(N,2),LINEDATA(N,3)) = YBUS(LINEDATA(N,2),LINEDATA(N,3))-...
        1 / (LINEDATA(N,4)+1j*LINEDATA(N,5));

```

```

YBUS (LINEDATA (N, 3) , LINEDATA (N, 2) ) = YBUS (LINEDATA (N, 3) , LINEDATA (N, 2) ) - ...
1 / ( LINEDATA (N, 4) + 1j * LINEDATA (N, 5) );
end

```

- **Jacobian matrix**

```

%Create Jacobian Matrix
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Bus and Line Numbers
[busnumber, busproperty] = size(BUSDATA);
[linenumber, lineproperty] = size(LINEDATA);
[admitnumber, admitproperty] = size(YBUS);

%Set scheduled active and reactive power
PGDi = BUSDATA(:, 5);
QGDl = BUSDATA(:, 6);

%Start of the iterations
%number of iterations
deltaP = ones(busnumber, 1);
deltaQ = ones(busnumber, 1);
iteration = 0;

while max(abs(deltaP)) > tole && iteration <= 3
    Pi = zeros(busnumber, 1);
    Qi = zeros(busnumber, 1);

    %Calculate injected powers
    for N = 1:busnumber
        if BUSDATA(N, 2) ~= 1 % if bus type not slack bus

            for M = 1:admitnumber
                if N ~= M && YBUS(N, M) ~= 0
                    Pi(N) = Pi(N) +
BUSDATA(N, 3) * BUSDATA(M, 3) * abs(YBUS(N, M)) * cos(angle(YBUS(N, M)) + BUSDATA(M, 4) -
BUSDATA(N, 4));
                    Qi(N) = Qi(N) +
BUSDATA(N, 3) * BUSDATA(M, 3) * abs(YBUS(N, M)) * sin(angle(YBUS(N, M)) + BUSDATA(M, 4) -
BUSDATA(N, 4));
                end
            end
            Pi(N, 1) = BUSDATA(N, 3) * BUSDATA(N, 3) * real(YBUS(N, N)) + Pi(N);
            Qi(N, 1) = -BUSDATA(N, 3) * BUSDATA(N, 3) * imag(YBUS(N, N)) - Qi(N);
        end
    end

    %Maximum differences
    deltaP = PGDi - Pi;
    deltaQ = QGDl - Qi;

    %The number of iterations start with zero and will be increased with
    %one for each cycle.
    iteration = iteration + 1;
end

```

---

```

%First create Jacobian N and Jacobian M matrices
JacobM = zeros(busnumber);
JacobN = zeros(busnumber);

for N = 1:busnumber
    %check slack bus
    if BUSDATA(N,2) ~= 1
        for M = 1:busnumber
            %check slack bus and N is not equal to M
            if N ~= M
                dPdAng = -
BUSDATA(N,3)*BUSDATA(M,3)*abs(YBUS(N,M))*sin(angle(YBUS(N,M))+BUSDATA(M,4)-
BUSDATA(N,4));
                dQdAng = -
BUSDATA(N,3)*BUSDATA(M,3)*abs(YBUS(N,M))*cos(angle(YBUS(N,M))+BUSDATA(M,4)-
BUSDATA(N,4));
                if BUSDATA(M,2) ~= 1
                    %for off-diagonal Jacobian M, Jacobian N matrix
                    JacobM(N,M) = dPdAng;
                    JacobN(N,M) = dQdAng;
                end
                %for diagonal Jacobian M, Jacobian N matrix
                JacobM(N,N) = -Qi(N)-imag(YBUS(N,N))*BUSDATA(N,3)^2;
                JacobN(N,N) = Pi(N)-real(YBUS(N,N))*BUSDATA(N,3)^2;
            end
        end
    end
end

