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Reactive Power Control for Voltage Management

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Abstract

Reactive Power Control for Voltage Management

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This thesis presents methods for voltage management in distribution systems with high photovoltaic (PV) power production. The high PV penetration leads to both new challenges such as voltage profile violation and reverse power flow, and also new opportunities. Traditionally, the voltage control in the distribution network is achieved by common devices in the networks such as capacitor banks, static synchronous compensators (STATCOMs) and on-load tap changers (OLTCs). This thesis has considered existing reactive power capable solar PV inverters together with STATCOMs to provide voltage support for the distribution network. In this thesis, two effective coordination methods using the STATCOM and PV inverters are developed in order to study their interaction and how they together can stabilize the voltage level. Data from existing low-voltage (LV) and medium-voltage (MV) networks are used for a case study. The first control method is developed for LV network's voltage control by means of PV inverter and STATCOM. The second control method is developed for both LV and MV networks' voltage control, where reactive power control in PV inverters and STATCOMs are used in the LV network and only STATCOMs in the MV network. The control methods follow a hierarchical structure where reactive power compensation using PV inverters are prioritized. The STATCOMs, first in the LV and thereafter in the MV network in the second control method, are used only when the PV inverters are not able to provide or consume enough reactive power. This is beneficial due to the significant reduction in numbers of STATCOMs and their operation. The simulation results indicate that the proposed method is able to control both the over- and undervoltage situations for the test distribution networks. It is also shown that reactive power supply at night by the PV inverters can be an important resource for effective voltage regulation by using the proposed coordinated voltage control method.

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Glossary

AC	Alternating Current
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generation
FACTS	Flexible Alternating Current Transmission Systems
GGC	German Grid Codes
GTO	Gate Turn Off
IGBT	Insulated Gate Bipolar Transistors
IGCT	Integrated Gate Communicated Thyristors
LV	Low Voltage
MV	Medium Voltage
OLTC	On Load Tap Changers
PCC	Point of Common Coupling
PV	Photovoltaic
SC	Shunt Capacitor
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
VSC	Voltage Source Converter

List of Symbols

θ_i phase angle of the grid bus voltage [radian]

θ_{sh} phase angle of the STATCOM voltage [radian]

θ_{gi} phase angle of the inverter voltage output [radian]

$cos\phi_{ref}$ reference power factor

$cos\varphi(P)$ power factor control dependent on the active power injection

b_{sh} susceptance of the STATCOM [siemens (s)]

g_{sh} conductance of the STATCOM [siemens, (s)]

P_i active power in the grid busbar [W]

P_{sh} active power of STATCOM [W]

P_n nominal PV power production capacity [W]

P_i^{ref} reference active power from inverter [W]

$Q(U)$ local reactive power control dependent on voltage

Q_i reactive power in the grid busbar [VAR]

Q_{Ii} reactive power of inverter [VAR]

Q_{ref}, Q^{ref} reference signal for reactive power [VAR]

Q_{PCC} measured reactive power at PCC [VAR]

$-Q_{max}$ maximum reactive power absorption [VAR]

$+Q_{max}$ maximum reactive power generation [VAR]

Q_{sh}^{Spec} reference signal for reactive power [VAR]

Q_{sh} reactive power from STATCOM [VAR]

$Q(U)$ reactive power control dependent on voltage [VAR]

Q_{stat}^{ref} reference signal for reactive power from STATCOM [VAR]

Q_{PV}^{ref} reference signal for reactive power from PV inverter [VAR]

S_i apparent power of inverter [VA]

U_{sh} voltage of the STATCOM [V]

U_{gi} inverter output voltage [V]

U_s, U_i voltage of grid bus [V]

U_i^{Spec}, U_{ref} reference signal for bus voltage [V]

U_1, U_2, U_3, U_4 reference voltages for $Q(U)$ control method [V]

U_{meas} measured bus voltage [V]

U_{sh}^{max} maximum reference voltage for STATCOM [V]

U_{sh}^{min} minimum reference voltage for STATCOM [V]

X_i transformer and line reactance [Ω]

X_{sh} reactance of STATCOM [Ω]

Z_{sh} impedance of the STATCOM [Ω]

Chapter 1

Introduction

1.1 Background

Voltage stability is one of the major concerns when planning and operating a modern power system, and it has earned much attention in recent years due to the increasing number of renewable Distributed Generation (DG) units. One of the fastest growing and cheap energy resources among the available renewable energy sources is solar Photovoltaic (PV) systems. Solar PV energy is considered as an important energy resource to meet the increasing medium and long term global energy demand [1].

