Voltage Unbalance Compensation in the Distribution Grid through Distributed Generation

DEPARTMENT OF ENERGY TECHNOLOGY
AALBORG UNIVERSITY

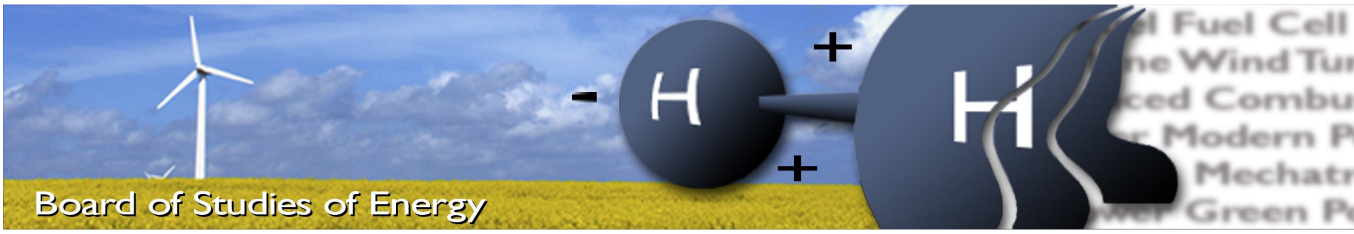
Master Thesis

Enrique Müller Llano

Aalborg University
Department of Energy Technology
Pontoppidanstræde 101
DK-9220 Aalborg

AALBORG UNIVERSITY
Department of Energy Technology
Pontoppidanstræde 101
DK-9220 Aalborg
Denmark
Web address: http://www.et.aau.dk

Printed in Denmark by UniPrint
ISBN: 978-87-92846-56-3



Title:	Voltage Unbalance Compensation in the Distribution Grid through Distributed Generation
Semester:	10th Semester
Semester theme:	Master Thesis
Project period:	01.02.15 to 03.06.15
ECTS:	30
Supervisor:	Florin Iov
Project group:	WPS4-1050

SYNOPSIS:

In the last years the integration of DG in the distribution network has significantly increased. With this increase in the injection of energy from decentralized generators the grid faces new challenges. Energy surplus coming from RES may produce a reverse power flow in the network altering the way conventional power systems operate. Due to this the presence of overvoltages and voltage unbalances will be more commonly seen in the grid. Classical compensation methods are typically used in the transmission level. However, this methods assume that the network has a high X/R ratio and SCR. In order to compensate for this problems in the distribution network a new approach has to be made considering the characteristic of the distribution network such as the low X/R ratio.

In this thesis different methods for voltage unbalance compensation using the grid connected converter of a DER are analyzed. The operation of the methods is verified using Power Factory 15.

Keywords *Voltage Unbalance, Distributed Generation, Distribution Network, Power Quality, X/R ratio, SCR*

Enrique Müller Llano

Copies:	6
Pages, total:	76
Appendix:	3

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

Summary

This thesis deals with the voltage unbalance compensation in the distribution grid by using available infrastructure of DER.

In recent years DER have seen a progressive increment in the distribution network modifying the way that grid behaves. Power surplus results in reverse power flow which rises the voltage level in the feeders. This voltage rise might provoke undesired over voltages in the network. Moreover, depending on the technology DER can also increase the level of voltage unbalance if various single phase DER are connected in a single phase of the distribution grid.

Until now multiple studies exist regarding voltage regulation and unbalance compensation in the transmission level. Nevertheless most of this methods rarely take into account the implications of applying this voltage compensation methods on the distribution grid were the X/R ratio is much lower compared to the transmission grid. Typically voltage regulation and unbalance compensation are done through the reactive power compensation. This approach might not be adequate for the distribution grid. In here a new approach is proposed that is valid for networks with any X/R ratio.

The effects of the X/R ratio and the SCR over the voltage profile are relevant for the compensation techniques. The grid strength determines the size of the voltage variations and with it how the compensation techniques work in each case. The distribution grid is usually characterized by its resistive nature and therefore a low X/R ratio. In such grid the voltage changes are determined by the active power flow, hence the effectiveness of reactive power compensation limited. Furthermore, the load demand and DER generation are also important factors to consider for the voltage unbalance.

The proposed method consists in compensating for the voltage changes with both active and reactive power and in this way have a more flexible control. This compensation method compensates the voltage drop/rise in each phase independently and therefore requires a natural frame control(control per phase). Another unbalance compensation technique is the negative sequence compensation method. This method aims to reduce the voltage negative sequence and thus lower the voltage unbalance. For comparison a steady state analysis is done for both unbalance compensation methods. Both of this methods were implemented in Power Factor 15.

It is always necessary the injection of unbalanced currents for unbalance compensation regardless of the compensation method. Moreover, the negative sequence method can manage to eliminate the voltage negative sequence and reduce the unbalance but it falls short in the presence of over or under voltages due to the effect that these have on the voltage positive positive sequence. The per phase method does not have the same capability for unbalance compensation as the negative sequence due to its limitations compensating for the voltage angle. However, it can successfully reduce the overvortlage and unvedervoltage. Finally, it is proven that through proper control of unbalanced current injection the voltage unbalances in the network can be mitigated and through the positive sequence the voltage rise/drop can be controlled.

Preface

This project was written from the 1st of February to the 3rd of June of 2015 by Enrique Müller Llano (WPS4-1050) as Mater's thesis for the study program of Wind Power Systems(WPS) at the Department of Energy Technology of Aalborg University. The thesis is about voltage unbalance compensation in the distribution grid through distributed generation. In this work the software MATLAB and Power Factory 15 have been used. This report has been written using LATEX.

Acknowledgment I would like to thank my supervisor Florin Iov for his invaluable support and guidance, the Mexican National Council of Science and Technology (CONACYT) for their financial support and Osvaldo Micheloud. I would also like to thank my family for their support and motivation.

Reader's guide The used information in the report has been found in literature, reports, information from the supervisors and from lectures. Through the report there will be references to these sources, which can be found in the Bibliography. The method for referring to these sources is the IEEE citation method, where it refers with [number]. All references used can be found in the CD attached to the present report. Tables, figures and equations are labeled with the number of the chapter. The CD attached to the report contains the Power Factory models, Matlab codes, and references.

Aalborg University, June 2, 2015

Enrique Müller Llano
<emulle13@student.aau.dk>

Contents

Nomenclature

Abbreviations

RES: Renewable Energy Source
GW:Giga Watt
CHP:Combined Heat and Power DG: Distributed Generation
DER:Distributed Energy Resource PCC: Point of Common Coupling
AC: Alternate Current
SCR: Short Circuit Ratio
VUF: Voltage Unbalance Factor
DC: Direct Current
PV: Photo voltaic
WTG: Wind Turbine Generator
kW: kilo-Watt
PLL: Phase Locked Loop
SRF: Synchronous Reference Frame
DSRF: Double Synchronous Reference Frame

Chapter 1

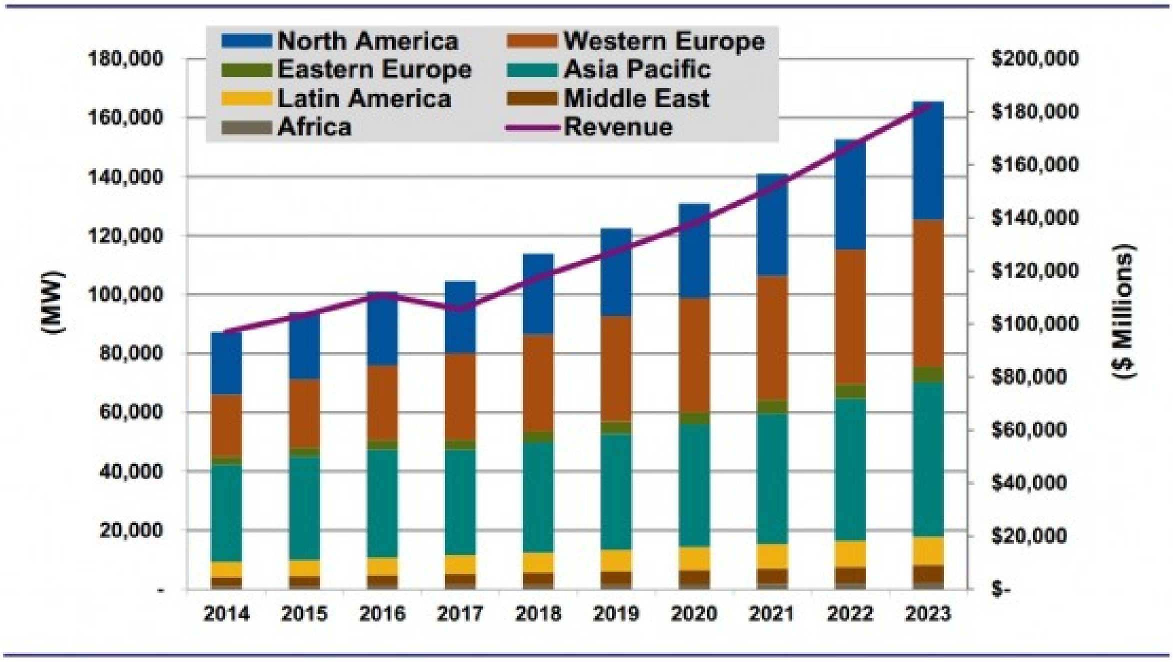
Introduction

1.1 Background

Since its creation in 1881 the operation of the electrical power system has not drastically changed until recently. Through the integration of new technologies, such as Distributed Generation(DG), the classical unidirectional power flow has slowly changed to a bidirectional power flow, allowing the active participation of the consumers and users on the electrical network[1].

Due to the benefits it brings DG has been rapidly growing in number in the last years, becoming an important component of the worlds future power systems. It is in the European grid were one of the largest expected growths in DG can be observed as shown in figure1.1. It is expected that the world DG installed capacity of 87.3 gigawatts(GW) will almost double to 165.5 GW by 2023 [2], from which the largest contribution comes from solar power followed by wind power. Denmark historically is a pioneer in adopting renewables and DG. Nowadays over 50 percent of its installed capacity comes from DG, mainly wind and small-scale Combined Heat and Power (CHP)[3].
DG has the advantage that it may be connected closer to the end user thus reducing transmission losses. Moreover, it can be separated into two general categories: controllable and uncontrollable. The first one refers to generators that can be started whenever the user requires it. The latter to the ones that depend on the weather conditions to generate energy; most of the Renewable Energies Sources(RES) fall into this category. Some of the benefits of changing to a decentralized power system include[1]:

- Avoid the need for building new infrastructure in the network
- Reduce the distribution network power losses
- Increase the systems flexibility
- Provide service support improving the continuity and reliability
- Help in “peak load shaving” and load management programs.



(Source: Navigant Research)

Figure 1.1: Expected DG installed capacity and revenue for different regions of the world[2]

However, DG may also create problems in the grid operation if new Distributed Energy Resources (DER) are installed without previous planning. As already mentioned, DER are usually installed close to the end user making the distribution network their main market. On the rural and suburban areas there is more available space for DER installation, but on the other hand the load density is much lower than in a urban setting. Furthermore, DER connected in the distribution network have been shown to provoke reverse power flow and hence raise the voltage level in the feeders leading to over voltages [4, 5, 6].Throughout the converters required for grid connection of solar and wind energy ancillary services may be included in their control in order to avoid the negative impacts of DER in the LV network.

1.2 Impact of DER in the Distribution Network

The integration of DG has multiple influence over the grid operation regarding[7]:

- power quality
- protection system
- fault level
- grid losses

The voltage rise in the distribution network is the main limitation of increasing the penetration of DER in it[6]. The effects of DG on the voltage in the distribution network are depicted in Fig. 1.2, where the DG is located where the generator "G" is placed. In the case nominal power is injected from the DER while the load power demand is at its lowest excess generation in the Low Voltage (LV) grid may lead to a reverse power flow and voltage rise. The opposite scenario is equally undesirable when the load demand is at its highest and the DER generation at its lowest creating an under voltage.

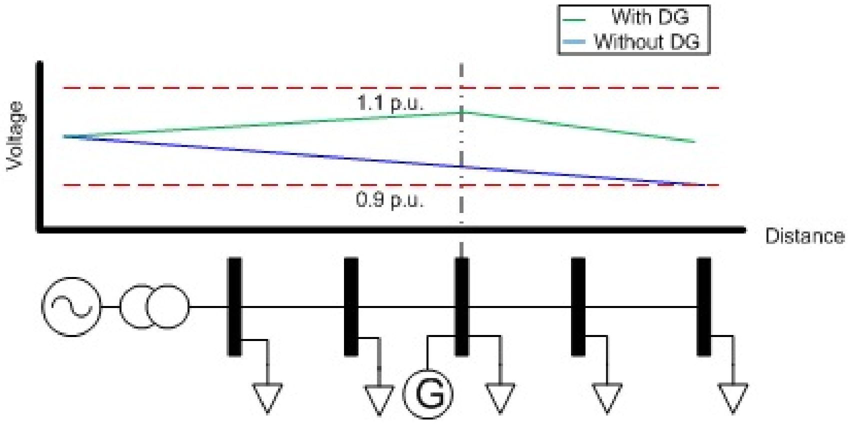


Figure 1.2: Effects of DG on the voltage profile of a radial on the distribution network

Additionally, the distribution grid also has the largest presence of unbalances in the network. Under normal conditions voltage unbalances and asymmetries come from the grid characteristics such as load demand and transmission lines. Until now, most studies and standards only take into account the voltage amplitude putting aside the phase differences. However, DG play an important role in the magnitude of unbalances and asymmetries. Single phase DER can further increment the differences between phases. High levels of DG integration in the grid make it necessary to take into account asymmetries to have a more precise measurement.

These phenomena is more prominent on rural and suburban areas where the loads are significantly smaller. The level of generation that can be connected to the distribution system depend on the Voltage at the DER, voltage level of the receiving end, size of the conductors as well the distance from DER, load demand on the system and other generation on the system [6]. In standard EN 50160 [8] the voltage variations in the LV network are limited to ± 10 percent.

One of the most popularized approaches to deal with the excess energy coming from RES is Active Power Curtailment(APC). In [9] it is shown that applying APC in the distribution grid to solve issues regarding over voltage may lead to a cascading effect and worse problems. Alternatively, other studies have proven that this raise in voltage may be used to the advantage of the voltage profile. DG may help to regulate the voltage in the distribution network, hence reducing the line power losses and control the unbalances[4, 10, 11].

1.3 Problem Statement

The growth of DG in the Danish distribution network increases the concerns regarding power quality. The reverse power flow due to DER power surplus together with the inherent voltage unbalances present in the distribution network represent an important challenge. This voltages may exceed the voltage unbalance limit set in standard EN 50160. In order to improve the power quality DER in the distribution network can be used to control the voltage unbalance.

1.4 Objectives

Considering the aforementioned effects the main objectives of this report/thesis are:

- Maintain the voltage in the distribution network feeders between the specified limits stated on EN 50160
- Compensate for steady state voltage unbalances through DG connected in the distribution grid

1.5 Scope

To study the impact of DG this thesis focuses the steady state analysis of a danish distribution network with high penetration of DER. An existent radial is selected from a low voltage benchmark grid as developed in appendix A.

1.6 Project Limitations

The project limitations for this thesis are the following:

- Assume that the controllers of the DER are operating correctly
- RES will be considered constant power source during the simulation period
- Study limited to steady state analysis
- Detailed study of the voltage dependency of the loads outside of projects scope

1.7 Report Structure

This thesis is separated into 5 different chapters including the introduction. On chapter 2 the distribution network and its characteristics are described. The principles of voltage compensation are explained and a study case is made to show how depending on the properties of the distribution network the voltage profile is affected. Moving on to chapter 3, the controllers required for implementing the unbalanced compensation methods are explained. In chapter 4, the distribution network shown in appendix A is used to implement and test the unbalance compensation methods. Lastly, in chapter 5 the final conclusions of the report are made and future works are suggested.

Chapter 2

Distribution Network Voltage Control

In this chapter the relevant characteristics of the distribution network and voltage control are explained. First, an overview of the general characteristics of the distribution network is done focusing on Denmark. The integration of DG and its effects over the network are described. Afterwards, a study case regarding the strength of the grid, load demands and DER generation is done to show their impact over balanced and unbalanced networks. Next, the methods mentioned in the literature for voltage regulation and unbalance compensation are analyzed. Further on, the proposed methods for voltage regulation and unbalance compensation are described.

2.1 Overview

Distribution networks are usually associated with the last level of any electrical system: the consumers. Grids have been built and operated until now with a vertical organization in which energy transfer follows a top to bottom pattern, meaning this that energy goes from generation to transmission thereafter to distribution and finally to the consumers[12].

The distribution and transmission networks differ substantially due to the objectives they were designed to fulfill. One of the differences between this two systems is that the connection topology in the distribution level are typically radial, whereas the transmission system has a meshed structure. This has to do with the fact that the distribution network was not designed for the connection of power generation devices[13]. Moreover, the lower voltage levels, power rating requirements and shorter transmission distances in the distribution network decrement the reactance to resistance (X/R) ratio. Transmission networks are characterized by higher X/R ratios typically around 7, while the distribution network has values around 0.5[14].

In the distribution network the DSO is the operator in charge of maintaining satisfactory system operation. In a traditional system the DSO is responsible for[12]:

- management, development and operation of the electricity distribution system in a secure and environmentally friendly manner
- connection and access to the network

- quality of supply.

2.1.1 Danish Network

In figure 2.1 the Danish energy consumption per sector is shown. The main sectors are the residential, manufacturing industry and the service and public sector(shown in the graph as "other"). In Denmark the residential and commercial consumers are typically connected to the distribution grid (400 V). Industry and companies are also usually connected to the this same voltage level but they also may connect to transmission level(20-6 kV)[15]. Most of the consumers in the danish network have a three phase connection.

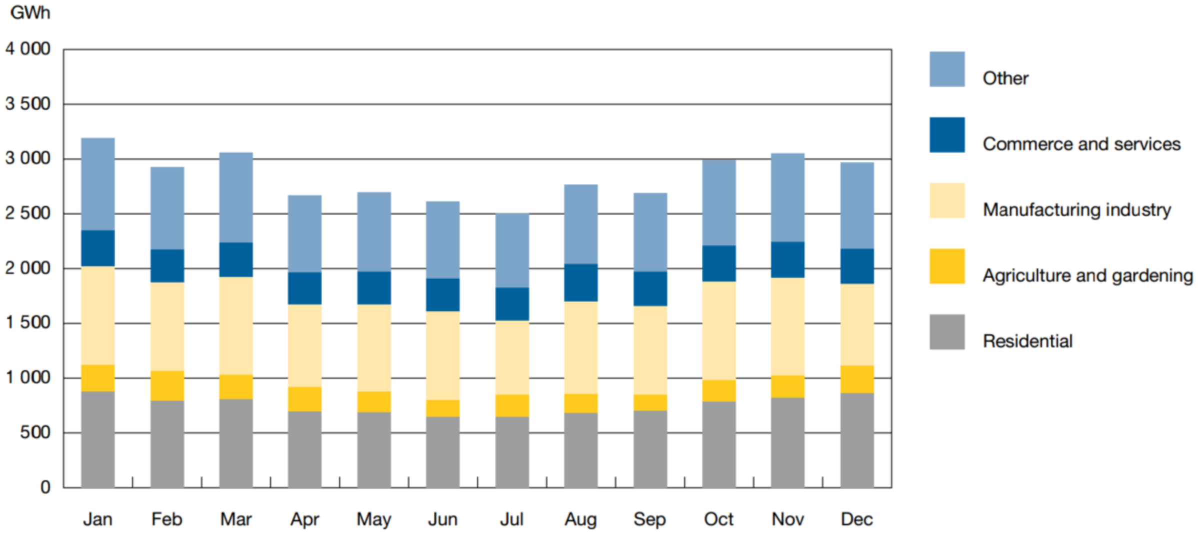


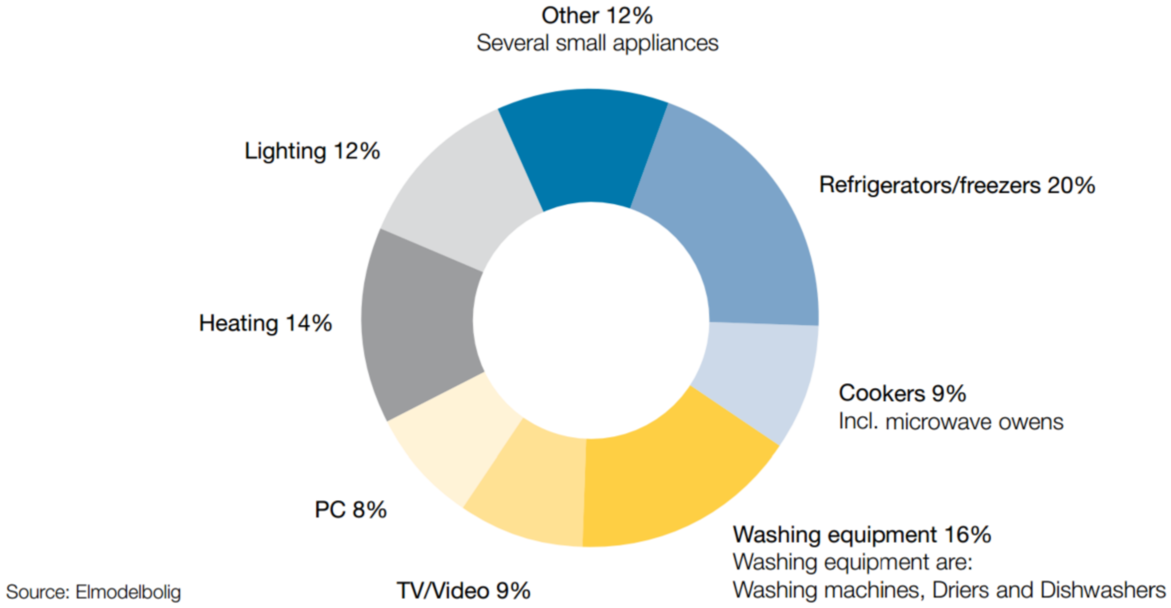
Figure 2.1: Monthly electricity consumption by main consumer categories in 2007[15]

In the Danish power system it is a common practice to put together the residential loads with some of the commercial loads. However, the industrial loads are typically separated from the other sectors. Furthermore, the residential sector can be separated into urban and rural. The urban sector has almost twice the electrical energy consumption than the rural sector[16]. This is mainly because in a urban environment there are more consumers, while the rural consumers have a higher energy consumption per capita. Figure 2.2 shows the participation of the most common loads in the residential sector. It can be seen that even though that three phase connections are common in the residential section most of the loads are single phase, with the exception of loads like electrical stoves and some heating devices that can have three phase connections.