%Second derivative Jacobian Npr and Jacobian Mpr matrices
JacobMpr = zeros(busnumber);
JacobNpr = zeros(busnumber);

for N = 1:busnumber
    %check slack bus
    if BUSDATA(N,2) ~= 1
        for M = 1:busnumber
            %check slack bus and N is not equal to M
            if N ~= M
                dPdV =
BUSDATA(N,3)*abs(YBUS(N,M))*cos(angle(YBUS(N,M))+BUSDATA(M,4)-BUSDATA(N,4));
                dQdV = -
BUSDATA(M,3)*abs(YBUS(N,M))*sin(angle(YBUS(N,M))+BUSDATA(M,4)-BUSDATA(N,4));
                if BUSDATA(M,2) ~= 1
                    %for off-diagonal Jacobian M, Jacobian N matrix
                    JacobMpr(N,M) = dQdV;
                    JacobNpr(N,M) = dPdV;
                end
                %for diagonal Jacobian M, Jacobian N matrix
                JacobMpr(N,N) = Qi(N)-imag(YBUS(N,N))*BUSDATA(N,3)^2;
                JacobNpr(N,N) = Pi(N)+real(YBUS(N,N))*BUSDATA(N,3)^2;
            end
        end
    end
end
end
end

```

---

```
tempbusnumber = busnumber;

while tempbusnumber > 0,

    % the row and column for Jacobian is cut out if slack bus

    if BUSDATA(tempbusnumber,2) == 1
        JacobM(tempbusnumber,:) = [];
        JacobM(:,tempbusnumber) = [];

        JacobN(tempbusnumber,:) = [];
        JacobN(:,tempbusnumber) = [];

        JacobMpr(tempbusnumber,:) = [];
        JacobMpr(:,tempbusnumber) = [];

        JacobNpr(tempbusnumber,:) = [];
        JacobNpr(:,tempbusnumber) = [];
        deltaP(tempbusnumber,:) = [];
        deltaQ(tempbusnumber,:) = [];

    end
    tempbusnumber = tempbusnumber-1;
end

% construct Jacobian from the 4 matrices

J1 = vertcat(JacobM,JacobN);
J2 = vertcat(JacobNpr,JacobMpr);
Jacobian = horzcat(J1,J2);
deltaPQ = vertcat(deltaP,deltaQ);

deltaAngV = (Jacobian)\deltaPQ;

deltaAng = deltaAngV(1:busnumber-1);
deltaV = deltaAngV(busnumber:end);

tempAng = zeros(busnumber,1);
tempV = zeros(busnumber,1);
delta1 = 1; %counter for deltaAng
delta2 = 1; %counter for deltaV

for N = 1:busnumber
    if BUSDATA(N,2) ~= 1
        tempAng(N,1) = deltaAng(delta1,1) + BUSDATA(N,4);
        delta1 = delta1 + 1;

        if BUSDATA(N,2) ~= 1
            tempV(N,1) = BUSDATA(N,3)*(deltaV(delta2,1) + 1);
            delta2 = delta2 + 1;
        end
    else
        tempAng(N,1) = BUSDATA(N,4);
        tempV(N,1) = BUSDATA(N,3);
    end
end
```

```

        end
    end

    %Update bus voltage magnitudes and angles
    BUSDATA(:,3) = tempV;
    BUSDATA(:,4) = tempAng;

    %xlswrite('Results.xlsm',tempV,6,'A1:A19');

    %Print iteration results only
    fprintf('----Results after iteration %d ----\n', iteration);
    fprintf('Bus Number      V(p.u.)          Phase angle (degrees) \n');

    for N = 1:busnumber
        fprintf('%d',N);
        fprintf('          %6.4f',BUSDATA(N,3));
        fprintf('          %6.4f\n',BUSDATA(N,4)*deg);
    end

```

- Objective function

```

function y = QFunction_correct(x,PG, G, B, BUSDATA)
% LINE LOSSES FUNCTION

```

```

[busnumber, busproperty] = size(BUSDATA);
G1 = zeros(1,busnumber);
G2 = zeros(1,busnumber);

y = sum(power(x(2*busnumber+2:end),2));

```

- Constraints

```

function [c, ceq] = Constraints(x,PG,S,BUSDATA, V2)
%NONLINEARCONSTRAINT Summary of this function goes here

```