PV systems can be integrated into high, medium and low voltage grids although they are mainly connected to the MV and LV grids. In the recent years, high penetration of PV systems is happening mostly in the LV grid networks because of their highly decentralized nature. This has led to challenges for the grid operators to maintain a stable power grid and comply with different grid codes. For example, according to [2] which is European grid standard EN 50160, and the voltage range has to be within $\pm10\%$ of rated voltage under normal operating conditions. One of the main challenges is voltage instability caused by the large number of distributed PV systems with their intermittent nature of power production [1].

In order to achieve the voltage stability, the power system needs to be operated within an acceptable voltage range even under disturbances. The very known disturbances in power system are sudden changes in loads, switches in loads, changes or losses in supply. Besides that, disturbances also occur when reactive power flows through the transmission lines and modify the line and bus voltages [2].

The main focus of this thesis is to propose an effective coordinated voltage control method by using two different reactive power compensation techniques to deal with the unwanted voltage problem associated with high PV penetrations. It is worth mentioning that the proposed control method will not only provide the voltage control scheme for LV network, moreover, it has considered the MV distribution grids' voltage control scheme as well. This thesis work will concentrate on the Swedish municipality of Herrljunga. It is important to keep the voltage under acceptable limits according to European standard EN 50160 regulation ±10% for both the LV and MV network while trying to integrate large number of PV systems into the existing power grid. The information about the studied grid structure and other grid related parameters are not revealed here in this report for the purpose of grid security.

1.2 Challenges and motivations

Distribution grids have been posed to numerous challenges such as reverse power flow and over voltage due to high penetration of PV systems. Over voltage is one major challenges in a power grid with high penetration of DG. Therefore, this voltage limit violation due to over production of power from PV systems causes serious problems on the stable operation of both supply-side units and demand-side equipment. One of the major effects of over voltage is the reduced lifetime of the equipment [3]. Thus, if no proper action is taken in this regard, integration of high number of PV systems into distribution grids might take long time. So, it is important to resolve the aforementioned consequences effectively.

There have already been numerous research works done to find out different possible remedies to deal with the unwanted voltage problem associated with high PV systems penetration and they are classified into mainly system level, plant level and interactive level. The system level deals with remedies that targets grid side whereas the plant level deals with PV plants or customer side. The interactive side focuses on in-between and installed at different locations in the grid with plant components and it requires the communication structures to link to the decision making units. The system level solution includes mainly grid reinforcement and On Load Tap Changers (OLTC), whereas the plant level remedies includes plant level storage, active power curtailment, reactive power control and Flexible Alternating Current Transmission Systems (FACTS) devices such as Static Var Compensator (SVC) [3]. The voltage regulation through reactive power control by the PV inverter is economical and preferred over other remedies because there is no technological barrier to do this. It is easier to modulate the PV inverter to have reactive power similar to producing active power and requires no additional physical equipment.

For example, Germany have allowed reactive power contribution from PV inverter in the LV grid. The voltage regulation methods encouraged by German Grid Codes (GGC) such as $cos\varphi(P)$ and $Q(U)$ have already been studied and implemented on the LV grid in Germany [3]. Therefore, one of the main focuses of this thesis is to use reactive power contribution from PV inverter for LV grids' voltage regulation along with the Static Synchronous Compensator (STATCOM).

Furthermore, due to the high number of PV systems in the power systems, the power flow is not unidirectional anymore. This changes the active and reactive power responses of LV grids to voltage variations in the MV grids. The changes in the voltage-power characteristic at the LV grids may affect the behavior of the MV grids. So, this thesis will also address how this high penetration of PV systems in LV grids would have impact onto MV grids and how to resolve this phenomenon with the help of coordinated control mechanism. Consequently, it is necessary to find a coordinated reactive power control method that can effectively control the voltage profile of the MV grids and LV grids with the high density of PV systems.

1.3 Literature review on voltage control in distribution network

In the recent years, several studies have been carried out on how to mitigate the voltage rise caused by PV generation, since voltage rise is one of the most important limitations towards effective integration [1],[4]. Two aspects are importantly considered in order to achieve the overall grid stability: types of devices operating as compensators and its overall control management [2].