Denmark has high level of DG with more than half of its total power being produced in this way[3]. The DG in Denmark are typically connected at 60 kV or lower voltage levels[15]. This makes the distribution network the main connection point for DG[1]. The DER may be either

---

[1] In the danish grid there is no clear separation in the voltage level to distinguish the transmission from distribution level[15].



Source: Elmodelbolig

Figure 2.2: Residential consumption according to types of appliances 2007[15]

have a three phase or single phase connection. Due to this difference in connection voltage unbalance in the grid will become more common.

2.1.2 Voltage Rise and Drop

Contrary to global grid parameters such as frequency, voltage is a local phenomenon[17]. Classical transmission systems are composed of long sets of over head lines which, depending on their length, are characterized by different parameters. Transmission lines are represented by the pi model shown in Fig. 2.3.

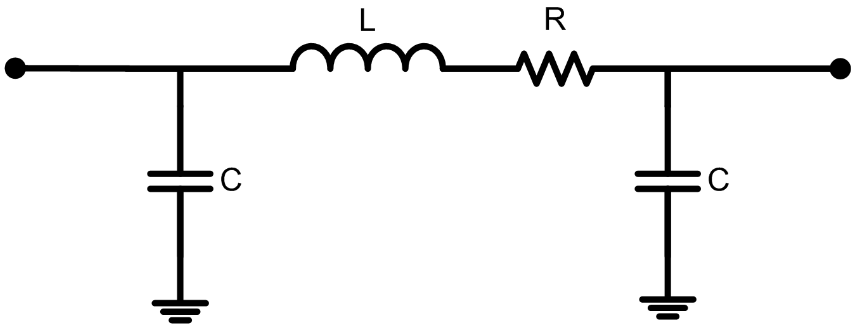


Figure 2.3: Transmission line PI model

The pi model is composed of a series resistance R to take into account the conductor resistivity, a shunt conductance G representing the leakage currents between the phase and the ground[2], a series inductance L to to the magnetic field in the conductors and a shunt capacitor C to represent the electric field between conductors[17].

Some of the main factors affecting the voltage profile in the system are:

- length and size of the transmission lines
- magnitude and power factor of the loads
- grid connected DER

Furthermore, a classical power system is commonly considered as mainly inductive. It is for this reason that reactive power is used for voltage compensation. Then, if all the reactive power that is being generated by C is consumed by L the line is said to be connected to its natural load[17]. In practice this is rarely achieved, hence voltage levels tend to be different than 1 pu. Voltage drops are often seen in the grid due to the inductive nature of the loads connected to it. This loads typically have power factors higher than 0.95[18].

However, this approach is only valid for systems with high values of X/R ratio. In [14] the effect of the X/R ratio over the voltage support of the grid is demonstrated. It is demonstrated that due to the higher resistive characteristic of lower values of X/R the reactive power plays a less important role in maintaining the voltage, while the active power has a higher impact. This can be clearly demonstrated through the phasor diagram shown in Fig 2.4. On the left a system with a high X/R ratio is shown where the voltage magnitude main component is the jX, while on the case with a low X/R ratio the R has a bigger influence over the magnitude of the voltage.

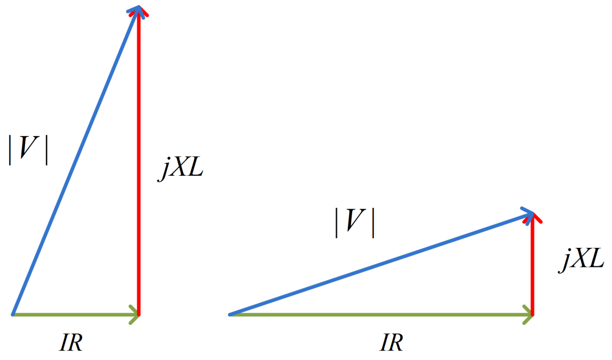


Figure 2.4: Voltage phasors for a low and high X/R ratio

2.1.3 Voltage Unbalance

Voltage unbalances are defined in standard EN 50160 as "a condition where the (Root Mean Square) RMS value of the phase voltages or the phase angles between consecutive phases in a

---

[2] Usually the effect of the shunt conductance is neglected due to its small influence in the system[17]

three-phase system are not equal"[19]. It is a common practice in the literature to use the term unbalance to describe both the phase and amplitude. This practice supposes that unbalances and asymmetries are the same, which might not be true. In this thesis the term "unbalance" will be used to refer to differences in RMS value while "assymetry" will be reserved specifically for phase angle deviations. Furthermore, unbalances are a result of three general factors: terminal voltage of the generators, impedance of the electricity system and currents drawn by the loads throughout the transmission and distribution grid[20].

First let us analyze the voltage unbalances originating from the transmission level. The voltage levels in the part of the generation are typically highly symmetric and the differences in line impedances are due to the nature of the transmission system. Voltage unbalance is caused by a physical asymmetry of generating and transmission equipment[21]. In order to avoid this issues the transmission lines are transposed with the objective of maintaining the symmetry between the cables. If this is not done this are permanent sources of unbalance in the grid that can become worst if the system is loaded with unbalanced load[21].

Since the distribution system is the last level of the electrical network the unbalances are usually more notorious. The main source of permanent voltage unbalance in the consumer level are transformer bank connection, transformer impedance, transmission system impedance, distribution network characteristics, three-phase and single-phase load magnitudes, load power factors, and transmission network voltage unbalance[22]. Moreover, load variations related to the different energy consumption habits of each consumer may also further increase the total unbalance in the system. In most practical cases, the asymmetry of the loads is the main cause of unbalance[20].

2.1.4 DG Integration

DG changes the classical Distribution Network control methodology that was used until now. The energy injection in the consumer level and the use of converters fo grid interaction has an important impact on the voltage profile and unbalance level of the system.

Energy surplus originating from DER produces a reverse power flow from the distribution network to the transmission system as shown in Fig 2.5. Excess power will rise the voltage profile locally. This voltage rise is a steady-state effect and it strongly depends on the X/R ratio, feeder load, injected power by the DG unit and the short-circuit power of the grid at the point of interconnection [7]. For the nature of the distribution grid, the voltage changes are predominantly a product of the active power. Furthermore, it is common practice in the transmission network to measure its strength with its X/R ratio and Short Circuit Ratio(SCR). The SCR relates the nodes short-circuit power and the rated power of a RES (typically a wind farm)[23].

Moreover, it is a common practice to test the design of a system under the worst case scenarios to asses that the network voltage profile is within the voltage limits. These scenarios are[7]:

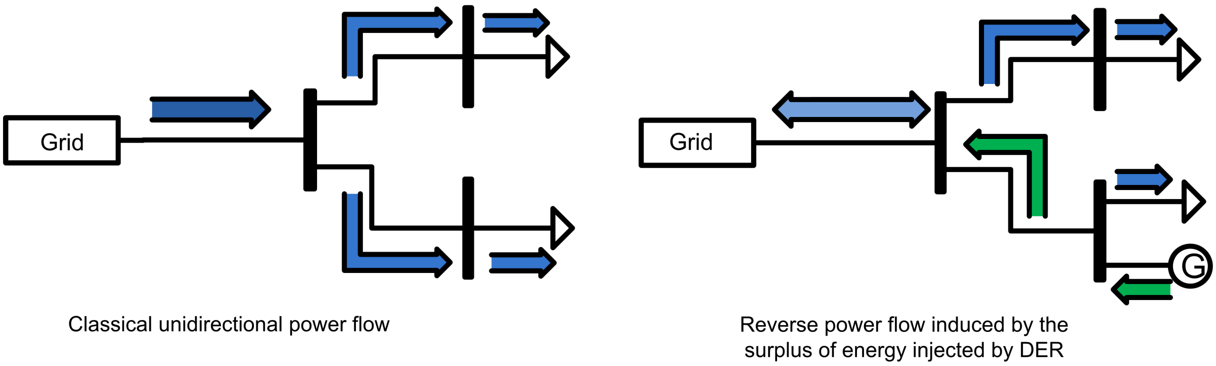


Figure 2.5: Classical and Reverse Power Flow

- no generation and maximum system demand
- maximum generation and maximum system demand
- maximum generation and minimum system demand

Until now the consumers "regulate" the power output of power from the DER. The consumers with DER will inject the maximum power they can depending on the weather conditions not on the network requirements. If the voltage exceeds the limits corrective actions have to be applied. Furthermore, the variability of energy injection from DER leads to a higher occurrence of the worst case scenarios. High levels of DG penetration may even require additional scenarios to ensure that the system is within its boundaries.

Typically sensitivity studies in the power system are done to better asses the correct operation of the network. Sensitivity is defined as the ratio of change relating small changes of some dependent variable to a small change of some dependent variable[24]. For example, in power systems it is a common practice to calculate the voltage sensitivity to active or reactive power. For this purpose different study cases were done to analyze the impact of the relevant parameters.

2.2 Study Cases

To study the parameters affecting the voltage characteristics a small radial(Fig.2.6) was selected from the low voltage benchmark grid[25]. The model is built in Power Factory15 for simulation. The parameters of the grid can be found in the appendix A. This radial counts with a series of residential loads and PV panels connected in each Connection Box(CB). The load and PV panels connected in CB 2 represent the cumulative loads and PV panels of the rest of the network. The system is connected to an external grid through a step down transformer.

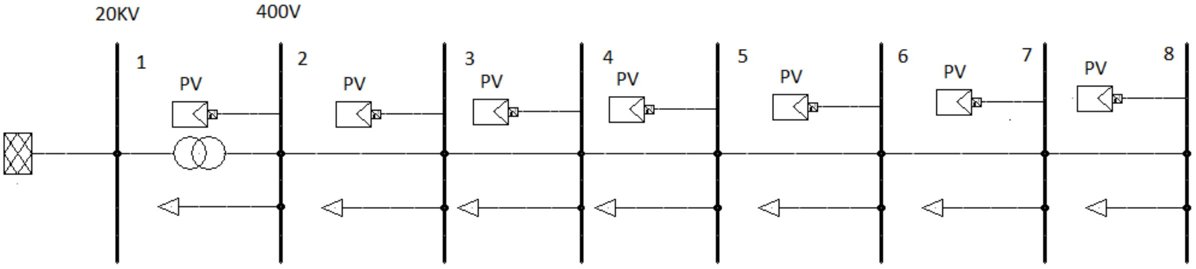


Figure 2.6: Radial network

The different scenarios analyze the effect of the relevant grid parameters on the voltage profile under different grid strengths. This is done to simulate from a urban scenario with a stiff grid to a rural setting with a weak grid. This parameters are the networks: X/R ratio, SCR, load demand and DER generation. The tested scenarios are the following:

- **Study Case 1**: X/R ratio and SCR impact at full load conditions without PV
- **Study Case 2**: Worst case scenarios in weak and stiff grids
- **Study Case 3**: Voltage and angle sensitivities in average stiff grids
- **Study Case 4**: X/R ratio and SCR impact under unbalanced loads and single phase PV

The first 3 study cases have the goal to measure the impact of SCR and X/R on voltage profile in balanced situations, while the last study case measures the impact of the same parameters over the unbalance.

For these studies it is important to take into consideration the voltage dependency of the loads especially for the weak grid scenarios. As mentioned before, the detailed analysis this subject is outside of the scope of the thesis.

Moreover, the X/R ratio and the SCR are used to determine the values of the resistance R_k and the impedance X_k of the external grid.

$$S_k = SCR * S_{load} \tag{2.1}$$

$$|Z_k| = \frac{|U_{grid}|^2}{|S_k|} \tag{2.2}$$

$$\theta_k = \arctan(\frac{X}{R}); \tag{2.3}$$

$$R_k = |Z_k| cos(\theta_k); \tag{2.4}$$

$$X_k = |Z_k| sin(\theta_k); \tag{2.5}$$

Where S_k is the Short Circuit Power and U_{grid} is the external grid voltage.

Study Case 1: X/R ratio and SCR impact at full load conditions without PV

The external grid, which would act as the slack bus, was replaced by a three phase voltage source to allow the voltage variations to appear. Furthermore, until now there is no definition nor calculation method for the SCR in the distribution network. Therefore, in this study the SCR was related to the ratio between S_k and the total installed load. In order to analyze more clearly the effects of each parameter an average stiff grid was used as the base case. The value for the SCR and X/R of the external grid were set to 10 and 5 respectively. First, the SCR was fixed at 10 while the X/R was changed from 0.5 to 10 (Fig.2.7a). Afterwards, the X/R was kept at a value of 5 while the SCR was varied from 3 to 15(Fig.2.7b). For the first simulation the loads were kept at its nominal power and the PV panels were disconnected.

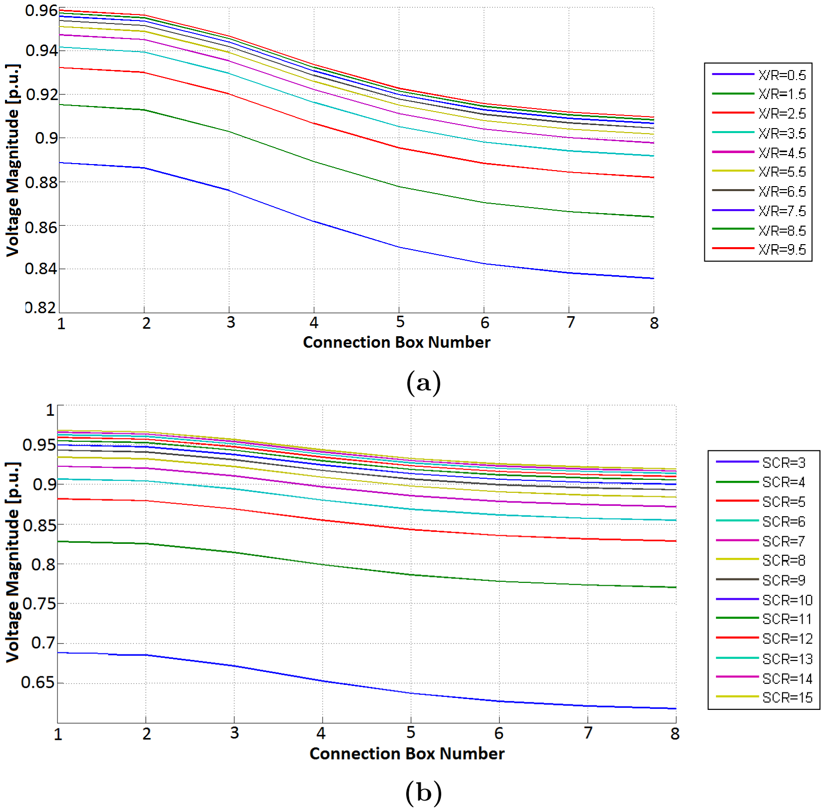


Figure 2.7: Separate effect of the X/R ratio and SCR variations impact on the voltage characteristics of average stiff grids

As can be seen the last CB has the lowest voltage in each case. Another simulation was made to observe the voltage behavior in the last CB by modifying both the X/R and SCR. In Fig. 2.8 the voltages for the last CB (number 8) are displayed, where each SCR is depicted with a different color. The voltage in the last CB is kept almost constant in a stiff grid while the voltage starts to have more notorious drops for weak grids. Furthermore, the voltage level is kept over the 0.9 p.u. voltage limit, marked in the graph with a red line, for values higher X/R=4 and SCR=8 proving the relevance of a stiff grid in maintaining the voltage constant.

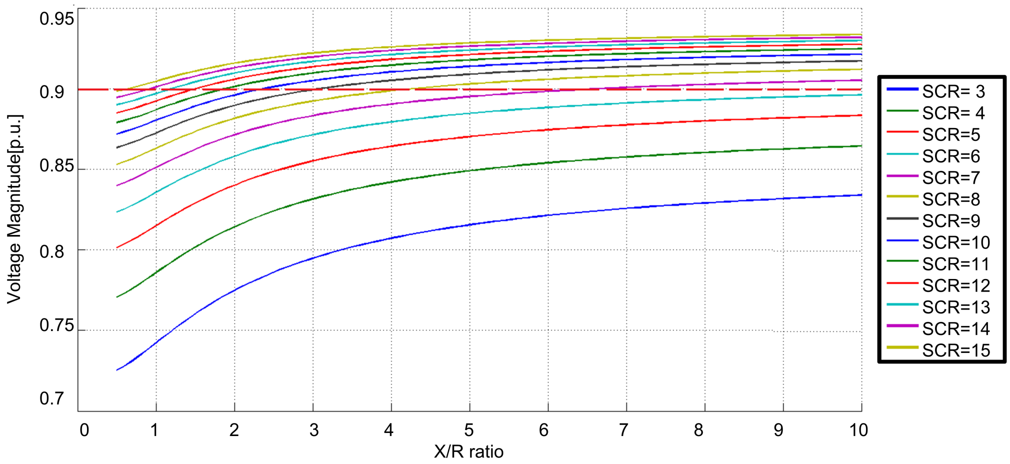


Figure 2.8: X/R ratio and SCR variations impact on the voltage(Balanced Loads)

Furthermore, the power input from the external grid to the system is directly proportional by the X/R ratio and SCR. Normally to calculate the power flow in a power system the resistive part R of the impedance is ignored. However, in our case its not possible to ignore R or the reactance X_L in order to correctly calculate the power with the changing X/R ratio. The next formula is used to calculate the complex power flow:

$$S = \frac{V_r V_s(cos(\delta) - jsin(\delta)) - V_r^2}{R - jX_L} \tag{2.6}$$

Where V_s and V_r are the voltage on the "sending" and "receiving" side of the line and δ is the angle difference between the two voltages. It can be seen that the maximum power flow is determined by V_r, V_s, R and X_L while the direction of the power flow depends on δ. Moreover, by increasing the SCR the magnitude of the impedance connecting the external grid voltage source to the system increases proportionally. Therefore, the networks are separated by limiting the maximum power flow between the external grid and the system as shown in Fig.2.9.

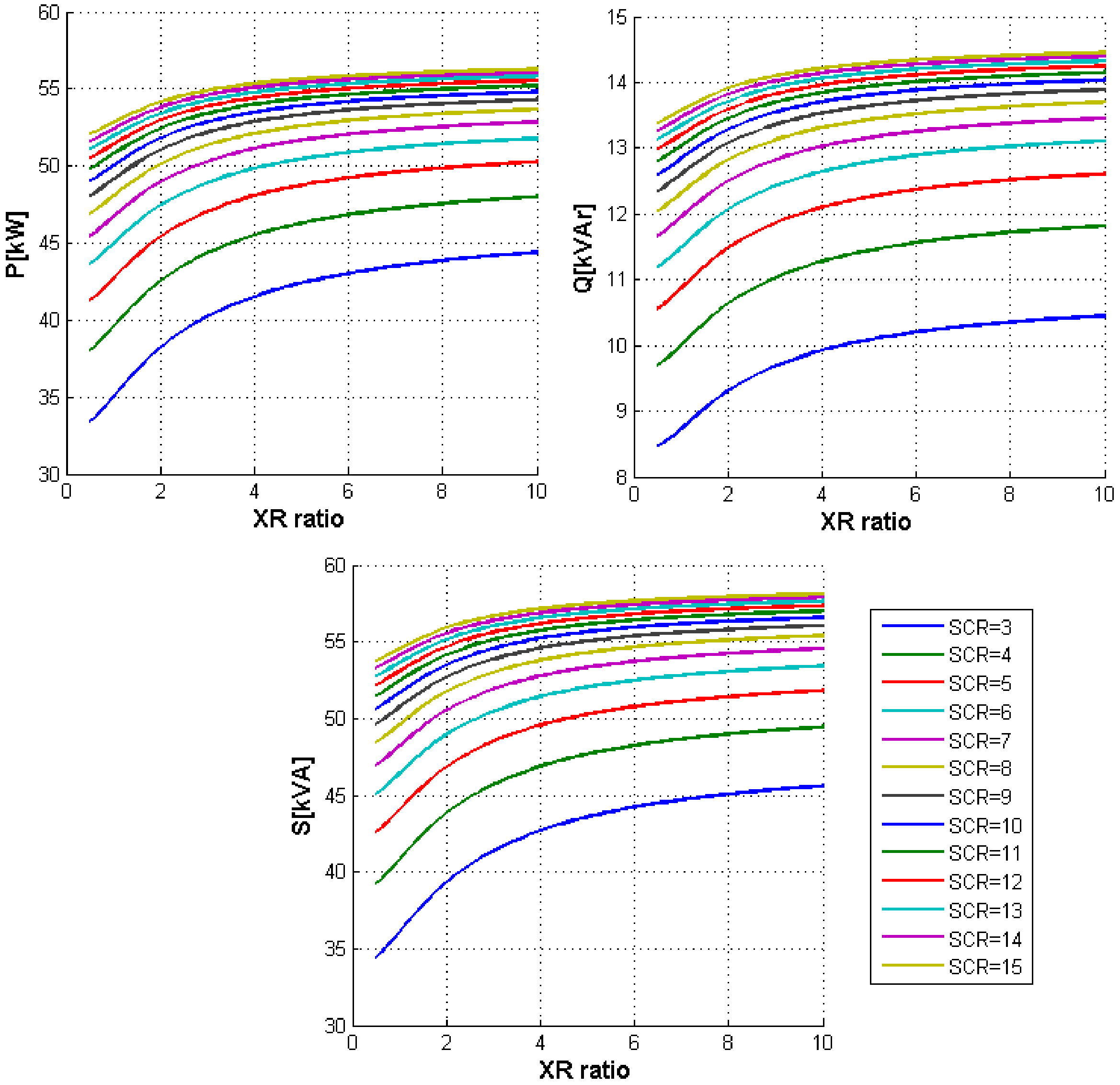


Figure 2.9: Active, Reactive and Apparent power flow between the external grid and the first bus bar

Study Case 2: Worst case scenarios in weak and stiff grids

In this case the PV panels and the loads are balanced three phase systems. These simulations focused on analyzing a system with high penetration of DG connected to a stiff and weak grids. The PV power injection and the residential loads were incremented in steps of 10 percent starting at 10 percent up to their nominal power. For every step of the PV power increment the loads were incremented the full range. The scenarios simulated were:

Table 2.1: Extreme worst case scenarios

Scenario	SCR	X/R	Load[p.u.]	PV[p.u.]
1	15	10	1.0	0.0
2	15	10	0.1	1.0
3	15	10	1.0	1.0
Full Load, No PV	10	5	1.0	0.0
10% Load, Full PV	10	5	0.1	1.0
Full Load, Full PV	10	5	1.0	1.0
4	3	0.5	1.0	0.0
5	3	0.5	0.1	1.0
6	3	0.5	1.0	1.0

In Fig. 2.10 the results are shown. As expected the PV raises the voltage profile specially at light load conditions. More notorious is the effects of the extreme scenarios on a weak grid where all the voltages are outside the limits. It is worth pointing out that these scenarios were made with the purpose of demonstrating the effects of RES on the consumer level .