```

[busnumber, busproperty] = size(BUSDATA);
H = zeros(1,busnumber);
H1 = zeros(1,busnumber);
H2 = zeros(1,busnumber);
H3 = zeros(1,busnumber);
H4 = zeros(1,busnumber);

```

```

%%%%%% equality constraints %%%%%%%%%%%
G1 = zeros(1,busnumber);
G2 = zeros(1,busnumber);

```

```

%%%%% Balanced power equations %%%%

```

```

for N = 1:busnumber
    if BUSDATA(N,2) ~= 1
        for M = 1:busnumber
            if N ~= M && G(N,M) ~= 0
                G1(1,N) = G1(1,N)-(x(N)^2*G(N,M)-
x(N)*x(M)*(G(N,M)*cos((x(busnumber+N)-
x(busnumber+M))))+B(N,M)*sin((x(busnumber+N)-x(busnumber+M)))));

```

```

        G2(1,N) = G2(1,N) - (-x(N)^2*B(N,M) -
x(N)*x(M)*(G(N,M)*sin((x(busnumber+N)-x(busnumber+M)))) -
B(N,M)*cos((x(busnumber+N)-x(busnumber+M)))));
    end
end
end
G1(1,N) = PG(1,N)-G1(1,N);
G2(1,N) = x(2*busnumber+N)-G2(1,N);
end

G1(1,1) = 0;
G2(1,1) = 0;

G3=x(20);           % slack bus angle
G4=x(39);           % slack bus reactive power reference
G5=x(1)-V2;         % slack bus voltage magnitude

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% inequality constraints %%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for N = 1:busnumber
    if BUSDATA(N,2) ~= 1
        H(1,N) = power(PG(1,N),2)+power(x(1,2*busnumber+N),2)-
power(S(1,N),2);
        H1(1,N) = x(1,N)-1.026;           %upper limit for voltage
        H2(1,N) = 1-x(1,N);               %lower limit for voltage
        H3(1,N) = x(2*busnumber+N);      % inverters only inject reactive power
        H4(1,N) = -x(busnumber+N);       % positive angles
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

ceq = [G1, G2, G3, G4, G5];               % equality constraints
c = [H, H1, H2, H3, H4];                  % inequality constraints

end

```



# Appendix G

## Source code for the CLIB application:

```

#include "stdafx.h"
#include <stdio.h>
#include <stdlib.h>
#include <clib32.h>
#include <iostream>
#include <cstdlib>
char board_name[] = "ds1103";

void grid_check(unsigned int board_index, UInt32* address);
double trip_check(unsigned int board_index, UInt32* address);
void reset_inverter(unsigned int board_index, UInt32* address);
void reset_pll(unsigned int board_index, UInt32* address);
void inverter_start(unsigned int board_index, UInt32* address);
void inverter_stop(unsigned int board_index, UInt32* address);
double read_signal(unsigned int board_index, UInt32* address);
void write_value(unsigned board_index, UInt32* address, double* parameter);

int _tmain(int argc, _TCHAR* argv[])
{
    int            error, state;
    unsigned int    board_index;
    UInt16          board_type;
    UInt32          var_address1, var_address2, var_address3, var_address4, var_address5,
var_address6, var_address7, var_address8, var_address9, var_address10, var_address11,
var_address12;
    double          dcvoltage, new_dcreference, trip, reset, start, pll, vgrms, dcurrent,
dcpower, rmsvoltage, rmcurrent, rmspower, dcreference;
    board_spec_tp    board_spec;

    printf("CLIB test application\n");

    /* The first thing to do when accessing the DSP Device Driver with      */
    /* CLIB is to register the host application with the DSP Device Driver.*/
    /* The CLIB function DS_register_host_app searches for the DSP Device   */
    /* Driver and, if found, performs a call to it which registers the      */
    /* application.                                                          */
    error = DS_register_host_app("TestAppCLIB");
    if(error != DS_NO_ERROR)
    {
        printf("DS_register_host_app: error = %d\n",error);
        exit(1);
    }
    /* Before accessing a processor board, the board index of that board    */
    /* must be obtained from the DSP Device Driver. The board index is a    */
    /* parameter for all CLIB functions accessing the board.               */
    error = DS_board_index(board_name, &board_index);
    if(error != DS_NO_ERROR)
    {
        printf("A board named %s is not registered with the"
            " DSP Device Driver\n", board_name);
    }
}

```