1.3.1 Devices currently operating as compensators

Voltage regulation is performed in two different ways- shunt and series regulation. The shunt regulation includes all types of reactive compensation devices connected in shunt with the grid. On the other hand, the series regulation includes voltage regulators and reactive compensators connected in series with the grid [2].

- **Voltage regulators**
  Traditionally, the voltage regulators are the most common devices used in grids, and it is the earliest device implemented for voltage drop compensation. It is mechanically driven and regulates the voltage by changing the number of windings. However, a voltage regulator according to [5] consists of a tapped auto-transformer and a tap changer. OLTCs are the most common type and used for a very long period of time. OLTCs are connected to the feeder in series, and any change in the secondary side would increase the voltage downstream along the feeder [2].

- **Capacitor bank**
  Capacitor banks are the cheapest and simplest from a technical perspective to be used as compensators. These devices are able to compensate loads with a poor power factor [2].

- **STATCOM**
  The STATCOM is a fast-acting and precise device. It supplies or absorbs adjustable amounts of reactive power to the networks for the voltage regulation whenever it requires. The amount and the direction of the reactive power flow are regulated by these devices. They adjust the magnitude and the phase of the reactive component of the current flowing through their Alternating Current (AC) side [2].

- **PV inverter**

  Reactive power compensation by the PV inverter is another way of voltage regulation. The operational principles of PV inverter are still lack of consensus [6]. Hoever, the reactive power control by the grid-connected inverters on LV distribution networks has already been considered by some countries for voltage such as Germany [4].

- **SVC**

  Over voltage due to high PV power generation in LV network can be suppressed by using the SVC and it is one of the members of FACTS family. However, installing the SVCs in the network is quite an expensive [3].

- **Other components**

  Some other devices are currently used in voltage control of grids such as active filters, power factor controllers, new energy storage loads, or electric vehicles [2].

These control devices have been used so far to tackle the voltage rise issue for connecting solar PV systems into network either by using one compensation device locally or co-ordination among several compensation devices at different level of grid network. Most of the literature or scientific works in [2],[7],[8],[9] so far found have focused on coordinated control based on theoretical simulations by using PV inverters with the SVC, OLTC or Shunt Capacitor (SC). However, very few studies on coordinated voltage control in a distribution grid using PV inverters and STATCOMs have been made. This thesis will therefore focus on coordinated voltage control by using the PV inverters and STATCOM at the LV and MV levels in order to keep the network voltage profile according to grid standard.

1.3.2 Current Volt/VAR management regulation systems

Volt/VAR management regulation is a technique that has been used for a long time in power distribution systems and deals with the voltage and reactive power control [2]. The devices that have been mentioned earlier are used to regulate the instantaneous voltage by controlling the reactive power flow. According to European standard EN 50160 regulation, the voltage should be within ±10% of rated voltage under normal operating conditions. Currently, Volt/VAR management is being used to keep the system within these levels by the distribution operator [2].

There are common types of control methods or structures that have been found in the literature which are used to control the compensator devices according to [10].

- **Decentralized control**

  The control actions are derived locally at each node to which Distributed Energy Resource (DER) is connected to provide voltage support from DERs. In this case only the local information is used without the knowledge of how control action effect the overall system because of no exchange of information [10].

- **Centralized control**

  The control decision in centralized control system is made only by the co-ordinator/central controller and the overall control strategy is stored at the central controller. Usually, it collects the complete information from the whole network and takes control action based on the data collected [10].

- **Hierarchical control**

  A hierarchical control is formed according to the existing structure of the grid network. The coordinator situated at the higher level calculates the set points, which are the reference signals for the lower level local controller. Thus it consists of multiple control layers, so in the case where it is not enough with the first control layer, the system continues with the next control layer. The main role of the higher level controllers is to ensure the consistent control behavior between the lower local controllers which will lead to improved overall global performance [10].

  This hierarchical control structure will be used in this thesis and the proposed solution will consider the different combinations of PV inverters and STAT-COM, and it will define in what order they should contribute to the voltage regulation for MV and LV grid network. The total control structure will be discussed in details in the subsequent chapter.