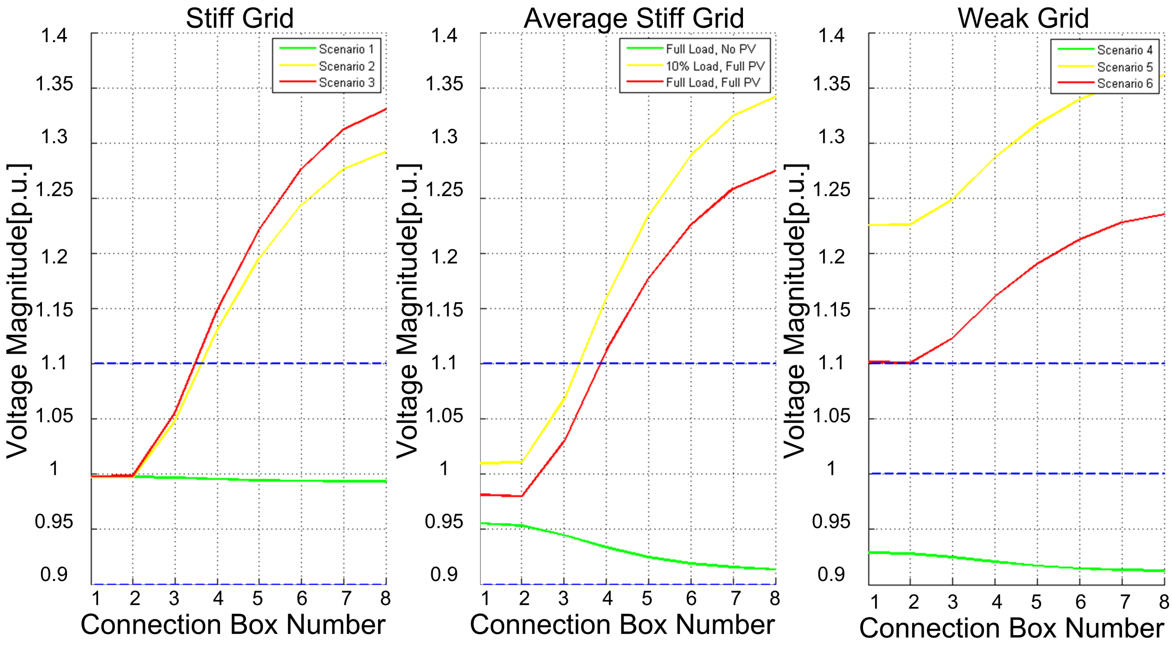


Figure 2.10: Worst Case Scenarios(Nominal Load with No PV, Nominal PV with Low Load)

Study Case 3: Voltage and angle sensitivity in average stiff grids

From the past study case it could be seen that the highest voltages where obtained at light load and nominal PV power injection. For this reason this scenario was chosen to study the voltage and angle sensitivities on a grid with X/R=5 and SCR=10. The same process of changing the X/R and SCR from the study case 1 was used in this study case. The results for the voltage sensitivity are shown in Fig. 2.11(a). The trends on the sensitivity are kept fairly constant in the case of the changes of X/R. On the other hand, the changes of SCR have a notorious effect on the sensitivity, specially on the sensitivity regarding reactive power. The voltage is more sensible to the changes of active than reactive power towards the end of the radial network. However, on the left graph in Fig.2.11(a) it can be seen that the changes in SCR have an important effect on the voltage sensibility, making the voltage more sensible to reactive power at SCR lower than 5.

The same experiment was repeated for the angle sensibilities, the results are shown in Fig. 2.11(b). The same trend as in the previous simulation is maintained; the X/R changes have minimal changes in the angle sensibility while the SCR has a larger influence. Nevertheless, It can be seen that the voltage angle is more susceptible to changes in reactive power having a negative increment in its value.

Study Case 4: X/R ratio and SCR impact under unbalanced loads and single phase PV

For this study case the load demand and the generation of each PV system was used to create increasingly higher unbalance levels. The scenarios analyzed are the next :

Table 2.2: Load and PV unbalances scenarios

	Load[p.u.]			PV power[p.u.		
Scenario	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	0.1	0.1	1.0	1.0	1.0	1.0
2	0.1	1.0	1.0	1.0	1.0	1.0
3	0.1	0.1	1.0	3.0	0.0	0.0

For the first scenario the results are shown in Fig. 2.12. Due to its bigger load the current in phase C is different than in the other two phases. Therefore, as would be expected the voltage of phase C has a different drop in magnitude the the two other phases.

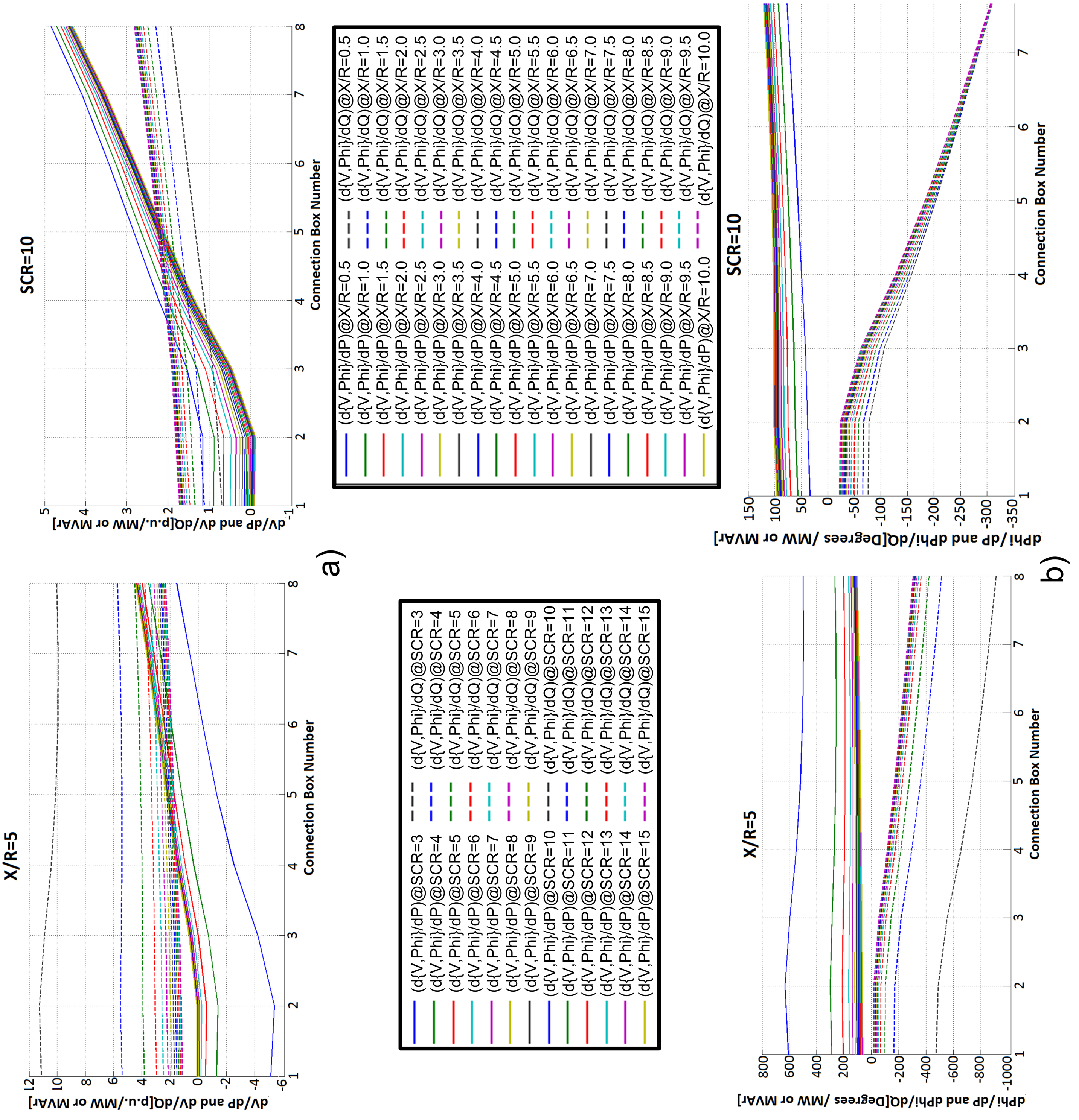


Figure 2.11: X/R and SCR impact on voltage sensitivities in a average stiff grid

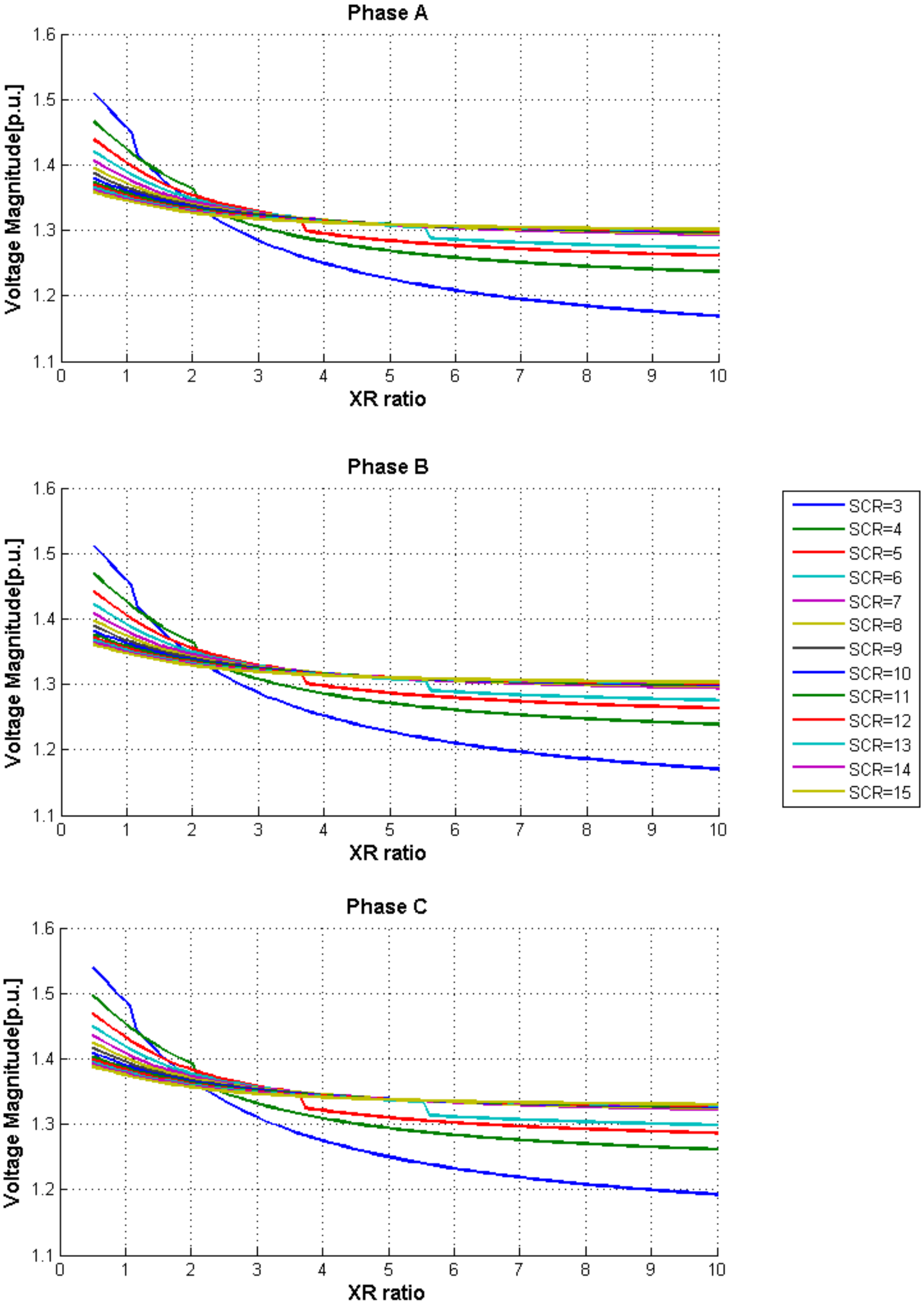


Figure 2.12: X/R ratio and SCR variations impact on the voltage(Scenario 1)

The loading of phase B was increased for the next scenario. Since phase A is the least loaded it was the most affected in this case. The voltages for CB 8 are shown in Fig. 2.13. It can be observed that increasing the load demand of phase B reduces the surplus of PV generation and therefore decreases the over-voltage in phase B and the system.

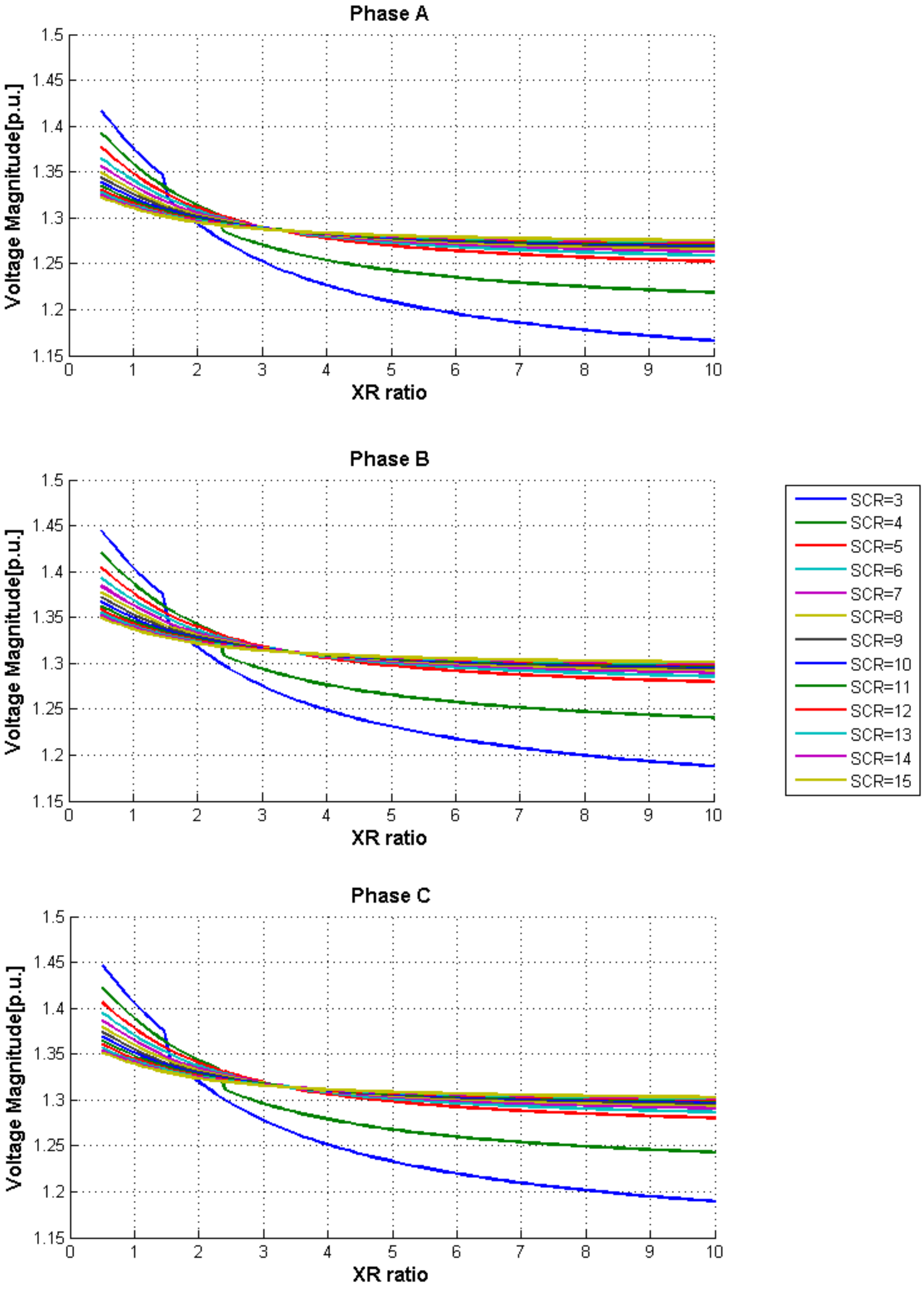


Figure 2.13: X/R ratio and SCR variations impact on the voltage(Scenario 2)

Finally, the last scenario is modified by changing the three phase PV panel to a single phase connected in phase A. As can be predicted the voltage unbalance is further increased together with the asymmetry. The focus in this scenario is the voltage asymmetry since it can be seen in Fig. 2.14 that the single phase PV panel can significantly increment the voltage asymmetry.

Phase A has a more prominent deviation in phase angle, while phases A and B show a similar deviation in phase angle, nevertheless not as big as in phase A.

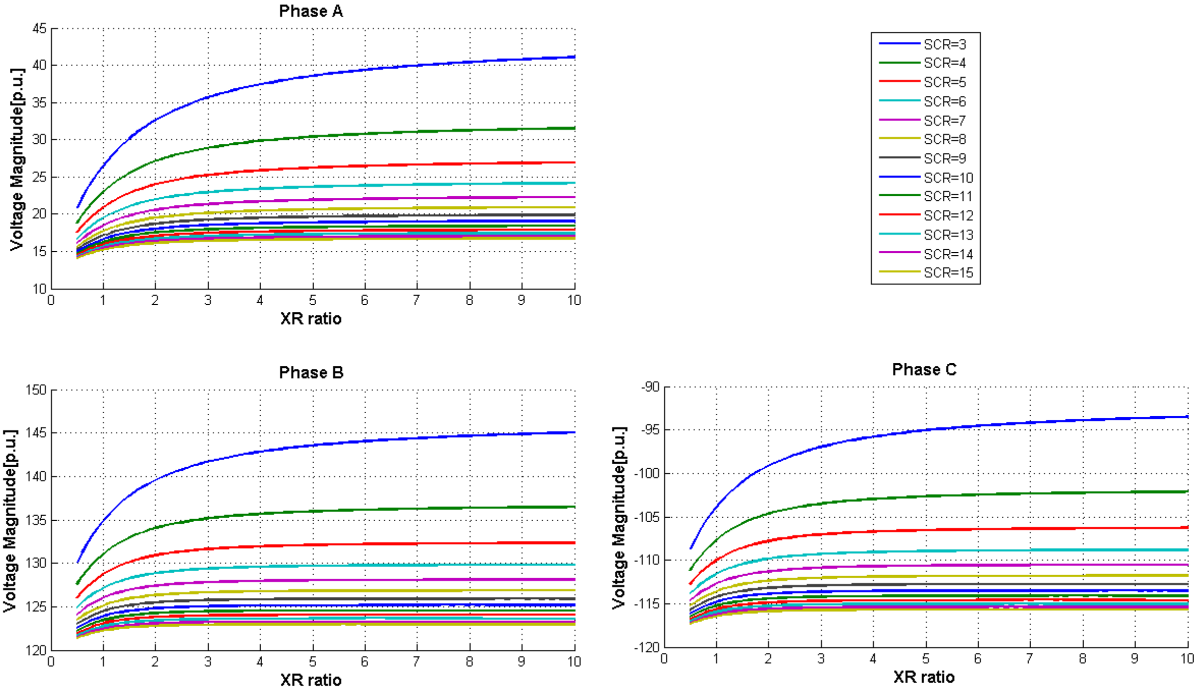


Figure 2.14: X/R ratio and SCR impact on the phase angle(Unbalanced Loads with single phase PV pannels)

Conclusion

With this study case it is shown that the X/R ratio and the SCR have an important effect over the voltage balance and symmetry. It is also noticeable that the voltage rise is more pronounced in the last CB. The voltage magnitude in this CB changes from a total 0.65 for the weakest grid to 0.93 for the stiffest grid. Moreover, DER also play an important role in the systems power quality. The voltage unbalance and asymmetry depends if the system is connected to a stiff or weak grid, the level of steady state unbalance in the external grid(supply voltage) and the DER technology(single or three phase).

The voltage unbalances can be measured through the Voltage Unbalance Factor(VUF). In this case the VUF were calculated with the equations suggested in IEC 610000 2-12:

$$VUF = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}}; \tag{2.7}$$

where:

$$\beta = \frac{V_{AB}^4 + V_{BC}^4 + V_{CA}^4}{(V_{AB}^2 + V_{BC}^2 + V_{CA}^2)^2}; \tag{2.8}$$

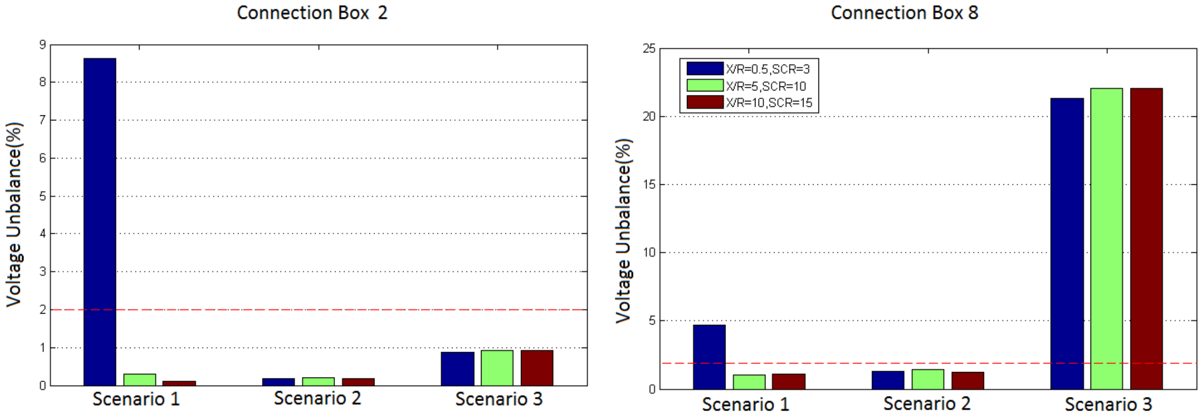


Figure 2.15: Voltage unbalance for the different scenarios

In Fig. 2.15 the unbalance for the first and las CB are shown for the different unbalanced scenarios (table 2.2). It can be seen that the weak grid has a higher influence on the light loaded phases of scenario 1. On the other hand two fully loaded lines in scenario 2 significantly lowers the unbalance level. This means light loading has an important influence over the unbalance level in weak grids. Furthermore, it is evident that the highest unbalance is present in the last CB on the lightly loaded lines and single phase PV systems of scenario 3.