```
    DS_unregister_host_app();
    exit(1);
}
/** In order to get more information about the selected board call the */
/** CLIB function DS_board_spec(). That function fills a board_spec */
/** structure with information like board type, board name, memory size */
/** etc. */
error = DS_board_spec(board_index, &board_spec);
if(error != DS_NO_ERROR)
{
    printf("DS_board_spec: error = %d\n",error);
    DS_unregister_host_app();
    exit(1);
}
printf("Board type = ");
switch(board_spec.board_type)
{
    case TYPE_DS1003:
        printf("DS1003\n");
        break;
    case TYPE_DS1005:
        printf("DS1005\n");
        break;
    case TYPE_DS1006:
        printf("DS1006\n");
        break;
    case TYPE_DS1102:
        printf("DS1102\n");
        break;
    case TYPE_DS1103:
        printf("DS1103\n");
        break;
    case TYPE_DS1104:
        printf("DS1104\n");
        break;
    case TYPE_DS1401:
        printf("DS1401\n");
        break;
    default:
        printf("unknown.\n");
        DS_unregister_host_app();
        exit(1);
        break;
}
/** Before accessing a board it is required to check if an application */
/** is running on that board. A board access is based on command server,*/
/** which is a part of the real-time application background. */
error = DS_is_reset(board_index, &state);
if(error != DS_NO_ERROR)
{
    printf("DS_is_reset: error = %d\n",error);
    DS_unregister_host_app();
    exit(1);
}
if(state == DS_TRUE)
{
    printf("No Application running on board %s.\n", board_name);
    DS_unregister_host_app();
}
```

```

        exit(1);
    }

/* Grid check - read address of grid voltage magnitude & perform grid check */
    printf("Grid check...\n");
    error = DS_get_var_addr(board_index, "Ug_mag", &var_address6);
    if(error != DS_NO_ERROR)
    {
        printf("DS_get_var_addr: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    grid_check(board_index, &var_address6);

/* Inverter Trip check - read address of trip value & perform trip check */
    printf("Inverter checking...\n");
    error = DS_get_var_addr(board_index, "Trip", &var_address1);
    if(error != DS_NO_ERROR)
    {
        printf("DS_get_var_addr: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    trip_check(board_index, &var_address1);
/* Reset Inverter - read address of reset value & reset the inverter */
    error = DS_get_var_addr(board_index, "Reset", &var_address2);
    if(error != DS_NO_ERROR)
    {
        printf("DS_get_var_addr: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    reset_inverter(board_index, &var_address2);

/* Reset PLL - read address of reset PLL value & reset the PLL */
    error = DS_get_var_addr(board_index, "PLL", &var_address4);
    if(error != DS_NO_ERROR)
    {
        printf("DS_get_var_addr: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    reset_pll(board_index, &var_address4);

    system("cls");                /* Clear screen */

/* Start Inverter - Read address of start & start inverter */
    error = DS_get_var_addr(board_index, "Start", &var_address3);
    if(error != DS_NO_ERROR)
    {
        printf("DS_get_var_addr: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    inverter_start(board_index, &var_address3);

```

```
trip = trip_check(board_index, &var_address1);
    if (trip == 0)
        inverter_stop(board_index, &var_address3);

        /* Read grid voltage (rms) */

    error = DS_get_var_addr(board_index, "VgRms", &var_address9);
    if(error != DS_NO_ERROR)
    {
        printf("DS_get_var_addr: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    rmsvoltage = read_signal(board_index, &var_address9);

        /* Read grid current (rms) */

    error = DS_get_var_addr(board_index, "IgRms", &var_address10);
    if(error != DS_NO_ERROR)
    {
        printf("DS_get_var_addr: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    rmscurrent = read_signal(board_index, &var_address10);