The achievement of this coordination will be carried out through simulations on a realistic MV and LV Swedish distribution network. In simulation, two scenarios will be tested: coordinated control for LV networks by PV inverter and STATCOM; and coordinated control for both MV and LV networks by PV inverter and STATCOM.

1.4 Thesis objectives

This thesis attempts to answer the following research objectives:

- Examine how power production in the LV grids from high number of PV systems would have the impact on LV and MV grids in terms of voltage instability.
- Examine actions that can be taken to suppress the voltage instability.
- Design a coordinated reactive power control model for PV interver and STATCOM to avoid over- and undervoltage situation in distribution grids.
- Evaluate the proposed model using the real data from Swedish MV and LV distribution grids.

1.5 Research approach

The penetration of large scale PV systems into existing power distributon grid is a growing trend, and therefore this thesis work examines voltage rise and drop in both MV and LV grids. The PV inverters and STATCOM will be investigated as means of dealing with these voltage variation problems at different level of the distribution network. Afterwards, a coordinated voltage control method will be proposed and demonstrated. The development and implementation of the proposed control method are based on modelling and simulations. The Matlab/Simulink software will be used for simulation and the developed control method will be examined with a case study. The solar PV is connected to the LV side of the studied grid in which PV power plants will represent the generation part, and loads also connected in the LV side represent the consumption part. A reactive power regulation of solar PV model would be developed for the local voltage support at plant level. In addition, the STATCOM will also provide the voltage control capabilities for both the MV and LV grids.

Finally, the coordinated voltage control algorithm will be tested on the test grid with a view to assess the consequences of control on node voltages and should allow the system to operate under the conditions defined by grid codes.

1.6 Limitations

This thesis work is limited by several different factors:

- This work only addresses technical aspects of possible solutions for keeping the voltage profile within the allowed voltage limit. The financial aspects are not analyzed here.
- The reactive power control model for STATCOM is considered as an ideal, and thus losses are not taken into consideration.

1.7 Boundary conditions

This thesis work has some boundary conditions that has been considered during the control algorithm development and simulation:

- The developed coordinated voltage control algorithm is tested and simulated for one LV network and 252 nodes of MV networks.
- The simulation has been carried out for one winter day and one summer day.
- The control of the PV inverters and the STATCOM overlapped. The methods works if the inverters get a signal from the STATCOM saying that they are "on" and that they should continue providing maximum reactive power until they disconnect.

- The capacity limit for the STATCOM is not considered for reactive power generation/absorption.
- The line losses and line capacity analysis are not part of this study.

1.8 Thesis outline

The rest of this thesis is organized as follows:

Chapter 2 briefly describes about two reactive power compensation devices (PV inverter and STATCOM), discusses about the grid codes, and presents brief information about the test grid.

Chapter 3 depicts the modelling of reactive power control methods for PV inverter and STATCOM based on voltage droop characteristics, and presents the proposed coordinated voltage control method for the LV network and MV network.

Chapter 4 presents the simulation of the test grid and the results.

Chapter 5 provides the discussion.

Chapter 6 highlights the main conclusions of the thesis and summarizes the ideas for future research work.

Chapter 2

Reactive Power Compensation Devices and Test Grid

Introduction

One of the main sources of voltage collapse is the lack of reactive power and this causes voltage instability in a power system [11]. To overcome the voltage instability issue the reactive power flow control method is one of the economical choices which has already been mentioned in the previous chapter. It is also mentioned previously that the most of the studies found in the literature focus on control strategies that integrate the coordinated control operation among the OLTCs, PV inverters, SVCs and SCs [2],[7],[8],[9]. However, the research was limited to assess the technical potential of coordinated control strategies that integrate both the PV inverter and STATCOM. That is why these two reactive power sources have been chosen to supply reactive power: PV inverter and STATCOM. This chapter will discuss about the PV inverter, STATCOM, grid codes and the test grids.

2.1 Photovoltaic (PV) inverter

It is already known that the fast expansion of PV systems into the lower parts of the grid has raised several concerns to the grid operator [3]. One of the concerns is grid voltage stability. The grid operators have to impose strict operational rules on

PV systems in order to keep the grid voltage stable. As a consequence they have proposed to the PV system manufacturers that the PV inverters should have the capability to control the voltage. One of the grid support functions that has been included into the PV inverters is the reactive power capability to stabilize the grid voltage [12].