This is not the same case for the first CB in which the highest registered unbalance is on the weak grid of scenario 1. This is mainly due to the cumulative load connected in this bus which helps to mitigate the effects of the PV energy surplus. Moreover, in general the stiff grids have a lower unbalance in the system except in the scenario 3 where the weak grid has a lower unbalance. This a product of the weak grid being more prone to voltage variations. To better understand this the grid can be compared to beams suspended in the air by springs connected with hinge joints as shown in Fig.2.16. The springs suspending them represent the grid stiffness, where the first spring represents the external grid in this case, and the weights on their sides the loads. If the first spring is stiff the displacement(voltage change) will be small. On the other hand, if it is a weak spring the starting displacement change will be much larger making the changes in the following beams larger. If the same example is used in a three phase system it cn be seen that this helps a weak grid to maintain the voltage unbalance lower since all the voltage levels have a more uniform variation but at the expense of a much larger voltage variation.

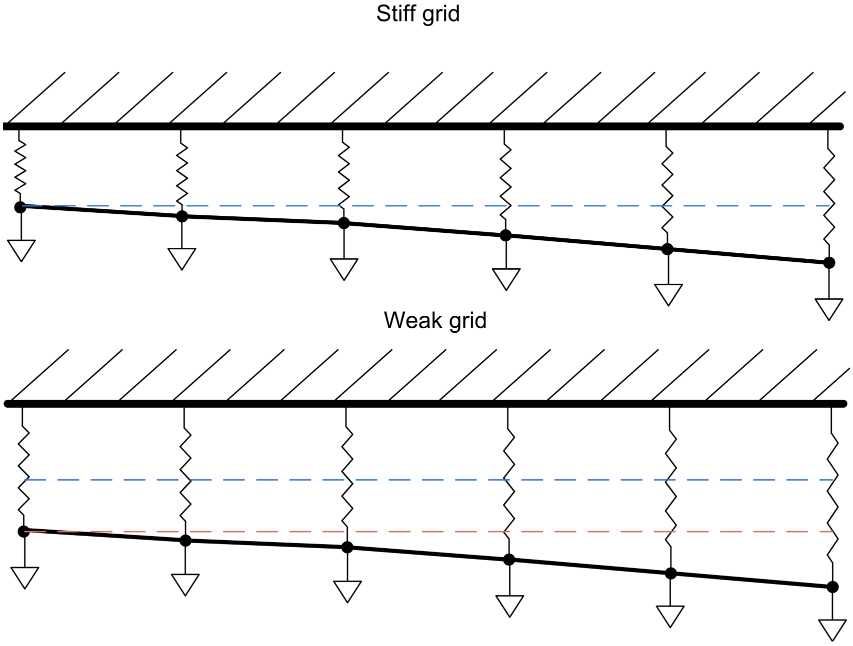


Figure 2.16: Comparison a weak and stiff grid with a set of beams suspended by springs. The "stiffer" the spring the less the beam will move up and down similar to the voltage variations on a stiff grid.

2.3 Technical Connection Requirements

Standard EN 50160: Voltage Disturbances In the Danish system this requirements are in Energynet's "Regulation for grid connection TF 3.2.1" which covers generating Facilities of 11 kW or lower[26]. The voltage limits in the distribution network are taken from stanard EN 50160 which specifies a maximum of 2 percent VUF and ± 10 percent voltage variation for medium and low voltage networks[19]. A resume of the relevant limits on standard EN 50160 are shown in table 2.3.

Supply voltage characteristics according to EN 50160

VUF	Voltage Magnitude Variations
2%	± 10 %

Table 2.3: Distribution Network Voltage standard according to EN 50160

2.4 Voltage Drop and Unbalance Compensation

For its nature, voltage needs to be locally controlled, meaning that voltage compensation has to be provided as close as possible to where it is required. Typically, the voltage is kept within the limits specified in the standards by coordinating various devices such as generators, on load tap changing transformers, static VAR compensator(STATCOM), etc[12]. This methods have been proven to be effective in compensating for voltage related problems, such as unbalances and voltage drops, in the classical system analyzed in the previous section. Nevertheless, when the consumers connect their DER these methods are not sufficient to maintain the voltage profile under safe limits. In order to increase the DG penetration in the grid DER require additional controls to maintain the voltage level within its tolerable limits.

Furthermore, DER energy injection in the consumer level can be used in benefit of the power quality and voltage profile of the grid. In this section some of the proposed methods mentioned in the literature for voltage regulation and unbalance control are analyzed.

2.4.1 Classical Voltage Regulation Methods

The two most common methods used by the DSO to regulate the voltage are the switched shunt capacitors and step voltage regulators[27]. These methodologies were created taking into account the top to down power flow the grid was designed to have originally.
The shunt capacitor is a simple solution. Its purpose is to supply additional reactive power to the grid in order maintain the voltage constant up to the distribution substations. However, the capacitor has little to no effect after the distribution substations due to the lower X/R ratio.
The step voltage regulators are typically implemented on the distribution substations or even further downstream[27]. They operate by changing taps to compensate for voltage changes, typically voltage drops. One of the most common technologies used for this is the on load tap changer(OLTC). The OLTC installed in the distribution system can have a larger effect on its voltage profile. Its mayor disadvantages is that OLTC have limited uses per day and control over the voltage, determined by the voltage change of each tap. When considering systems with high penetration of DG the conventional OLTC voltage control methods may be insufficient to cover the voltage changes[28].

2.4.2 Converter based Voltage Regulation Methods

Nowadays the most common of these technologies used in the grid is the STATCOM. It has the capacity to inject or consume reactive power in the grid to keep the voltage magnitude constant. However, STATCOM is intended to be used on the medium voltage level(X/R higher than 4); its cost it too high to justify its use in the low voltage level.

Let us first analyze the control structure for grid connected RES. A ideal Renewable Energy Sources and Storage(RES&S) has a four quadrant converter(inject or absorb active and reactive power) as shown in Fig.2.17. DER usually operate at quadrants I and IV injecting active power and are required to operate at a Power Factor(PF) above 0.9[29]. Modern power converters can offer a complete decoupling of the active and reactive power. However, the amount of reactive power it can dispatch depends on the rating of the converter. Furthermore, DER connected in the consumers Point of Common Coupling(PCC) typically inject maximum power to the grid depending on the weather conditions.

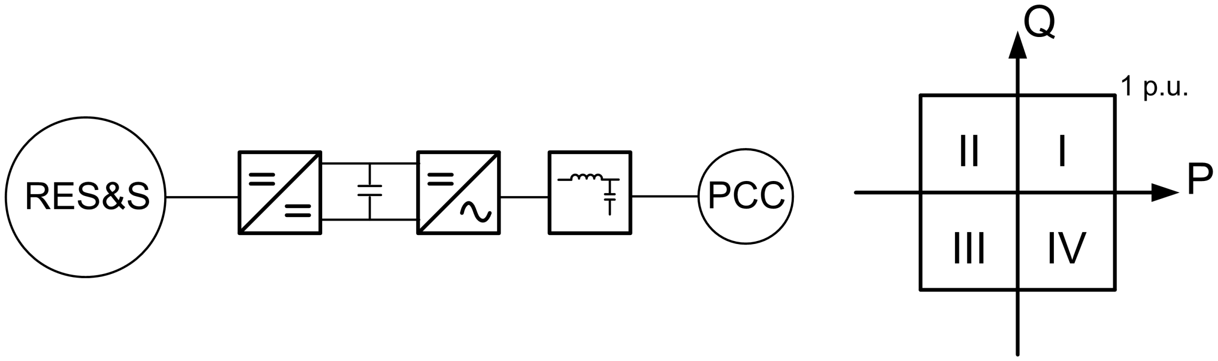


Figure 2.17: PV system with capability of injection and absorption of active and reactive power(ideal PQ chart)

Moreover, one of the most common and simple approaches for voltage regulation using DER only takes into account the rating, operating power factor and location of the DER to keep the voltage profile within limits[30]. However, this method is ineffective to compensate for voltage unbalances. Some of the voltage control methods regarding DER active participation proposed in the literature are analyzed next.

2.4.3 Voltage Regulation

In general, these methods try to keep the voltage between specified boundaries by controlling the power injection from the DER. In [31] the author states that depending on the voltage state a single unit may be in one of three operating modes. The normal state is when the voltage is within desired voltages; in this state the converter should have a P/Q control. When the voltage surpasses the desired values and enters the disturbed state then the operating mode should be changed to P/V control to correct the voltage magnitude. Finally, if the critical state is reached and the voltage exceeds the maximum or minimum admissible voltage levels, the DER should change to active power regulation mode. Moreover, a Droop control is used to set the power references for the outer loop controllers.

As far as voltage support is concerned its methods can be either centralized or decentralized[32]. Centralized control requires communication with all the DER connected in a grid so a higher level central controller can take care of setting the references of the DER. Current and voltage measurements are taken in the PCC of the DER as shown in Fig.2.18. This measurements are sent to the central controller. The measurements are fed to the droop controller and afterwards the power reference are sent to the local controllers.

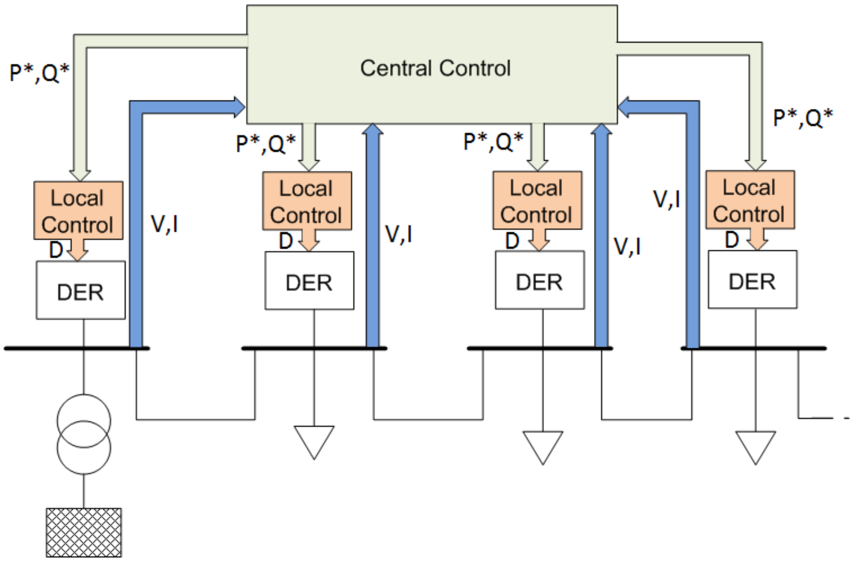


Figure 2.18: Centralized DER control in Distribution Networks

Using DER for voltage control can result in conflictive operation with the OLTC due to uncoordinated operation. Furthermore, the controls of the central controller can also be extended to the OLTC in the substation transformer to coordinate the DER and the OLTC operation. This methods commonly use a hierarchical arrangement to decide the contribution from each device depending on the electrical position, cost of generation, or other relevant parameters. In [33] the sensitivity towards the distribution substation with the OLTC and the DER are calculated and multiplied with a cost dependent weight factor. Afterwards, the control zones for the DER and OLTC are selected by plotting the sensitivity profiles and finding the intersection between the two plots. In [34] a similar approach is used using dynamic programming to calculate the optimum dispatch. The goal is to improve the networks efficiency by reducing the real power losses.

Until now all the aforementioned methods require communication between various grid components. This is an important drawback since it requires additional infrastructure, more complex control structures and add communication time delays that affect the control performance. In decentralized voltage support this is no longer a problem. For this topology the voltage support is embedded directly on the local control of the DER making it more reliable. Moreover, the voltage compensation can be shared within multiple DER connected in the network by using a droop controller as done in [35, 36, 37]

2.4.4 Voltage Unbalance Compensation

In the previous section the methods analyzed are specific for balanced power injection into the system. This is not enough to compensate for voltage unbalances in the network. Since the voltage unbalance is a product of the unbalanced elements such as line impedance, load demands and generation in the network a more selective method is required.

For the most part the literature relates unbalances with fault conditions. Nevertheless, in general the same the theory applies for steady state unbalances. In order to compensate for voltage unbalances these methods rely on the injection of unbalanced currents. The power injection from each phase has to be individually controlled. For this reason, these methods make use of the symmetrical components.

In [38] the Clark transformation is used together with a sequence extractor which separates its V_α and V_β into its positive and negative sequence as shown in Fig.2.19. The voltage measurements are fed to the outer loop control where there are used to set the power references. Furthermore, active and reactive power references are generated by a DC link voltage controller and voltage support controller respectively. The outer loop outputs the current references I^*_α and I^*_β for the current controller. Additionally two control parameters k^+ and k^- are added to the reactive power component of I^*_α and I^*_β to balance the negative and positive sequence voltage for a more flexible voltage support.

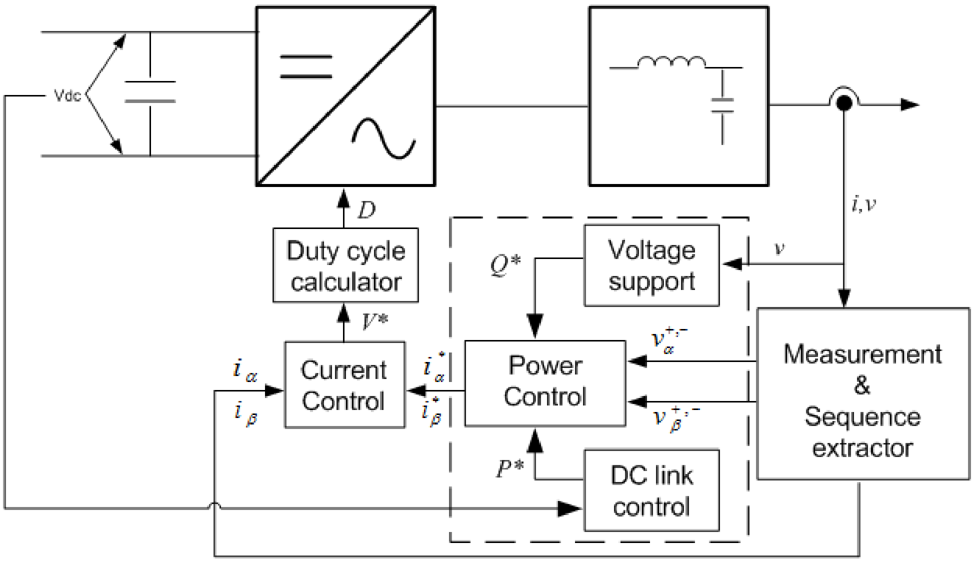


Figure 2.19: Grid side converter control for voltage unbalance compensation

Another approach is taken in [39] where the control is made per phase. This means that each one of the phases has its own control loop that determines its phase power injection. This is called as vectorial or natural frame control[29].

As can be seen many approaches exist for voltage regulation control and unbalance compensation. However, they mostly focus on the reactive power. Due to the distribution grid predominant resistive nature reactive power compensation might not be adequate for managing the voltage profile.

The X/R ratio has an important influence on the effectiveness of using either the reactive or the active power for voltage compensation. For this reason, in the next section a more in detail analysis of the theory related to voltage control is made.

2.5 X/R ratio effect on the Voltage Compensation technique

A small circuit is used in this case to demonstrate the effects of the X/R ratio over the voltage regulation techniques. An external grid consisting of a AC voltage source and a impedance Z_k is connected to a load of 1 kW with a power factor of 0.9 (lagging) as shown in Fig.2.20. The Z_k is calculated by means of the X/R ratio and the SCR of the grid as done in section 2.2.

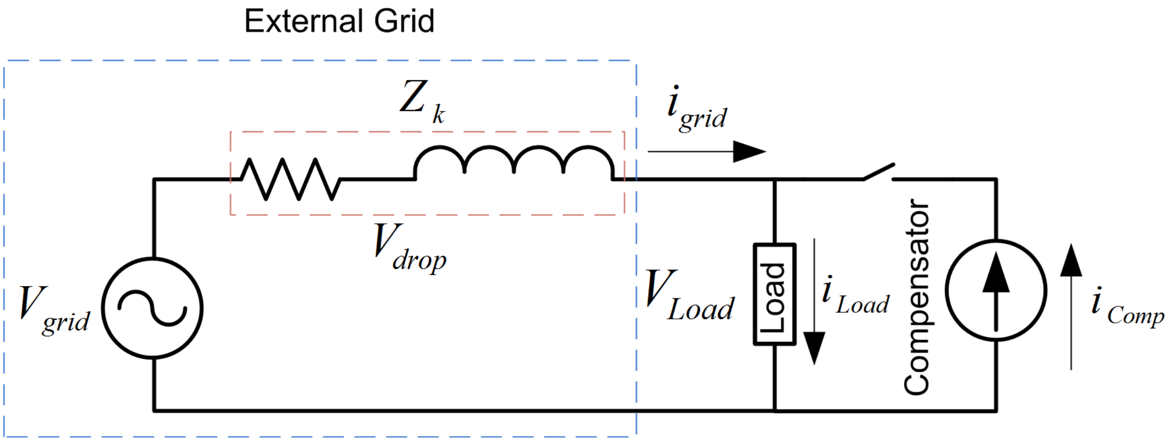


Figure 2.20: Test circuit for voltage compensation

Additionally, a current source is connected to the load in parallel. This element will act as the compensator by injecting current to the circuit. For all test the rated power of the compensator is the same as the rated power of the load.

The phasor diagram is an important tool to better understand the principles of voltage regulation. In Fig. 2.21 the phasor diagram for the circuit without a compensator is shown. It can be clearly observed that the load voltage V_{Load} has a phase and magnitude displacement from the grid voltage due to the line voltage drop V_{drop}. In this simple case the V_{drop} is the difference between V_{grid} and V_{Load}:

$$V_{drop} = V_{grid} - V_{Load} = (R_k + j * X_k) * i_{grid} \tag{2.9}$$

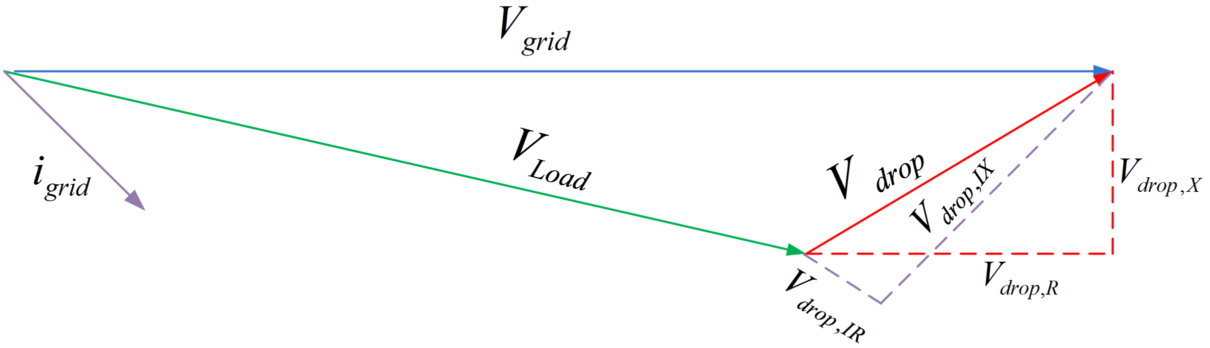


Figure 2.21: Phasor diagram for the voltage compensation test circuit

Moreover, the voltage drop can be further separated into different components to analyze its behavior. By multiplying the line current i_{grid} with the R_k and X_k it can be clearly seen how much each one of the line components contributes with the voltage drop. The component related to the resistance $V_{drop,IR}$ is in phase with i_{grid}, and therefore it is rotated clockwise from V_{drop} the phase of Z_k. Furthermore, the contribution from the impedance $V_{drop,IX}$ is in quadrature with $V_{drop,IR}$.

This equation is the starting point to separate the voltage change ΔV into other components which can be more useful for voltage compensation. The term ΔV will be used in this case to refer to the difference between two voltage phasors. In [40] the components are separated into its real and imaginary parts. In this approach some assumptions are made considering a transmission network such as neglecting the resistive part. A more generic approach is done here in order to consider any grid:

$$\Delta V = (R_k + jX_k)(\frac{P_{load} - jQ_{load}}{V_{load}})\ ; V_{load} = V_r + jV_i \tag{2.10}$$

$$\Delta V = (R_k + jX_k)[\frac{P_{load}V_r + jQ_{load}V_i}{V_r^2 + V_i^2} + j\frac{P_{load}V_i - jQ_{load}V_r}{V_r^2 + V_i^2}] \tag{2.11}$$

From which the real and imaginary components(ΔV_r andΔV_x respectively) are:

$$\Delta V_r = R_k\frac{P_{load}V_r + jQ_{load}V_i}{V_r^2 + V_i^2} - X_k\frac{P_{load}V_i - jQ_{load}V_r}{V_r^2 + V_i^2} \tag{2.12}$$

$$\Delta V_x = R_k\frac{P_{load}V_i - jQ_{load}V_r}{V_r^2 + V_i^2} + X_k\frac{P_{load}V_r + jQ_{load}V_i}{V_r^2 + V_i^2} \tag{2.13}$$

This components are also depicted in Fig. 2.21 for the V_{drop}. It is important to notice that P_{load}, Q_{load}, resistance and impedance are present in both the imaginary and the real part. This shows how much all the components are related in voltage regulation, specially on X/R ratio values close to 1.