        /* Read grid power (rms) */

    error = DS_get_var_addr(board_index, "Prms", &var_address11);
    if(error != DS_NO_ERROR)
    {
        printf("DS_get_var_addr: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    rmspower = read_signal(board_index, &var_address11);

        /* Read measured DC link voltage */

    error = DS_get_var_addr(board_index, "Udc", &var_address5);
    if(error != DS_NO_ERROR)
    {
        printf("DS_get_var_addr: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    dcvoltage = read_signal(board_index, &var_address5);

        /* Read DC link current */

    error = DS_get_var_addr(board_index, "Idc", &var_address7);
    if(error != DS_NO_ERROR)
    {
        printf("DS_get_var_addr: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    dccurrent = read_signal(board_index, &var_address7);
```

---

```

        /* Read DC link power */

error = DS_get_var_addr(board_index, "Pdc", &var_address8);
if(error != DS_NO_ERROR)
{
    printf("DS_get_var_addr: error = %d\n",error);
    DS_unregister_host_app();
    exit(1);
}
dcpower = read_signal(board_index, &var_address8);

printf("PV system monitoring\n");

printf("Vdc%lf\t Idc%lf\t Vrms%lf\t Irms%lf\t Pdc%lf\t Pac%lf\t Efficiency%lf\n",
dcvoltage, dccurrent, rmsvoltage, rmscurrent, dcpower, rmspower, rmspower/dcpower);

trip = trip_check(board_index, &var_address1);
if (trip == 0)
    inverter_stop(board_index, &var_address3);

    /* Memory address of DC link reference voltage */

error = DS_get_var_addr(board_index, "Udc_ref", &var_address12);
if(error != DS_NO_ERROR)
{
    printf("DS_get_var_addr: error = %d\n",error);
    DS_unregister_host_app();
    exit(1);
}

    /* Read old DC link reference voltage */

dcreference = read_signal(board_index, &var_address12);

printf("Previous DC voltage reference was %lf\n", dcreference);
printf("Write the new DC voltage reference = ");
scanf_s("%lf",new_dcreference);
dcreference=new_dcreference;

    /* Write new DC link reference voltage to memory address of Udc_ref*/

write_value(board_index, &var_address12, &dcreference);

    /* Check that the new ref was written */

dcreference = read_signal(board_index, &var_address12);
printf("\nNew DC voltage value is %f\n", dcreference);

trip = trip_check(board_index, &var_address1);
if (trip == 0)
    inverter_stop(board_index, &var_address3);
system("pause");

printf("PV system monitoring\n");

rmsvoltage = read_signal(board_index, &var_address9);
rmscurrent = read_signal(board_index, &var_address10);
rmspower = read_signal(board_index, &var_address11);
dcvoltage = read_signal(board_index, &var_address5);

```

---

```
dccurrent = read_signal(board_index, &var_address7);
dcpower = read_signal(board_index, &var_address8);

printf("Vdc%lf\t Idc%lf\t Vrms%lf\t Irms%lf\t Pdc%lf\t Pac%lf\t Efficiency%lf\n",
dcvoltage, dccurrent, rmsvoltage, rmscurrent, dcpower, rmspower, rmspower/dcpower);

trip = trip_check(board_index, &var_address1);
    if (trip == 0)
        inverter_stop(board_index, &var_address3);
system("pause");

        /* Stop inverter */

inverter_stop(board_index, &var_address3);

    /*** * Each application has to unregister itself before exiting. The DSP */
    /** * Device Driver has a limited number of host application indices, */
    /** * and the function DS_unregister_host_app() frees the index ob- */
    /** * tained by the previously called function DS_register_host_app(). */
    DS_unregister_host_app();
    return 0;
}