In this equations the change in voltage is proportional to the power demanded by the load. Hence, the voltage can be controlled by substituting the P_{load} by $P_k = P_{load} + P_{comp}$ if the compensation is desired to be done with the active power or and Q_{load} by $Q_k = Q_{load} + Q_{comp}$ if by reactive power. In this way a part of the load power consumption is being supplied by the compensator. The compensation powers P_{comp} and Q_{comp} are used to rotate the phasor ΔV to control the voltage drop. Moreover, V_x is usually ignored in voltage regulation techniques since it is related mostly with the phase change[40]. However, in this case it is taken into account to have more flexibility in the voltage control.

By adding together equations 2.9,2.12 and 2.13 the next equation is obtained:

$$|\Delta V|^2 = |V_{grid}|^2 - |V_{Load}|^2 \therefore \tag{2.14}$$

$$|V_{grid}|^2 = (V_r + P_k A + Q_k B)^2 + (V_i + P_k B - Q_k A)^2 \tag{2.15}$$

Where:

$$A = \frac{R_k V_r - X_k V_i}{V_r^2 + V_i^2} \tag{2.16}$$

$$B = \frac{R_k V_i + X_k V_r}{V_r^2 + V_i^2} \tag{2.17}$$

The correction in the voltage drop due to the transmission line is limited by the power rating of the compensator. An ideal compensator would be able to absorb or inject always the required active and reactive power. In Fig. 2.22,the voltage compensation limits set by the compensator nominal capacity is shown as a brown circle. Moreover, the voltage compensation circle has its center in V_{load} and has a radius of $\sqrt{\Delta V_r^2 + \Delta V_x^2}$ substituting P_{load} and Q_{load} for P_k and Q_k. In this case the voltage compensator has multiple power combinations available which will result in a 1 p.u. voltage magnitude, represented with a blue circle of 1 p.u. voltage. Through equation 2.15 the required compensation power can be found to control the magnitude of V_{Load}. The compensated voltages are shown with doted lines and are indicated with the letter "c" in their subindex. Notice that if only the magnitude is compensated the phase and power factor will also be affected[40].

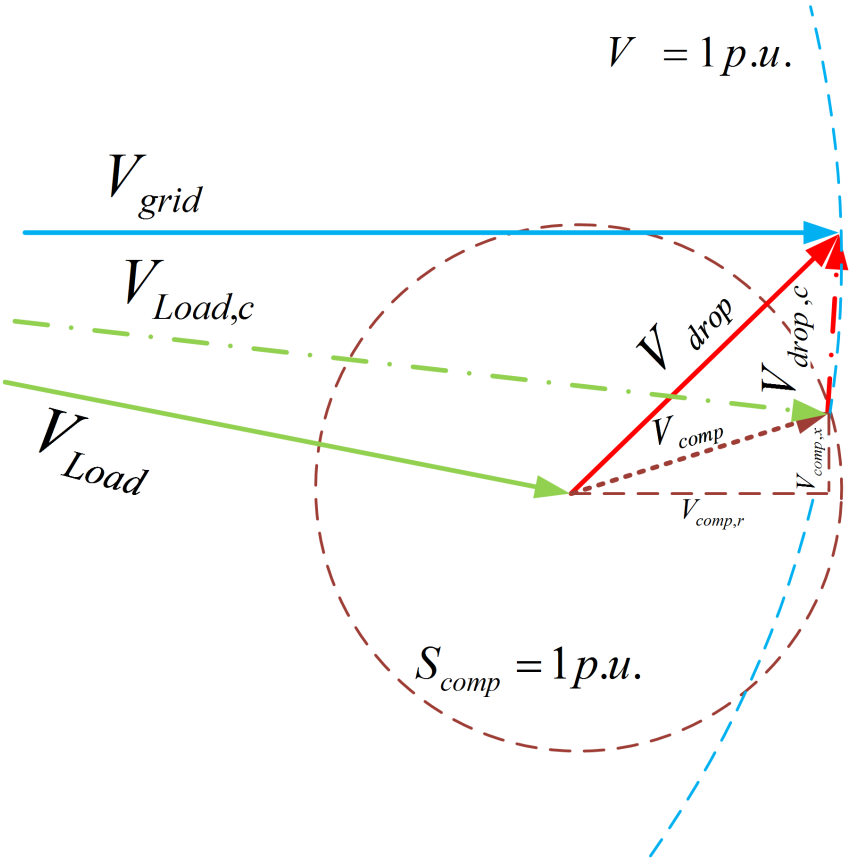


Figure 2.22: Effect of the rating of the compensation device over the voltage compensation capability (depicted with a brown circle)

Compensation methods usually assume that the grid has a high X/R ratio making it possible to ignore the resistive component. Typically voltage control is done through reactive power for the inductive nature of the grid. However this might not be the best solution. On the consumer level the X/R ratio tends to be much smaller than in the rest of the grid. In such networks reactive power compensation has a limited influence over the voltage magnitude. To demonstrate how this affects the voltage the compensation power was varied for the full range to absorb or inject active and reactive power at nominal power for different X/R ratios.

In Fig.2.23 the phasor diagrams resulting from these tests are shown, separating the voltage drop phasor into the components related to the active(blue) and reactive(green) power. The first thing that can be noticed is that the active power component has a more predominant effect in low X/R ratios as expected, while the reactive power component has a weaker influence. The opposite can be observed for high X/R ratios. Furthermore, it is also possible to observe that depending on the X/R ratio the compensated voltage phasor is different for the same compensation power. The increase of the X/R ratio produces a counter clockwise rotation on the phasor of the compensated voltage. The center of each one of the circles is also in a different position, this is due to the influence of the X/R ratio over the resulting uncompensated voltage.

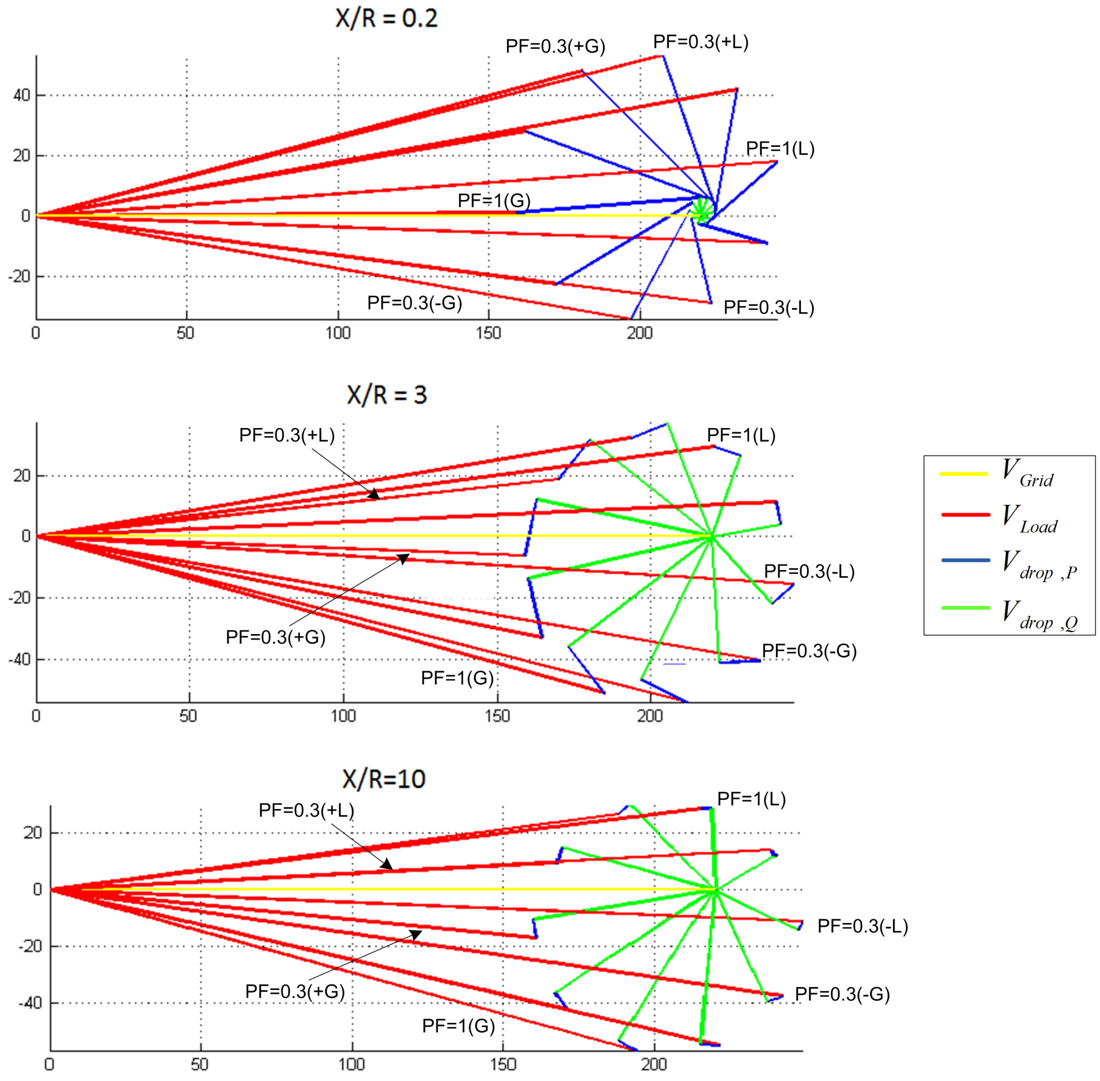


Figure 2.23: Compensation power components for different X/R ratio where the "G" indicates the compensator injecting power to the grid and "L" indicates its absorbing power from the grid

This influence over the voltage compensation can lead to scenarios were reactive power compensation is no longer effective. In [41] it is shown how the voltage compensation may produce different voltage changes depending on the X/R ratio of the system as shown in Fig.2.24. Using the compensator at half of its nominal power all the compensated voltages end up between the voltage limits. However, while the X/R ratio is lowered more compensated voltages appear outside of the voltage limits. This makes it more difficult to control the voltage.

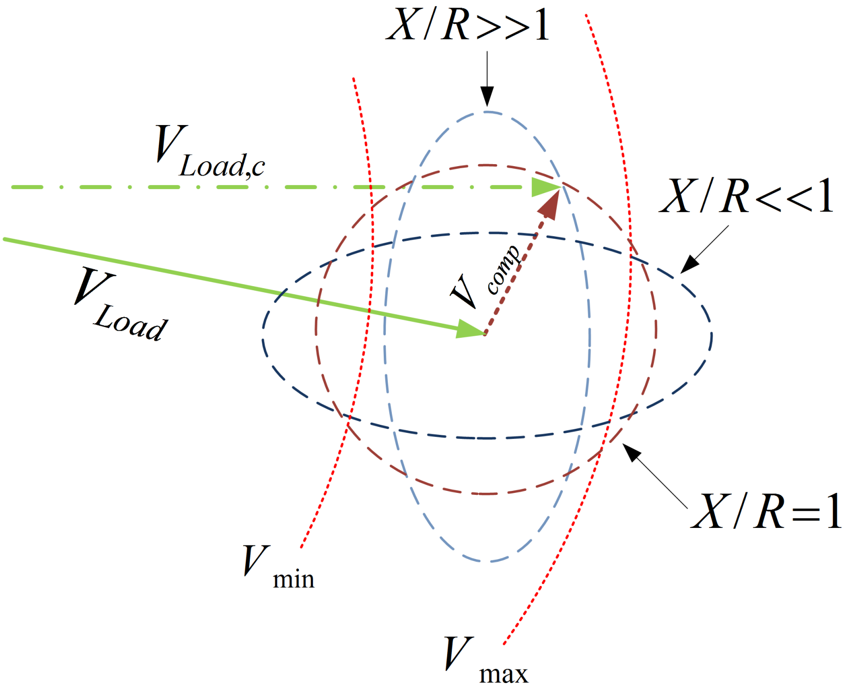


Figure 2.24: Effects of the X/R ratio over the voltage compensation capability

Until now the voltage control has not taken into consideration the phase angle. To do so phasors have to be used as in equation 2.9. V_{grid} can be substituted by the phasor of the desired magnitude and phase.

Going back to Fig. 2.22 it can be seen that the voltage magnitude can only be kept at unity if the phase angle is kept in the 1 p.u. circle. The limits for this are given by the intersection points between the 1 p.u. blue circle and the voltage compensation limits brown circle:

$$|\Delta V|^2 = (x - V_r)^2 + (y - V_i)^2 \tag{2.18}$$

$$|V_{1p.u.}|^2 = x^2 + y^2 \tag{2.19}$$

Where the intersection points are given by:

$$x = \frac{\Delta V^2 - V_{1p.u.} - V_i^2 + 2V_i y - V_r^2}{-2V_r} \tag{2.20}$$

And for the "y"(imaginary) the quadratic equation can be used with the following coefficients:

$$\begin{aligned} A &= (1 + \frac{V_i^2}{V_r^2}) \\ B &= \frac{V_i(|\Delta V|^2 - V_{1p.u.}^2 - V_r^2 - V_i^2)}{V_r^2} \\ C &= \frac{(|\Delta V|^2 - V_{1p.u.}^2 - V_r^2 - V_i^2)^2}{4V_r^2} - V_{1p.u.} \end{aligned} \tag{2.21}$$

If it is not of critical importance to mantain the voltage at unity the phase angle can be further compensated only limited by the voltage limits. By changing the value of $V_{1p.u.}$ to the voltage limits the phase angle compensation boundaries can be found.

To improve the voltage compensation active power curtailment or converter overrating can be implemented. The first option is effective to compensate for over voltages in low X/R ratio grids or to allow additional reactive power injection in the case of high X/R ratio. The second option increments the diameter of the compensation voltage. In [41] it is shown that overrating is ineffective at low X/R ratio networks while power curtailment shows better results.

2.6 Voltage Unbalance Compensation

For its nature a voltage unbalance in the system can be treated as different voltage variations in each of the phases. Hence, the unbalance can be mitigated by using single phase voltage controllers as explained in the previous chapter.

Another common method for unbalance compensation makes use of the symmetrical components. To simplify analysis a set of unbalanced three phase voltages can be represented by their symmetrical components as shown in Fig.2.25.

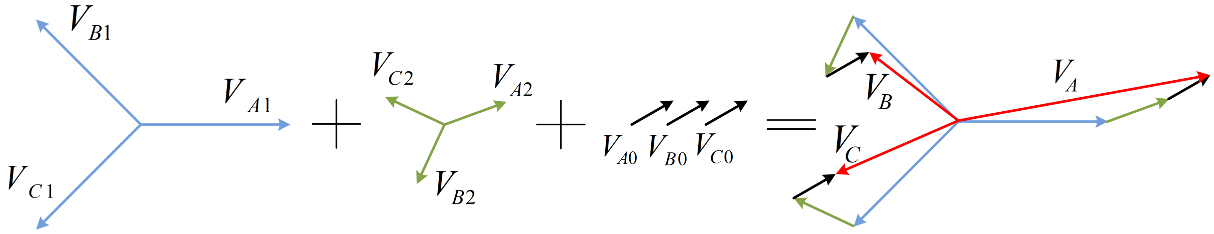


Figure 2.25: The unbalanced voltages of the grid can be represented by the sum of its symmetrical components

The symmetrical components consist of a positive, a negative and a zero sequence component for each phase, indicated with the additional upper index "+","-" and "0" respectively. Each set of components are of the same magnitude. The positive components are in phase with the grid balanced voltages. On the other hand, the sequence is inverted for the negative sequence and the zero sequence are homopolar[18]. Moreover, the sum of these sequence components will produce the unbalanced system.

$$\begin{bmatrix} V^+ \\ V^- \\ V^0 \end{bmatrix} = \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2.22}$$

The zero sequence component is not present in three wire systems. This component can also be blocked by using a delta wye transformer. Without this components the voltage unbalance will only be a product of the negative sequence. Furthermore, the currents can also be separated into its components. This helps to analyze more in detail the system.

The grid can be separated into its sequence components. In Fig. 2.26 the negative sequence network of a converter connected to a grid through a transmission line is shown. If the grid voltage V_g^- is considered constant it is clear that the voltage of the converter V_{PCC}^- depends on the voltage drop on the negative sequence impedance Z_l^-. Therefore, the theory of voltage compensation shown in the previous section may be applied to control V_{PCC}^-.

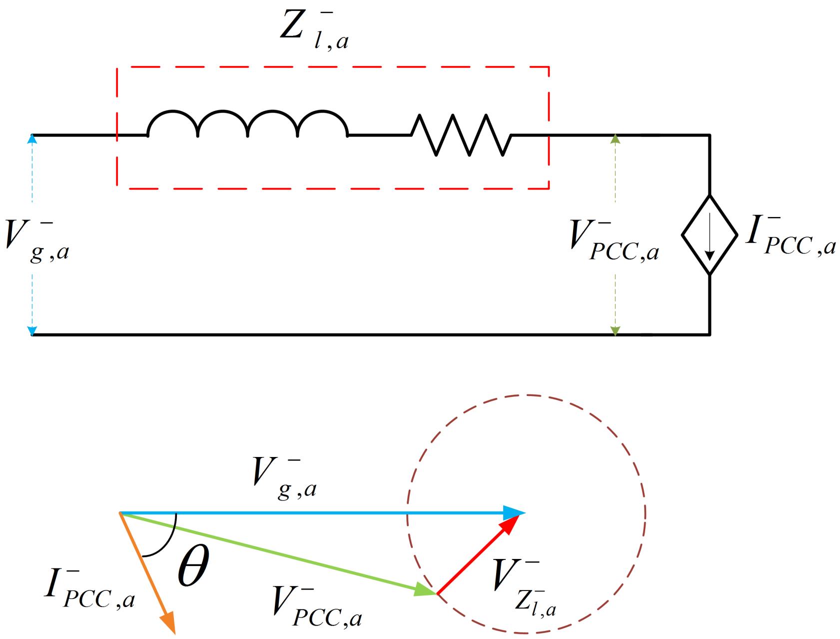


Figure 2.26: Negative sequence voltage voltage compensation through its corresponding network

The negative sequence current from the converter I_{PCC}^- can be used to control $V_{Z_l}^-$ [35]. The maximum compensation is when the angle of the current Θ (used to rotate the voltage vector) is equal to the angle of Z_l. As in the previous section the amount of compensation depends on the ratings of the device. Furthermore, the same idea can be used for compensating the zero sequence.

There are many methods used to calculate I_{PCC}^{-} to mitigate unbalances. Using a voltage controller the VUF can be used as a constrain to eliminate the negative sequence voltage at the PCC [35, 36, 37]. Another approach is to inject a set of currents which opposes the undesired sequence components.

Even though the differences between the European and American three phase systems are evident a remark worth making is that since the American system has the inverse phase sequence than the European system the symmetrical components matrix changes in phase rotation. Care has to be to avoid using incorrect transformation equations.

Furthermore, notice that regardless of the method the injection of unbalanced currents appears as a requirement to compensate for the voltage unbalances. The implications and effects of this corrective action will be analyzed more in detail in the next section.

2.7 Summary

In this chapter the different factors influencing voltage unbalance compensation where analyzed. First, a brief analysis of the methods proposed in the literature is made. In here the classical methods for voltage compensation and the more sophisticated techniques using power converters are explained. It is also shown how most of the methods rely on the reactive power for voltage compensation assuming that the grid has a high X/R ratio.

Then, the effects of the X/R ratio and the SCR were shown through a study case. It is demonstrated that on a weak grid the voltage variations are more frequently outside the limits, while in a stiff grid the voltage is mostly within the voltage limits. In addition, the X/R ratio also influences how much the active or reactive power influence in the voltage compensation. Furthermore, it is also proven how important is the load demand and the generation by DER in the distribution systems. The coincidence of low loading and nominal generation by the DER may lead to over voltages.

Afterwards, an introduction to the theory of voltage regulation was made. The phasor diagrams were used to illustrate how controlling the voltage drop through the transmission line can help improving the voltage profile. Furthermore, the factors affecting the voltage compensation such as the X/R ratio and the rating of the converter were analyzed. The rating and loading of the converter are shown to limit its voltage compensation capability, while the X/R ratio affects the effectiveness of active or reactive power in voltage compensation. This methods usually focus on compensation of the voltage magnitude disregarding the effect on the voltage angle this might have.

Finally, two different approaches for unbalance mitigation where mentioned: single phase control and negative sequence control. The first one uses a set of controllers per phase to control each phase individually. The second method makes use of the theory of the first one to compensate the unbalance through the negative sequence currents.For their nature these two methods lead to different compensated voltages. Nevertheless, both of them require an unbalanced injection of currents which will have a negative effect on the networks current unbalance.

From now on the study will focus on decentralized compensation techniques considering both active and reactive power in order improve the voltage compensation flexibility in grids with any X/R ratio.

Chapter 3

Converter control

In this chapter the control structures necessary to implement the unbalance compensation methods on a grid side converter are explained. First, the control based on the Synchronous Reference Frame(SRF) is described. Furthermore, the chapter continues by explaining the control of the negative sequence current through the Double Synchronous Reference Frame(DSRF). Afterwards, the topology of the natural frame control structure is explained. Once the control topologies are described the implementation of the suggested unbalance compensator is described. Finally, the drawbacks and side effects of unbalance compensation through unbalanced currents is shown by use of the instantaneous power theory.

A converter is an electronic component that performs a power conversion stage from AC to DC or vice versa, AC to AC and DC to DC[13]. Converters are the devices that enable RES to operate in the power system, allowing them to interact with the grid. To do so the controllers have to control the voltage magnitude, frequency and phase in the converters output in order to synchronize with the network.

A general topology of a grid side converter is shown in Fig. 3.1. The main objective of the grid side converter is to maintain the DC link voltage fixed[29]. This is done by controlling the amount of power absorbed from the available DC link power P_{DC}.

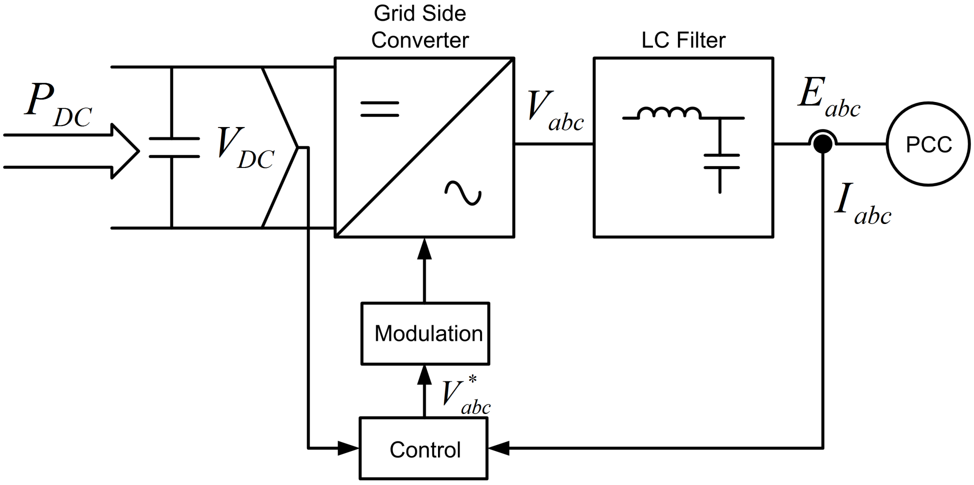


Figure 3.1: General grid side converter topology

In this chapter the SRF control, DSRF control and natural frame control are explained.

3.1 SRF Based Control

Disregarding the RES technology there are some basic functions that are common for any grid connected inverter, mainly:

- Grid Synchronization
- Inner control loop
- Outer control loop

The current and voltage AC measurements are acquired from the PCC and fed to the converter controllers. Furthermore, the controllers of the converter are in cascade. An outer loop controller adjusts the controller parameters based on the operating conditions to then feed reference signals to an inner loop controller. In order to ensure stability the inner control loop is faster than the outer controller[29].

In Fig. 3.2 a common control structure for a DER converter is depicted. The inner loop control is in charge of controlling the current and the outer loop control of maintaining the DC link voltage constant. Moreover, The DC link voltage controller sets the active power output[29]. A Phase Locked Loop(PLL) is used to allow the controller to synchronize and interact with the grid. The angle θ obtained in the PLL is used by the rest of the controllers of the converter.

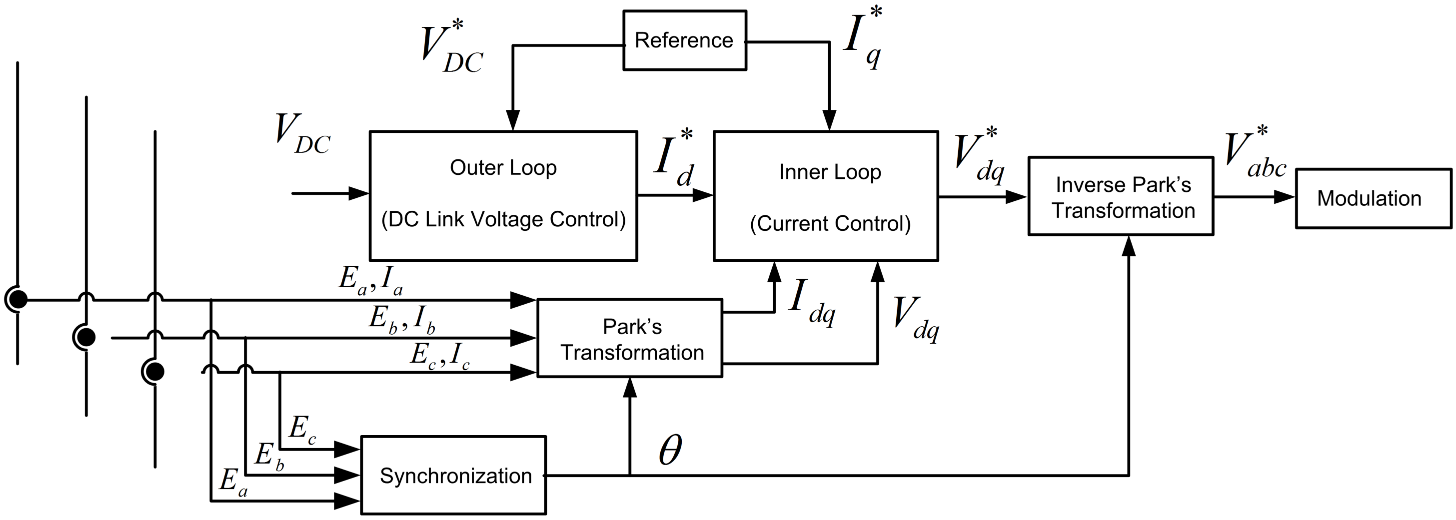


Figure 3.2: Common DER control structure

SRF topologies uses two PI controllers as the Current Controller(CC) to manage the dq components independently. In Fig. 3.3 the inner loop CC is shown. It can be seen that the d and q components are coupled together by the cross coupling terms ΩL. In order to decouple the d and q components a voltage feed forward is implemented by adding the measured grid voltages V_d and V_q.

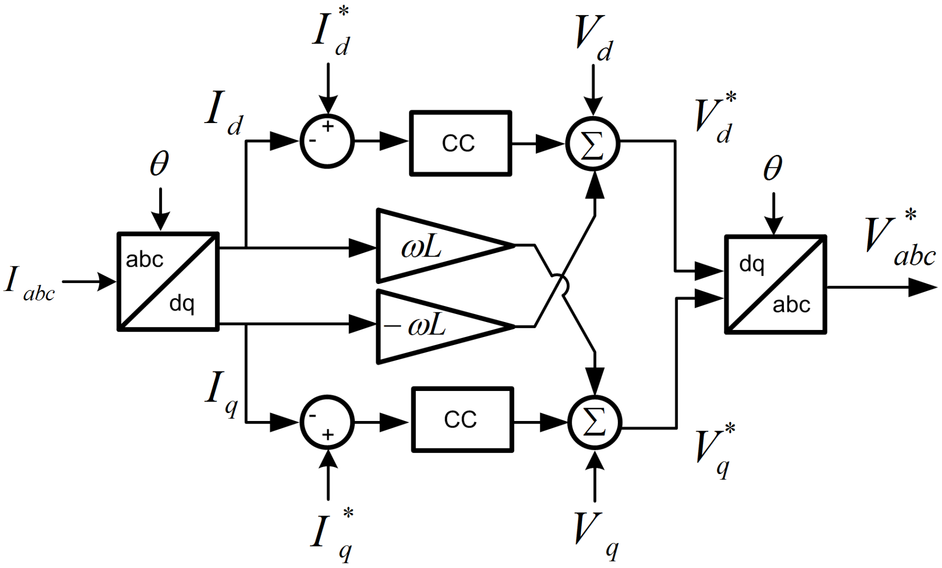


Figure 3.3: SRF current controller

Typically the control of a grid side converter is done only in the positive sequence. While this might be enough for voltage compensation in a balanced system it falls short in the presence of unbalances. To enable the converter to manage the positive and negative sequence components independently the symmetrical components have to be taken into consideration in the CC.

3.2 DSRF Based Control

The DSRF allows the converter to control the negative sequence currents and therefore mitigate voltage unbalances. The DSRF consists of two sets of CC, one for the positive sequence and another for the negative sequence as shown in Fig. 3.4.

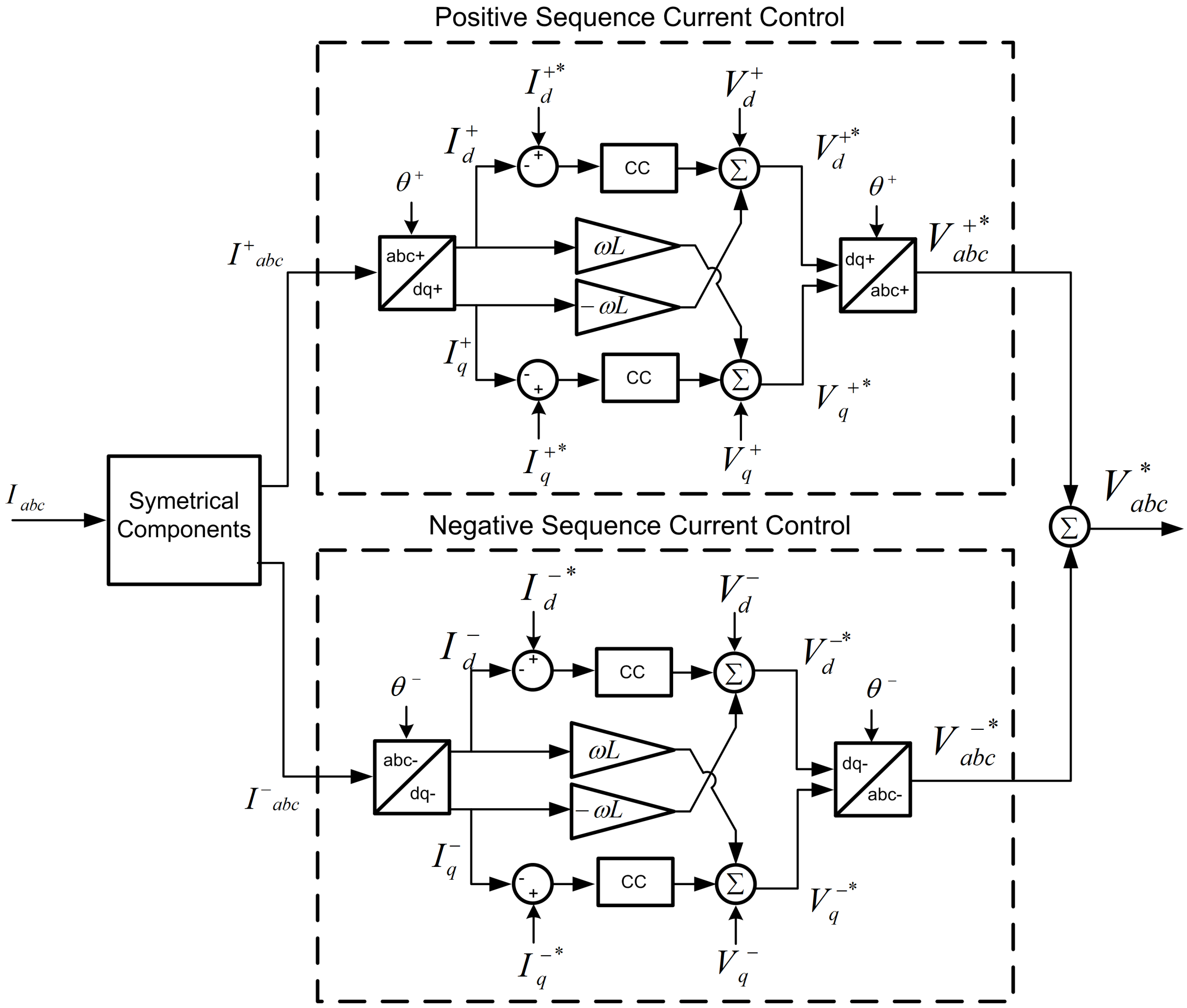


Figure 3.4: DSRF current controller

The measured voltage and currents are transformed to their symmetrical components and fed to their corresponding sequence controller. Moreover, notice that since the negative sequence rotates in the opposite direction of the positive sequence a negative angle θ^{-} has to be used in the park transformation.

The unbalance compensation can be done by feeding the negative sequence reference currents to the negative sequence current controller.

3.3 Natural Frame Based Control

For this topology a set of controllers is required for each of the phases. As shown in Fig. 3.5, the phase voltage and current measurements are used to calculate the power. A power controller is included to allow the per phase voltage compensation. The reference generator uses this information to calculate the current reference per phase which is used by the current controller.

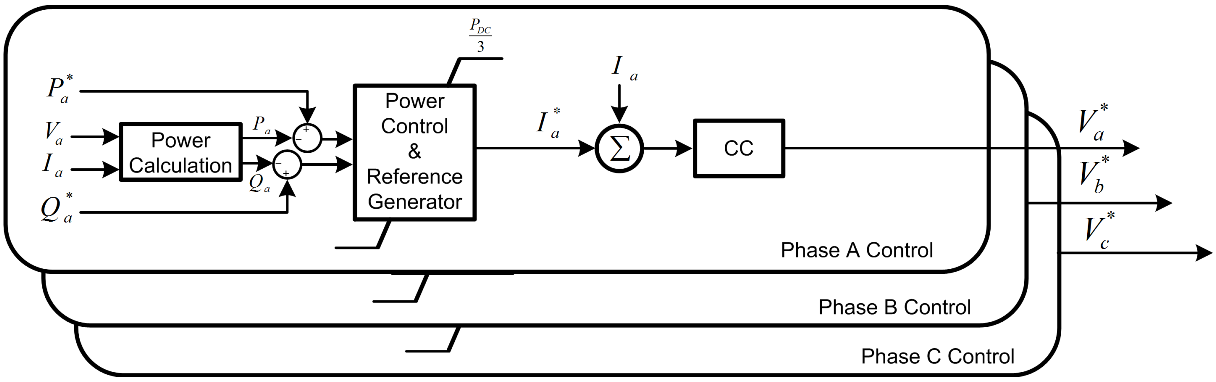


Figure 3.5: Natural frame control

Since in this case the signals fed to the CC are sine waves a Proportional-resonant controller is preferred. Furthermore, the power references obtained in the unbalance compensation method explained in the previous chapter can be used in this topology to correct the phase voltage and hence compensate for the unbalances.

However, most of these approaches do not take into account the full impact of a unbalanced network. Even though this thesis focuses exclusively on voltage unbalance compensation this issues are relevant in the control.

3.4 Side effects of Voltage Unbalance Compensation

As mentioned before, to compensate voltage unbalances it is required to inject unbalanced currents to the grid. These unbalances produce undesired power oscillations. To better analyze this phenomenon instantaneous power theory is useful.

Going back to the most basic expression, electrical power is the product of current and voltage. By separating the voltage and current into their symmetrical components we can observe how they interact with each other.

$$\begin{aligned} v &= \sum(v^+ + v^- + v^0) \\ i &= \sum(i^+ + i^- + i^0) \end{aligned} \tag{3.1}$$

For simplicity this can be done in terms of the dq components. The active power can be calculated by multiplying the components that are in phase with each other and the reactive power by doing the same with the components that are orthogonal to one another[42]:

$$p = P_0 + P_c cos(2\omega t) + P_s sin(2\omega t) \tag{3.2}$$

$$q = Q_0 + Q_c cos(2\omega t) + Q_s sin(2\omega t) \tag{3.3}$$

Now both power equations are conformed by a constant value and two oscillating terms at double the grid frequency, where its amplitude is determined by :

$$\begin{aligned} P_0 &= \frac{3}{2}(V_d^+ I_d^+ + V_q^+ I_q^+ + V_d^- I_d^- + V_q^- I_q^-) \\ P_c &= \frac{3}{2}(V_d^+ I_d^- + V_q^+ I_q^- + V_d^- I_d^+ + V_q^- I_q^+) \\ P_s &= \frac{3}{2}(V_q^- I_d^+ - V_d^- I_q^+ - V_q^+ I_d^- + V_d^+ I_q^-) \\ Q_0 &= \frac{3}{2}(V_q^+ I_d^+ - V_d^+ I_q^+ + V_q^- I_d^- - V_d^- I_q^-) \\ Q_c &= \frac{3}{2}(-V_d^+ I_q^- + V_q^+ I_d^- - V_d^- I_q^+ + V_q^- I_d^+) \\ Q_s &= \frac{3}{2}(V_d^+ I_d^- + V_q^+ I_q^- - V_d^- I_d^+ + V_q^- I_q^+) \end{aligned} \tag{3.4}$$

P_0 and Q_0 are the active and reactive power. They are product of the multiplication of components from only the same sequence. The rest of the components are the product of two elements of different sequence. Knowing this it is easily seen that if there is no unbalance in the voltage nor current only P_0 and Q_0 remain. In any other case the unbalance, either of current or voltage, will produce oscillations in the power.

This oscillations make it more difficult to properly control the converter. Moreover, the DC link control is specially affected by the active power oscillations. In [43] the author suggests to cancel the active power oscillations by extending the DSRF control as shown in Fig. 3.6.

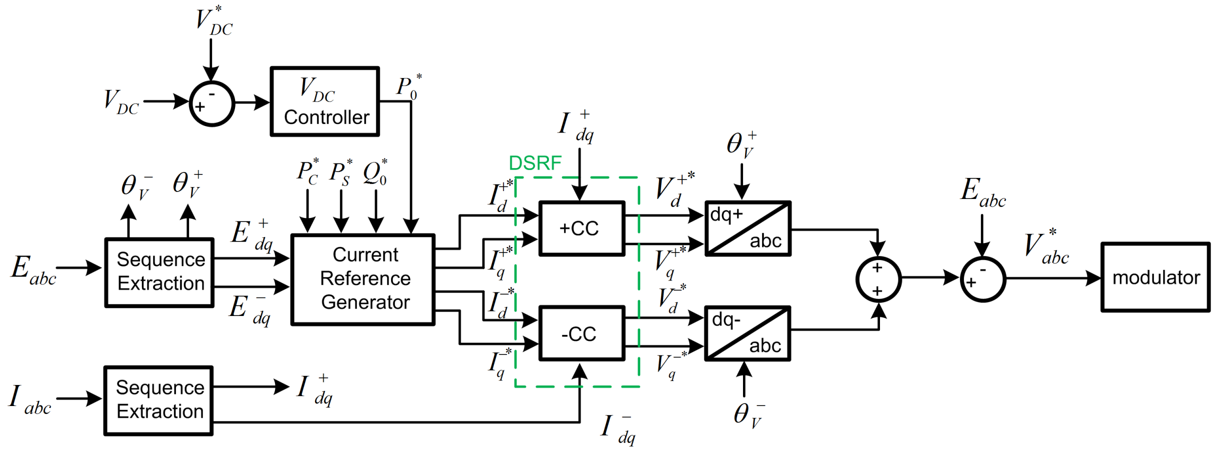


Figure 3.6: Grid side converter control considering the power oscillations due to the negative sequence components

Where the current references can be calculated by the solving the following equation:

$$\begin{bmatrix} P_0 \\ Q_0 \\ P_c \\ P_s \end{bmatrix} = \frac{3}{2} \begin{bmatrix} V_d^+ & V_q^+ & V_d^- & V_q^- \\ V_q^+ & -V_d^+ & V_q^- & -V_d^- \\ V_d^- & V_q^- & V_d^+ & V_q^+ \\ V_q^- & -V_d^- & -V_q^+ & V_d^+ \end{bmatrix} \begin{bmatrix} I_d^+ \\ I_q^+ \\ I_d^- \\ I_q^- \end{bmatrix} \tag{3.5}$$

3.5 Summary

The unbalanced current injection required for voltage unbalance compensation can be achieved by implementing any of the controllers mentioned in this chapter.

The DSRF topology has the advantage that by controlling the negative sequence current the angle and magnitude of the voltage can be controlled. Furthermore, this control will fall short in large voltage variations that also affect the positive sequence magnitude. This voltage rise or drop can be controlled by compensation of the positive sequence.

In the natural frame the angle and magnitude can be controlled per phase which allows for a more selective control. However, additional controllers are required to ensure the voltage symmetry.

Furthermore, the voltage or current unbalance will produce power oscillations which will interfere with the control of the converter. For example, the PLL is sensible to the presence of unbalances in the voltage measurement, and the real power oscillations affect the DC link voltage control. A trade-off has to be made between voltage unbalance and power oscillation compensation.

Chapter 4

Simulation and Results

In this chapter the proposed voltage unbalance compensation methods are implemented and tested in Power Factory 15. First, the per phase method is tested in a single phase to verify correct operation of the compensator on the grid. Afterwards, the unbalance compensation methods are tested under different unbalance levels and grid strengths. Finally, the results of the tests are analyzed to judge the performance of each compensation method.

Both of the unbalance control methods presented in the previous chapter are tested and compared in this chapter. For this purpose, the methods are tested in the network that was used for the study case in section 2.2. The unbalance of scenario 3 (shown in table 2.2 is chosen to verify the efficiency of the unbalance compensation methods.

In the steady state simulation it is assumed that the controllers are working correctly even under unbalanced conditions. A current source that will represent a DER with unbalance compensation is added at the last CB as depicted in Fig. 4.1. The rated power of this compensator is set to 2 kW. Furthermore, the compensation methods were applied in steady state.

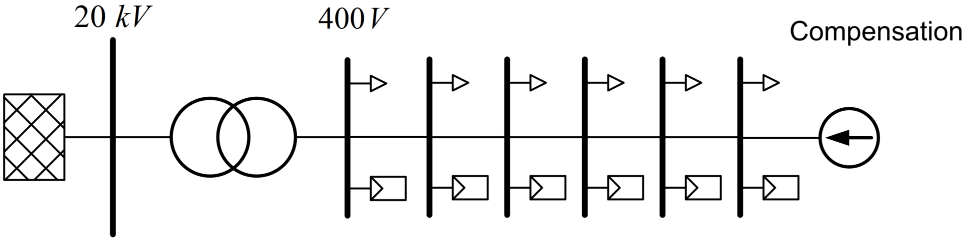


Figure 4.1: Adapted model with compensator for unbalance mitigation tests

First, the single phase voltage compensation technique was implemented to validate its correct operation in the grid.

4.1 Single Phase Voltage Compensation

To test the Single phase voltage regulation method the X/R ratio is set to 1. In this case the voltage compensation is done through the $V_R$and V_X components. In Fig. 4.2 the phasor diagram for the compensated and uncompensated voltage are depicted, were the red phasor represents the load voltage, the yellow phasor is the desired voltage magnitude and the blue and green phasors the V_R and V_X components of the voltage drop.

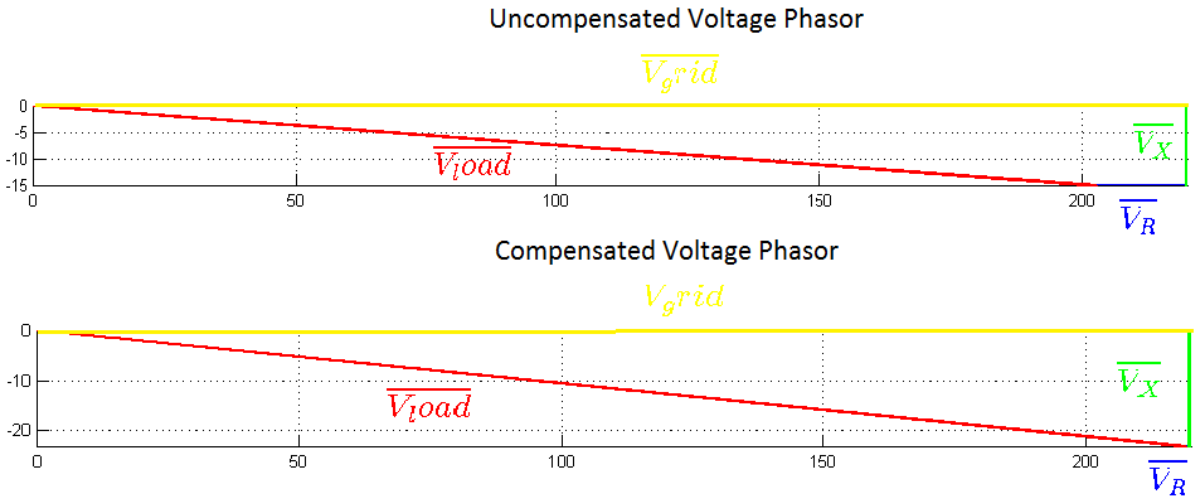


Figure 4.2: Results for the single phase voltage compensation test

After the compensation is done the magnitude of V_{load} is at the desired 1 p.u.. On the other hand, due to the compensation the angle has now grown.