        /* Grid check function */

void grid_check(unsigned board_index, UInt32* address)
{
    int error;
    double vgrms;

        error = DS_read_64(board_index, *address, 1, (UInt64 *)&vgrms);
    if(error != DS_NO_ERROR)
    {
        printf("DS_read_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }

    if (vgrms>300 && vgrms<350)
        printf("Grid on. Continue...\n");

    else
        do
        {
            printf("Grid out. Waiting for connection...\n");
            error = DS_read_64(board_index, *address, 1, (UInt64 *)&vgrms);
            if(error != DS_NO_ERROR)
            {
                printf("DS_read_64: error = %d\n",error);
                DS_unregister_host_app();
                exit(1);
            }
        }
        while(vgrms<300 || vgrms>350);

    system("cls");
    printf("Grid on. Grid voltage is %lf", vgrms, "V. Continue...\n");
    system("pause");
}
```

---

```

        /* Trip check function */

double trip_check(unsigned board_index, UInt32* address)
{
    int error;
    double trip;
    error = DS_read_64(board_index, *address, 1, (UInt64 *)&trip);
    if(error != DS_NO_ERROR)
    {
        printf("DS_read_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }

    printf("Trip check...\n");

    if (trip==0)

        printf("Inverter interface problem. Check hardware!\n");
    else
        printf("No trip detected\n");

    return trip;
}

        /* Reset inverter function */

void reset_inverter(unsigned board_index, UInt32* address)
{
    int error;
    double reset;
    error = DS_read_64(board_index, *address, 1, (UInt64 *)&reset);
    if(error != DS_NO_ERROR)
    {
        printf("DS_read_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }

    reset=1;

    error = DS_write_64(board_index, *address, 1, (UInt64 *)&reset);
    if(error != DS_NO_ERROR)
    {
        printf("DS_write_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    reset=0;
    printf("Inverter was reset\n");

    error = DS_write_64(board_index, *address, 1, (UInt64 *)&reset);
    if(error != DS_NO_ERROR)
    {
        printf("DS_write_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
}

```

---

```
        /* Reset PLL */

void reset_pll(unsigned board_index, UInt32* address)
{
    int error;
    double pll;
    error = DS_read_64(board_index, *address, 1, (UInt64 *)&pll);
    if(error != DS_NO_ERROR)
    {
        printf("DS_read_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }

    pll=0;
    error = DS_write_64(board_index, *address, 1, (UInt64 *)&pll);
    if(error != DS_NO_ERROR)
    {
        printf("DS_write_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }

    pll=1;
    error = DS_write_64(board_index, *address, 1, (UInt64 *)&pll);
    if(error != DS_NO_ERROR)
    {
        printf("DS_write_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    printf("PLL was reset\n", pll);
}

        /* Start inverter */

void inverter_start(unsigned board_index, UInt32* address)
{
    int error;
    double start;
    error = DS_read_64(board_index, *address, 1, (UInt64 *)&start);
    if(error != DS_NO_ERROR)
    {
        printf("DS_read_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }

    if (start==0)
        printf("Inverter is OFF. Please start the inverter\n");

    start=1;
    error = DS_write_64(board_index, *address, 1, (UInt64 *)&start);
    if(error != DS_NO_ERROR)
    {
        printf("DS_write_64: error = %d\n",error);
    }
}
```



```
        DS_unregister_host_app();
        exit(1);
    }
    printf("Inverter is ON!\n", start);
}

/* Stop inverter */

void inverter_stop(unsigned board_index, UInt32* address)
{
    int error;
    double start;
    start=0;
    error = DS_write_64(board_index, *address, 1, (UInt64 *)&start);
    if(error != DS_NO_ERROR)
    {
        printf("DS_write_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    printf("Inverter is OFF!\n");
}

/* Read signal */

double read_signal(unsigned board_index, UInt32* address)
{
    int error;
    double value;
    error = DS_read_64(board_index, *address, 1, (UInt64 *)&value);
    if(error != DS_NO_ERROR)
    {
        printf("DS_read_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
    return value;
}

void write_value(unsigned board_index, UInt32* address, double* parameter)
{
    int error;
    error = DS_write_64(board_index, *address, 1, (UInt64 *)&parameter);
    if(error != DS_NO_ERROR)
    {
        printf("DS_write_64: error = %d\n",error);
        DS_unregister_host_app();
        exit(1);
    }
}
```