4.2 Voltage Unbalance Compensation

To study the behavior of the control methods scenarios with different X/R ratio and SCR were created: a weak network(X/R=0.5,SCR=3), a network with low X/R ratio(X/R=0.5,SCR=10) and a stiff network(X/R=5,SCR=10). Moreover, the power output of the PV systems is set to 1 and 2 kW to simulate two unbalance levels with different severity in each one of the three scenarios. This values where selected for demonstration purposes only in order to make it easier to see the effect of the compensation on the phasor diagrams.

In each one of the scenarios the voltage compensation method(shown in the grpahs with a solid line) is compared against the uncompensated voltage phasors(shown in the graphs with a dashed line).

4.2.1 Study Case 1: Stiff Grid

First the compensation methods are used in for the case where the PV panels operate at 1 kW.

In Fig. 4.3 the per phase voltage unbalance compensation is shown. The symmetrical components of each phase are depicted with the subindex 0,1 and to for the zero, positive and negative sequence respectively. On the left compensation is done only taken into account the magnitude as is done commonly in voltage compensation methods. As is to be expected the method compensates for the voltage magnitude and thereby has a negative effect on the voltage symmetry. The Angle is corrected and the result is shown to the right in Fig. 4.3.

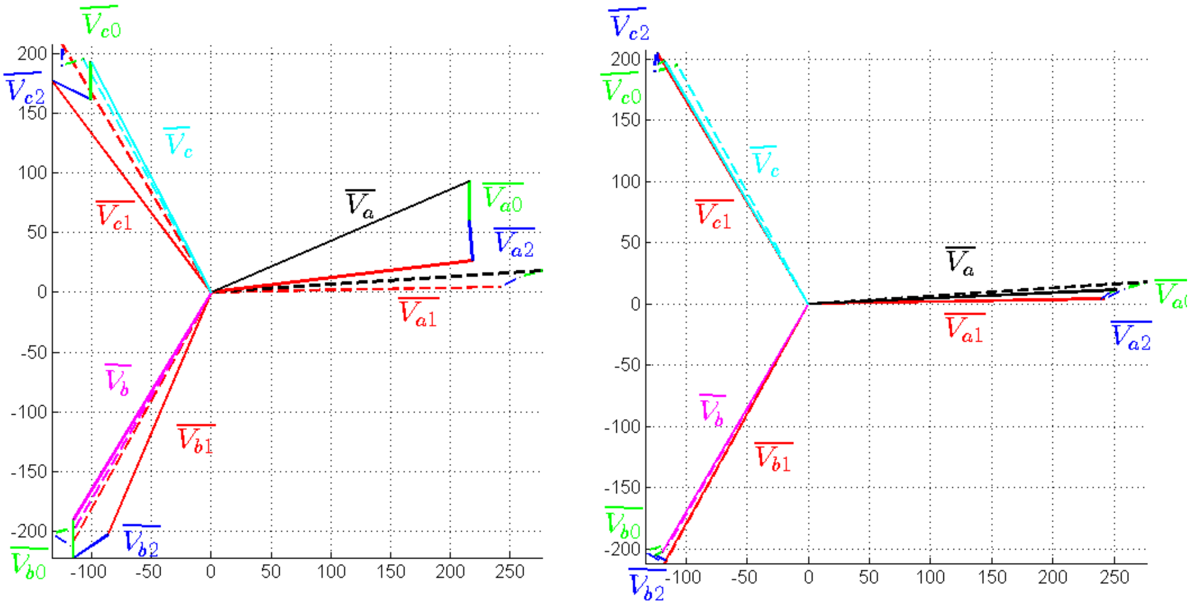


Figure 4.3: Per phase unbalance compensation method in a stiff grid with and without considering the voltage angle(right and left respectively) [each PV injecting 1 kW]

On the contrary to the previous method, the negative sequence compensation takes into account magnitude and angle correction as shown in Fig. 4.4. Furthermore, the unbalance is compensated as much as the rating of the compensator allows.

When the power contribution from the PV panels increases so does the unbalance. The compensator mitigates part of the unbalance but has almost no effect over the voltage magnitude as shown in Fig. 4.5. This is due to an increase in the positive sequence of the voltage. Since the compensator only targets the voltage negative sequence it is insensible to the changes in positive sequence.

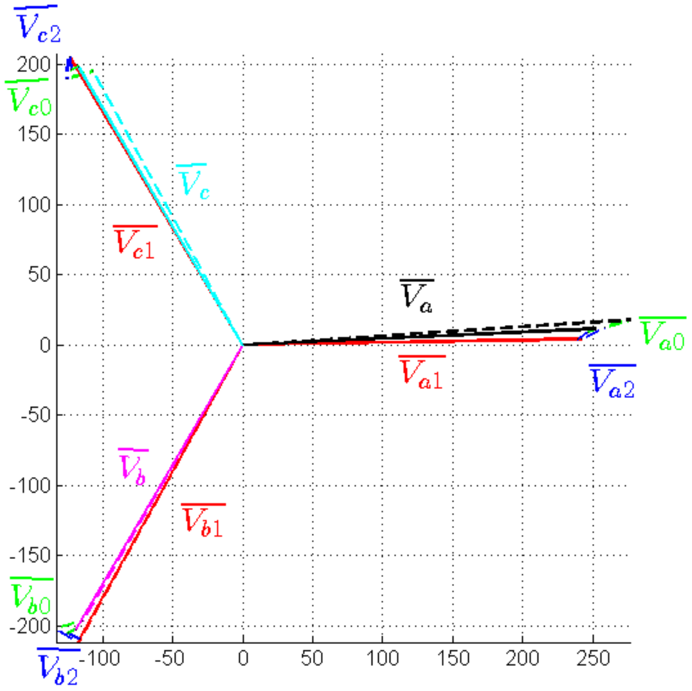


Figure 4.4: Negative sequence compensation method in a stiff grid[each PV injecting 1 kW]

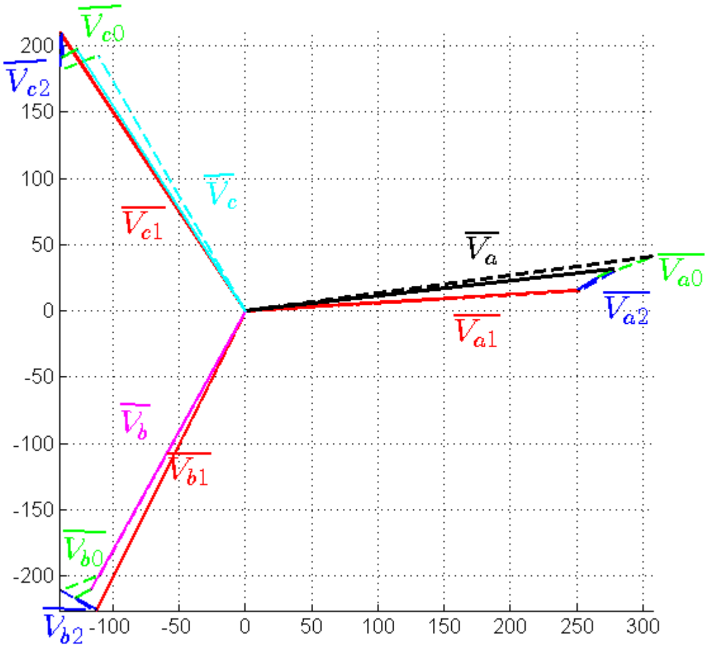


Figure 4.5: Negative sequence compensation method in a stiff grid[each PV injecting 2 kW]

4.2.2 Study Case 2: Low X/R ratio

In order to test the compensation on a mostly resistive network the X/R ratio was lowered down to 0.5 . The same process as in the stiff grid was followed to improve the symmetry in the per phase compensation method. The results for the 1 kW case are shown in Fig.4.6. It is evident that the compensator is able to control the positive sequence voltage magnitude. Nevertheless, it still struggles with the angle control.

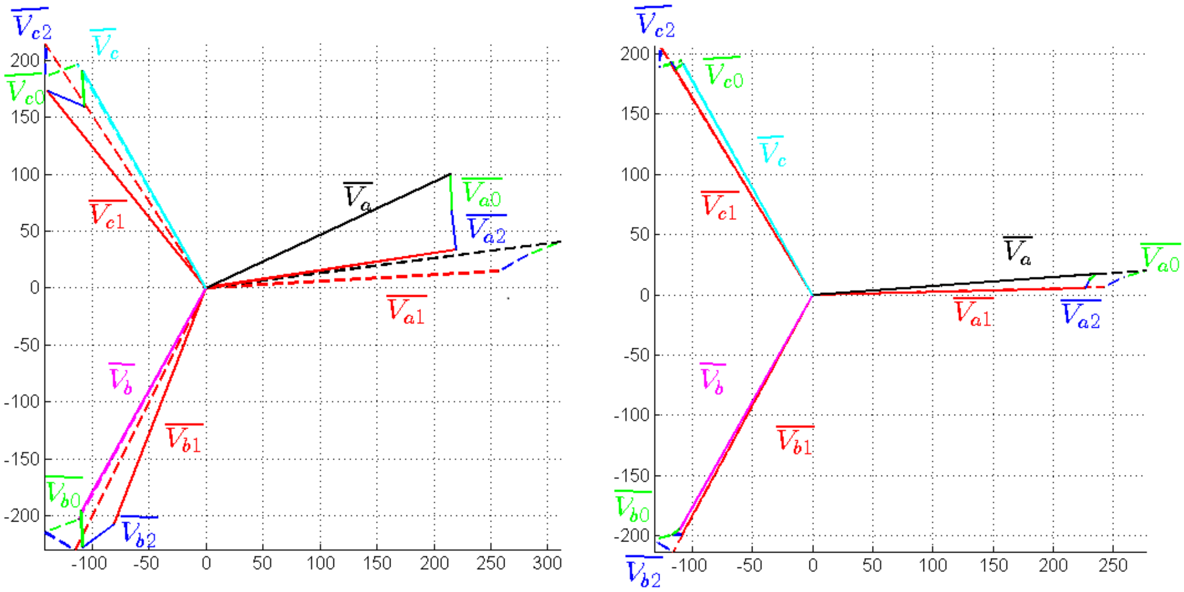


Figure 4.6: Per phase unbalance compensation method in a grid with low X/R ratio with and without considering the voltage angle(right and left respectively)[each PV injection 1 kW]

The 2 kW PV injection case with negative sequence compensation is shown in fig. 4.7. In comparison, the control of the negative sequence allows the voltage unbalance to be reduced taking into account the angle. Notice that the compensation method is capable to distinguish between voltage rise and drop and the direction of the voltage angle deviation. Even though the voltage phasors are controlled in both angle and magnitude the negative sequence compensation still falls short to reduce voltage variations that might be present due to the voltage positive sequence.

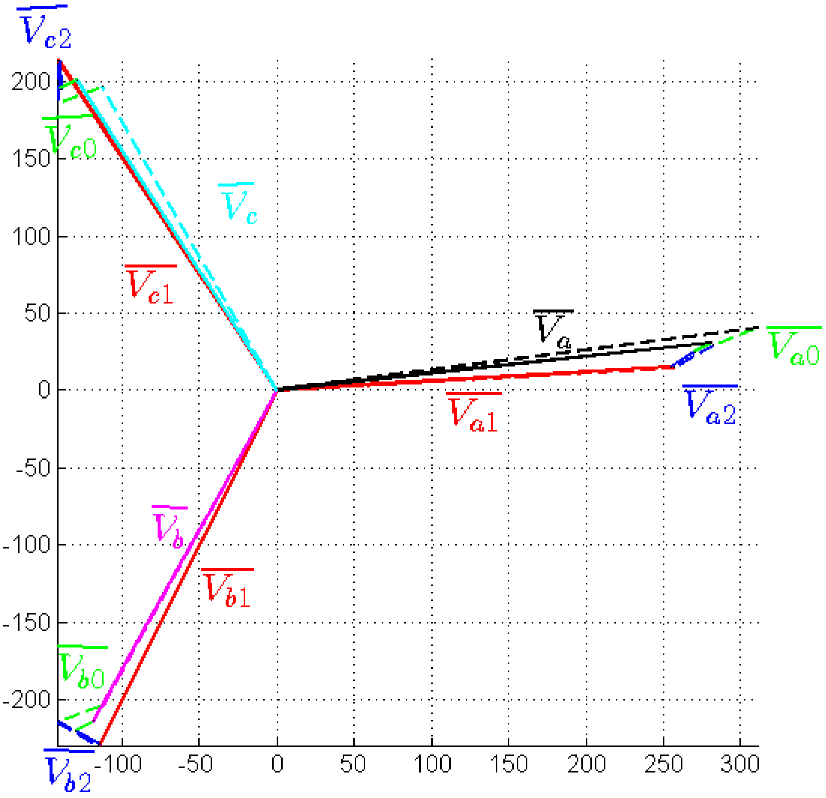


Figure 4.7: Negative sequence compensation method in a grid with low X/R ratio[each PV injecting 2 kW]

4.2.3 Study case 3: Weak Grid

From the previous scenario the SCR is set to 3 to create a weak grid. Furthermore, the weak grid allows greater voltage variation as shown in the study case on section 2.2. These higher variations have the greatest influence over the positive sequence of all the studied scenarios. This affects both of the compensation methods.

The compensation through the negative sequence continues to be effective to reduce the unbalance as can be seen in Fig. 4.8. However, voltage variations in the positive sequence are yet a limiting factor for the voltage compensation.

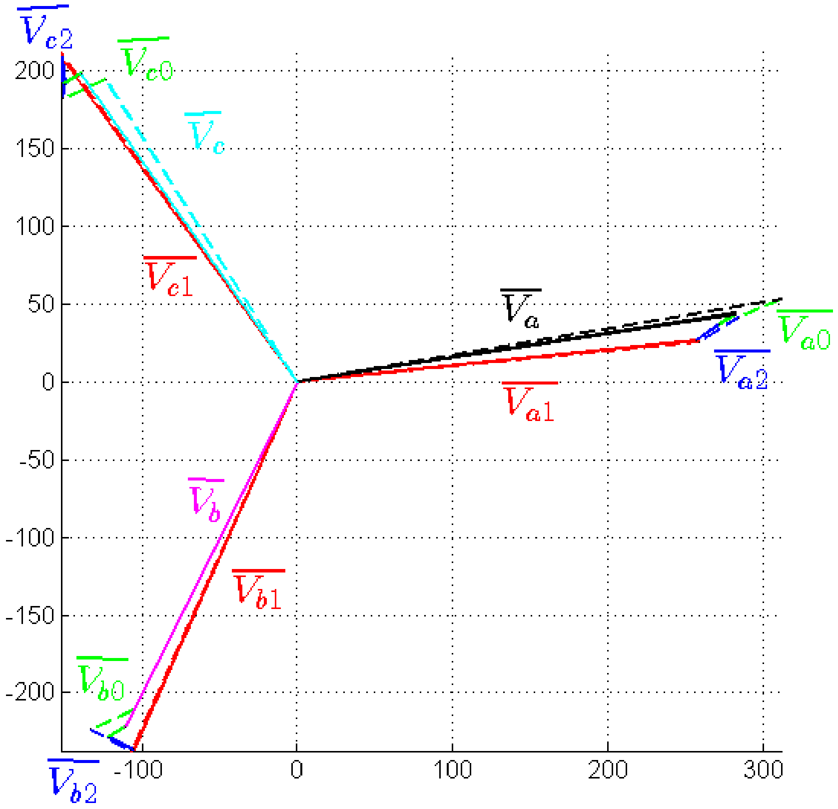


Figure 4.8: Negative sequence compensation method in a weak grid[each PV injecting 2 kW]

The negative effects of the weak grid can also be seen in the per phase control. The weak grid makes it difficult for the compensation to be performed resulting in overcompensation as shown in Fig. 4.8. Furthermore, the importance of considering the phase angle is reiterated here were a notorious increase in the negative sequence voltage is present when only the voltage magnitude is compensated(Fig.4.9, left).

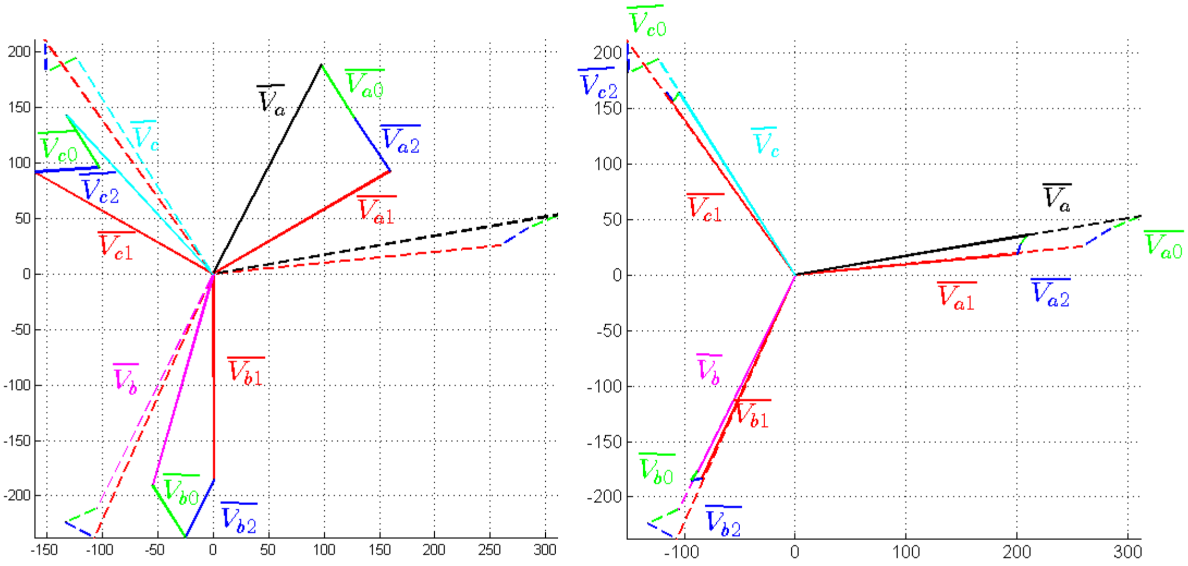


Figure 4.9: Per phase unbalance compensation method in a weak grid with and without considering the voltage angle(right and left respectively)[each PV injecting 2 kW]

As already stated, this compensation does not come without a price. Additional current unbalance is produced in order to compensate for the voltage unbalances. To illustrate how compensation affects the currents the voltage and current waveforms were plotted before and after the zero sequence compensation of this scenario(Fig.4.10).

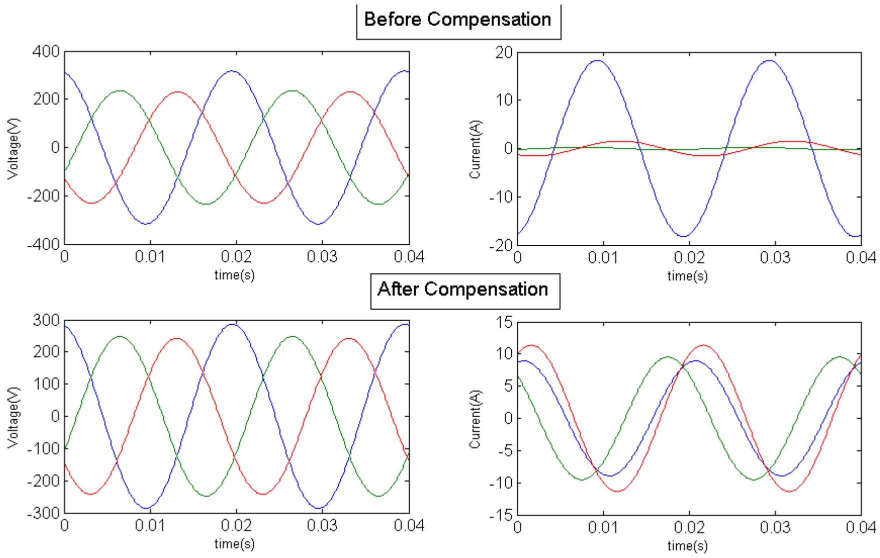


Figure 4.10: Voltage and current waveforms before and after the compensation through the negative sequence method

4.3 Results and Analysis

Throughout the different scenarios the advantages and disadvantages of each one of the methods could be seen.

In Fig. 4.11 the unbalance compensation capability of each method is shown for the different scenarios. As can be seen the negative sequence has the best performance reducing the most the unbalance level. On the contrary, the per phase voltage magnitude compensation method worsens the unbalance due to the increase in voltage asymmetry it produces.

In the case of 1 kW injected through each PV unit the unbalance can be reduced to approximately half the uncompensated unbalance value. On the case of 2 kW the unbalance compensation is reduced to 30 percent of the total unbalance. Moreover, the compensation capability of the methods is maintained practically constant for each of the unbalance level.

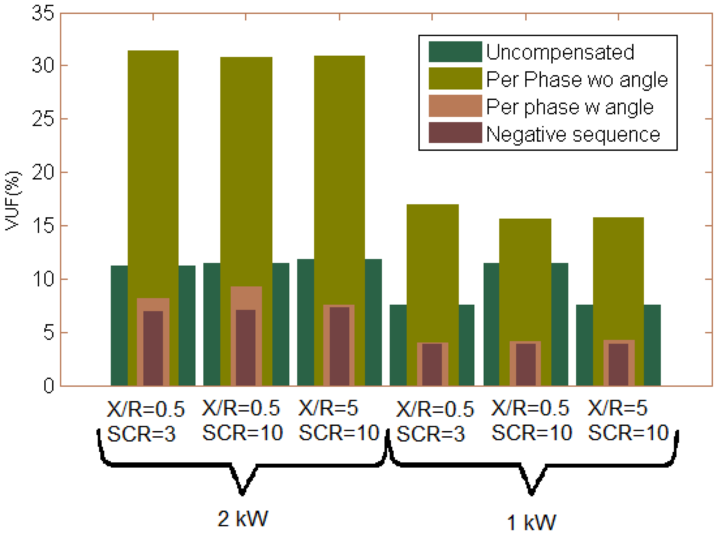


Figure 4.11: VUF comparison of the different compensation methods and the uncompensated voltage

Now let us analyse the voltage magnitude of each method. In Fig.4.12 the voltage magnitude per phase of the uncompensated and compensated systems is shown, where the gray and orange dashed lines represent the upper and lower voltage limits. In the 1 kW scenarios the methods have similar responses, being the per phase compensation slightly better. It is in the more severe unbalances where the methods have a different response in the voltage magnitude compensation. While the negative sequence method achieves to correctly compensates the voltage rise and drop respectively it does not manage to lower the voltage rise caused the PV panels under the upper voltage limit. The per phase method on the other hand manages to maintain the voltage level of all phases within the voltage limits. However, the overcompensation results in low voltages. This is specially true in the case of the weak grid were the voltage magnitude of two phases is already under the lower voltage limit.

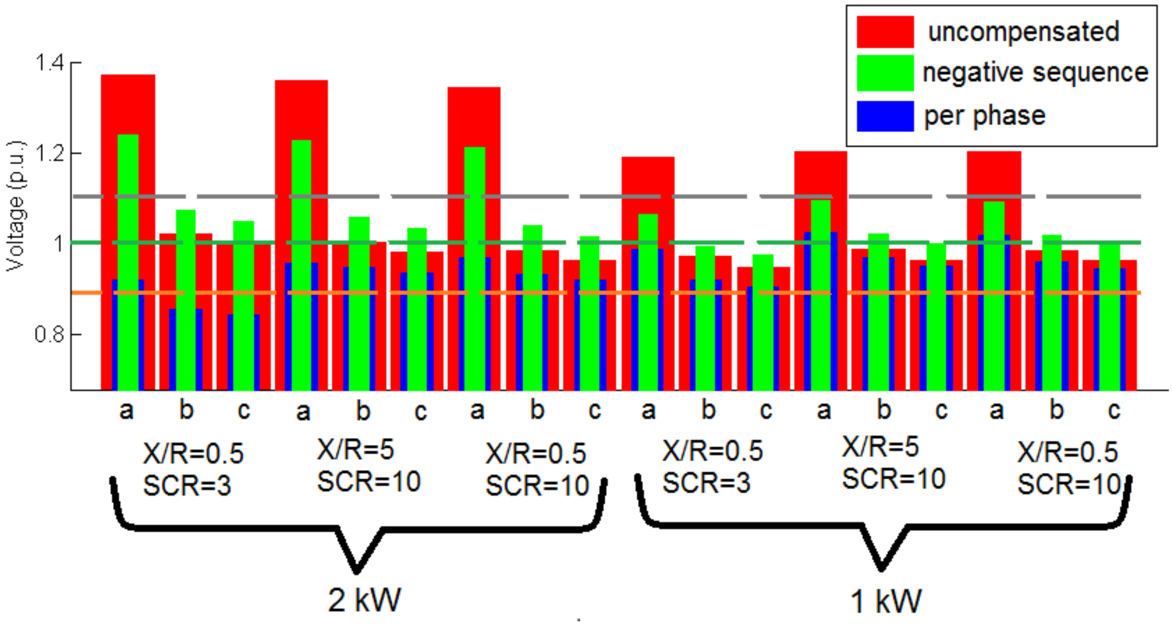


Figure 4.12: Voltage magnitude per phase comparison of the different compensation methods and the uncompensated voltage

Finally, the voltage angle is compared. In Fig. 4.13 the voltage angle of each phase are displayed for each of one of the methods. The first thing that can be noticed is the notorious angle change the per phase method produces by itself without taking into account the angle compensation. Comparing with the voltage magnitude compensation shown in Fig. 4.12 we can say that the voltage magnitude compensation is followed by a proportional angle deviation in the per phase method. This is not the case of the negative sequence method in which the voltage angle is compensated and therefore the voltage is kept as symmetric as possible.

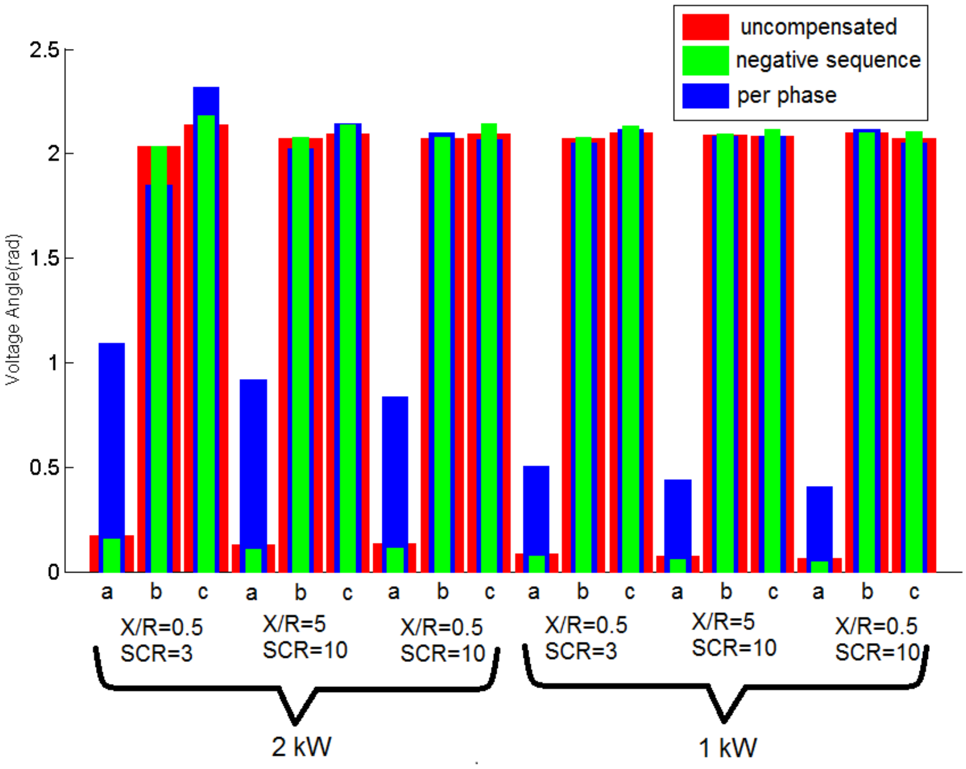


Figure 4.13: Voltage angle per phase comparison of the different compensation methods and the uncompensated voltage

4.4 Summary

The unbalance sequence compensation method ended up with the best results in unbalance compensation. Whereas the per phase compensation method resulted to be the least ideal method for unbalance compensation for its problems with keeping the voltage symmetry.

The grid strength proved to be an important factor for unbalance compensation. The compensation methods could compensate for the voltage unbalance in networks with high SCR but started having a bigger error on the weak grids, specially the per phase method. Moreover, the power surplus from the PV systems contribute negatively the unbalance compensation. The combination of both factors produce larger voltage changes which will end up in voltage rise/-drop and finally modifying the voltage positive sequence. For this reason the negative sequence method is unable to compensate for the voltage rise and limits to mitigating the voltage negative sequence.

Chapter 5

Conclusions and Future Works

5.1 Conclusion

The unbalance compensation methods analyzed in this thesis have their strengths and weakness. The negative sequence compensation method is ideal for unbalance compensation since it compensates for the voltage angle and magnitude. However it falls short compensating for voltage unbalances that affect the positive sequence. On the other hand the per phase control gives good results compensating for voltage rise or drops affecting the voltage positive sequence but it is limited capabilities when compensating for the voltage angle. The advantages of both of the methods can be used to create an improved controller that is able to compensate for voltage unbalances and voltage rise or drop in the steady state.

In the simulations it was proven that the compensation methods are fully capable of mitigating the unbalances even in severe unbalances as studied. Furthermore, even though in the studied scenarios the compensation was not able to lower the VUF under 2 percent due to the magnitude of the unbalance it is completely feasible in less extreme scenarios.

Moreover, the rating of the converter is of critical importance for the compensating capabilities. Moreover, enabling a DER for unbalance compensation means that part of its power output its used for this purpose. Taking into account that DER will not be used exclusively for unbalance compensation and only a percentage of its rated power will be used for this purpose the capacity for unbalance compensation is greatly reduced. It has to be a cooperative operation between multiple DER to have a significant impact on the networks power quality.

Finally, the power oscillations in the converter due to the presence of negative sequence symmetrical components has to be taken into account. This power oscillations will affect the control of the converter and have to be dealt with in order to allow the compensator to inject unbalanced currents.

In summary, the achieved goals and contributions of this thesis:

Goals

- Reducing the voltage unbalance to under the VUF limit in a distribution grid with high penetration of DG through compensation methods implemented in the DER converter.
- Mitigating the voltage rise/drop in each phase and keeping the voltage magnitude within the voltage limits.

Contributions

- Impact analysis of the effects of high penetration of DG in the distribution grid over the power quality
- Create a voltage compensation method that is valid for any X/R ratio

5.2 Future Works

For its impact in the compensation of voltage unbalances the power osculations due to the interaction of the negative and positive sequence components needs to be taken into account. Multiple control methods have been suggested until now but few of them actually take into account the effect of this power oscillations over the control. In order to do so a control that can cancel out this power oscillations and simultaneously compensate for voltage unbalances is necessary.

Furthermore, the compensation methods can be improved as mentioned before by combining the capabilities of both methods. Since the DSRF method has the capacity to control the negative and positive sequence independently it can be used for this purpose.

Lastly, the dynamic studies of the compensation method is suggested to further analyze the compensation methods and the effects over the controllers.

Bibliography

[1] Guido Pepermans, Johan Driesen, Dries Haeseldonckx, Ronnie Belmans, and William Dhaeseleer. Distributed generation: definition, benefits and issues. *Energy policy*, 33(6):787–798, 2005.

[2] Global distributed generation deployment forecast(solar pv, small wind, fuel cell, natural gas generator set, and diesel generator set capacity and revenue by country and technology: 2014-2023), August 2014. URL `https://www.navigantresearch.com/research/global-distributed-generation-deployment-forecast`.

[3] Markku Lehtonen and Sheridan Nye. History of electricity network control and distributed generation in the uk and western denmark. *Energy Policy*, 37(6):2338–2345, 2009.

[4] Tan Hongen, Wang Bo, Liu Dichen, and Guo Suxuan. Analysis of distributed generation system based on micro-grid and its impaction on voltage distribution. In *Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific*, pages 1–4. IEEE, 2011.

[5] Jianing Liu, Weiqi Zhang, Rui Zhou, and Jin Zhong. Impacts of distributed renewable energy generations on smart grid operation and dispatch. In *Power and Energy Society General Meeting, 2012 IEEE*, pages 1–5. IEEE, 2012.

[6] MA Mahmud, MJ Hossain, and HR Pota. Worst case scenario for large distribution networks with distributed generation. In *Power and Energy Society General Meeting, 2011 IEEE*, pages 1–7. IEEE, 2011.

[7] Edward J Coster, Johanna MA Myrzik, Bas Kruimer, and Wil L Kling. Integration issues of distributed generation in distribution grids. *Proceedings of the IEEE*, 99(1):28–39, 2011.

[8] Henryk Markiewicz and Antoni Klajn. Voltage disturbances–standard en 50160. *Copper Development Association, lEE Endorsed Provider, Wroclaw University of Technology*, 2004.

[9] PMS Carvalho, LAFM Ferreira, and MD Ilic. Distributed energy resources integration challenges in low-voltage networks: Voltage control limitations and risk of cascading. *Sustainable Energy, IEEE Transactions on*, 4(1):82–88, 2013.

[10] W El-Khattam and MMA Salama. Impact of distributed generation on voltage profile in deregulated distribution system. In *Proceedings of the Power Systems 2002 Conference, Impact of Distributed Generation, Clemson, SC, USA*, pages 13–15, 2002.

[11] Maciej Fila, Jonathan Hiscock, David Reid, Peter Lang, and Gareth A Taylor. Flexible voltage control in distribution networks with distributed generation-modelling anlaysis and field trial comparison. In *Electricity Distribution-Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, pages 1–4. IET, 2009.

[12] Nouredine Hadjsaid and Jean-Claude Sabonnadiere. *Electrical Distribution Networks*. John Wiley & Sons, 2013.

[13] Thomas Ackermann and Valery Knyazkin. Interaction between distributed generation and the distribution network: operation aspects. In *Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES*, volume 2, pages 1357–1362. IEEE, 2002.

[14] B Blazic and I Papic. Voltage profile support in distribution networks influence of the network r/x ratio. In *Power Electronics and Motion Control Conference, 2008. EPE-PEMC 2008. 13th*, pages 2510–2515. IEEE, 2008.

[15] Dansk Energi Branchestatistik. Danish electricity supply 2007, statistical survey.

[16] Henrik Klinge Jacobsen. Regional energy consumption and income differences in denmark. *Journal of Environmental Policy & Planning*, 5(3):269–283, 2003.

[17] Prabha Kundur, Neal J Balu, and Mark G Lauby. *Power system stability and control*, volume 7. McGraw-hill New York, 1994.

[18] J Duncan Glover, Mulukutla Sarma, and Thomas Overbye. *Power System Analysis & Design, SI Version*. Cengage Learning, 2011.

[19] EN Standard. 50160: Voltage characteristics of electricity supplied by public distribution systems. *European Standard, CLC, BTTF*, pages 68–6, 1994.

[20] Johan Driesen and Thierry Van Craenenbroeck. Voltage disturbances, introduction to unbalance. *Copper Development Association*, 2002.

[21] Isaac Plummer. *Asymmetry in Distribution Systems: Causes, Harmful Effects and Remedies*. PhD thesis, Louisiana State University, 2011.

[22] *ABB Distribution Transformer Guide, Revised March, 2002.*

[23] Jonas Persson, Urban Axelsson, Daniel Wall, and Per-Olof Lindström. Need for standardization of wind power models for stability studies.

[24] John Peschon, Dean S Piercy, William F Tinney, and Odd J Tveit. Sensitivity in power systems. *Power Apparatus and Systems, IEEE Transactions on*, (8):1687–1696, 1968.

[25] Florin Iov Jayakrishnan R Pillai. Smart control of energy distribution grids over heterogeneous communication networks. *SmartC2Net, Benchmark Grid*, 2012.

[26] Regulation for electricity generating facilities of 11 kw or lower regulation for grid connection tf 3.2.1.

[27] WH Kersting. Distribution feeder voltage regulation control. *Industry Applications, IEEE Transactions on*, 46(2):620–626, 2010.

[28] C Gao and MA Redfern. Advanced voltage control strategy for on-load tap-changer transformers with distributed generations. In *Universities Power Engineering Conference (UPEC), Proceedings of 2011 46th International*, pages 1–6. VDE, 2011.

[29] Remus Teodorescu, Marco Liserre, and Pedro Rodriguez. *Grid converters for photovoltaic and wind power systems*, volume 29. John Wiley & Sons, 2011.

[30] Ke Dang, Jiqing Yu, Tong Dang, and Bo Han. Benefit of distributed generation on line loss reduction. In *Electrical and Control Engineering (ICECE), 2011 International Conference on*, pages 2042–2045. IEEE, 2011.

[31] T Tran-Quoc, TMC Le, C Kieny, N Hadjsaid, S Bacha, C Duvauchelle, and A Almeida. Local voltage control of pvs in distribution networks. In *Electricity Distribution-Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, pages 1–4. IET, 2009.

[32] Yanbo Wang, Yongdong Tan, Zhe Chen, Xiongfei Wang, and Yanjun Tian. A communication-less distributed voltage control strategy for a multi-bus ac islanded microgrid. In *Power Electronics Conference (IPEC-Hiroshima 2014-ECCE-ASIA), 2014 International*, pages 3538–3545. IEEE, 2014.

[33] Kashem M Muttaqi, An DT Le, Michael Negnevitsky, and Gerard Ledwich. A coordinated voltage control approach for coordination of oltc, voltage regulator and dg to regulate voltage in a distribution feeder. In *Industry Applications Society Annual Meeting, 2013 IEEE*, pages 1–8. IEEE, 2013.

[34] Ki-Seok Jeong, Hyun-Chul Lee, Young-Sik Baek, and Ji-Ho Park. Coordinated voltage and reactive power control strategy with distributed generator for improving the operational efficiency. *Journal of Electrical Engineering & Technology*, 8(6):1261–1268, 2013.

[35] K Jayakumar, N Sriharish, and Ch Rambabu. Voltage unbalance correction in a grid using inverter. *Editorial Committees*, page 201.

[36] Kuang Li, Jinjun Liu, Zhaoan Wang, and Biao Wei. Strategies and operating point optimization of statcom control for voltage unbalance mitigation in three-phase three-wire systems. *Power Delivery, IEEE Transactions on*, 22(1):413–422, 2007.

[37] Mehdi Savaghebi, Josep M Guerrero, Alireza Jalilian, and Juan C Vasquez. Hierarchical control scheme for voltage unbalance compensation in islanded microgrids. In *IECON 2011-37th Annual Conference on IEEE Industrial Electronics Society*, pages 3158–3163. IEEE, 2011.

[38] Antonio Camacho, Miguel Castilla, Jaume Miret, Juan C Vasquez, and Eduardo Alarcón-Gallo. Flexible voltage support control for three-phase distributed generation inverters under grid fault. *Industrial Electronics, IEEE Transactions on*, 60(4):1429–1441, 2013.

[39] Ruwan Chandrasena, Farhad Shahnia, Sumedha Rajakaruna, and Arindam Ghosh. Control, operation and power sharing among parallel converter-interfaced ders in a microgrid in the presence of unbalanced and harmonic loads. In *Proceedings of the 2013 Australasian Universities Power Engineering Conference (AUPEC)*, pages 1–6. IEEE, 2013.

[40] Timothy John Eastham Miller. *Reactive power control in electric systems.* Wiley, 1982.

[41] Johan Morren. *Grid support by power electronic converters of Distributed Generation units.* TU Delft, Delft University of Technology, 2006.

[42] Hirofumi Akagi, Edson Hirokazu Watanabe, and Mauricio Aredes. *Instantaneous power theory and applications to power conditioning*, volume 31. John Wiley & Sons, 2007.

[43] Ion Etxeberria-Otadui, Unai Viscarret, Marcelino Caballero, Alfred Rufer, and Seddik Bacha. New optimized pwm vsc control structures and strategies under unbalanced voltage transients. *Industrial Electronics, IEEE Transactions on*, 54(5):2902–2914, 2007.

Appendix A

Low Voltage Benchmark Grid

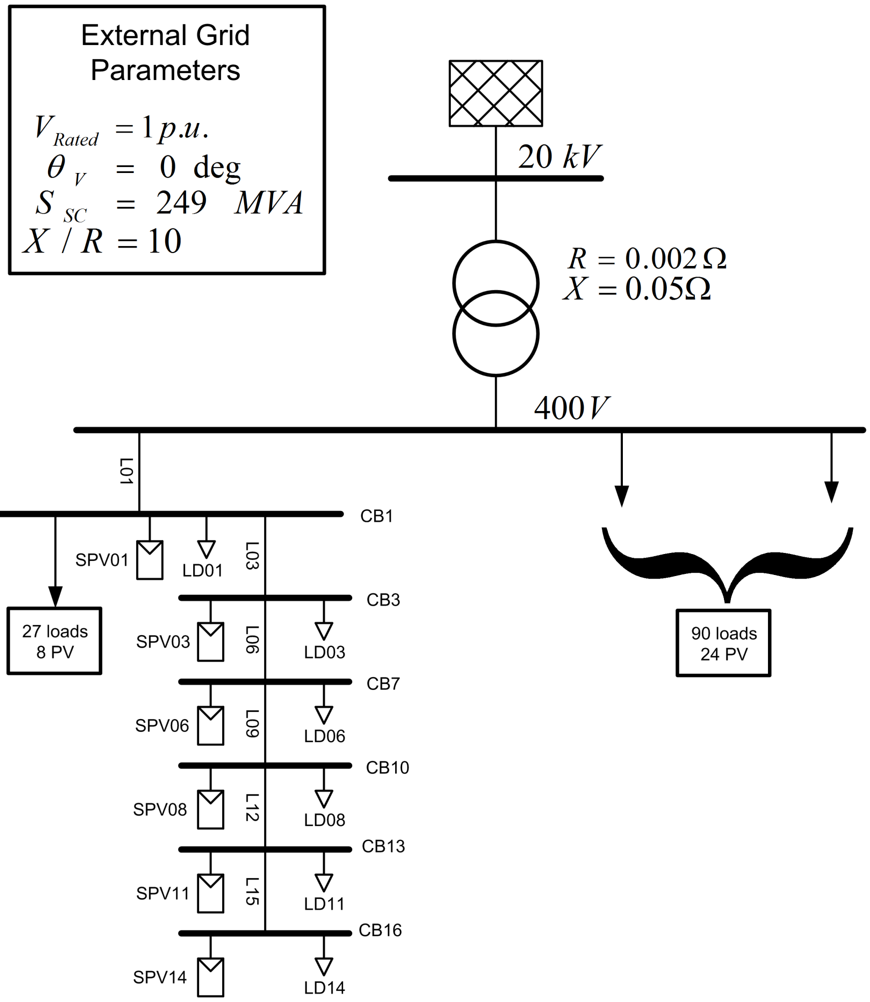


Figure A.1

In the Fig.A.1 the radial used for simulation is shown. This radial was built in Power Factory 15. This grid is part of the low voltage benchmark grid.
The parameters of the components of the grid are shown in table A.1.

Table A.1: Distribution Grid Parameters

Household label (number of houselholds)	*LD01(8),LD03(3),LD06(5),LD08(4),LD11(2),LD14(3)*
Annual Average Consumption	*4000-5000 kWh/household*
Power Factor	*0.97*
Solar PV Power	*aggregated 6 kW per SPV unit*
400 V Cable Parameters	*Resistance=0.208(ohm/km), Reactance=0.052(ohm/km)*

Appendix B

CD content

1. Power Factory simulation models
2. Matlab codes
3. Report PDF
4. References
5. Figures