2.1.1 Inverter reactive power range

The capacity of inverter and its internal loss decide the amount of reactive power output of PV power plants when inverters are used as a reactive power source. Figure 2.1 is showing the equivalent circuit of an inverter within a PV system connected to the grid in which U_{gi} is the inverter output voltage; U_s is the voltage of the grid bus; θ_{gi} is the phase angle of the inverter output; X_i is the transformer and line reactance; Q_{Ii} is the reactive power of the inverter; S_i is the apparent power of the inverter; P_i is the active power of the grid busbar; and Q_i is the active power of the grid busbar [13]. The power equations of the system 2.1 can be derived as following

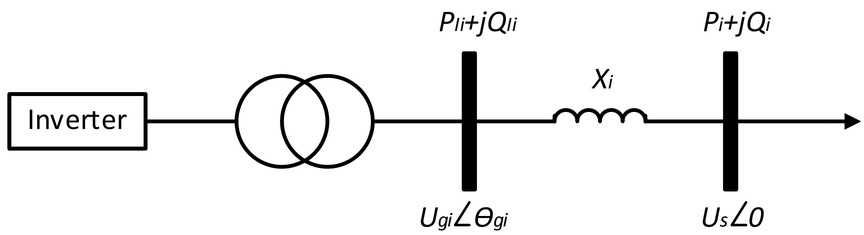


Figure 2.1: PV power plant equivalent circuit.

according to [13]:

$$P_i = \frac{U_s U_{gi} sin\theta_{gi}}{X_i} \tag{2.1}$$

$$Q_i = \frac{U_s(U_{gi}cos\theta_{gi} - U_s)}{X_i} = \frac{U_s U_{gi} cos\theta_{gi}}{X_i} - \frac{U_s^2}{X_i} \tag{2.2}$$

By using the equations (2.1) and (2.2), the following can be deduced.

$$P_i^2 + \left(Q_i + \frac{U_s^2}{X_i}\right)^2 = \left(\frac{U_s U_{gi}}{X_i}\right)^2 \tag{2.3}$$

When the value of $Q_i = 0$ and then the equation (2.3) becomes:

$$P_i = \sqrt{\left(\frac{U_s U_{gi}}{X_i}\right)^2 - \left(\frac{U_s}{X_i}\right)^2} = \frac{U_s}{X_i}\sqrt{U_{gi}^2 - U_s^2} \quad (2.4)$$

The equation (2.3) gives the range of reactive power that the inverter can supply to the bus bar connected to the grid and which can be defined by:

$$-\sqrt{\left(\frac{U_s U_{gi}}{X_i}\right)^2 - P_i^2} - \frac{U_s^2}{X_i} \leq Q_i \leq \sqrt{\left(\frac{U_s U_{gi}}{X_i}\right)^2 - P_i^2} - \frac{U_s^2}{X_i} \quad (2.5)$$

Inverters normally operate at rated active power to maintain the active power output of the PV system, and therefore the inductive and capacitive reactive power output range is limited for an inverter [13].

2.1.2 Reactive power control methods of PV inverter

There are four different reactive power control methods that have been suggested according to [14]: fixed power factor, constant reactive power, power factor control dependent on the active power injection $cos\varphi(P)$, and local reactive power control dependent on voltage $Q(U)$. The last technique is of the interest for this study as the $Q(U)$ method directly use the local voltage information to stabilize the weak bus voltage.

This thesis focuses on the voltage control by the PV inverter using $Q(U)$ method. This control action maintains the acceptable voltage range at the PCC by providing the reactive power into the network from PV inverter. The details of $Q(U)$ control method modelling is discussed in the next chapter.

2.2 Static synchronous compensator (STATCOM)

STATCOM is the most widely used member of FACTS, and is usually used as a source to provide reactive power to control the transmission voltage. This reactive power compensation is mainly shunt compensation with the AC system. The reactive power compensation by the STATCOM is based on Voltage Source Converter (VSC) which is much faster and has a bigger range of control because of the usage of semiconductor switches instead of mechanical switches [15]. In the following section the details about the STATCOM are presented.

2.2.1 Power semiconductor devices

A STATCOM is usually consists of one VSC with a capacitor on a Direct Current (DC) side of the converter and one shunt connected transformer which is shown in Figure 2.2. The VSC is built with thyristors with turn-off capability like Gate Turn Off (GTO) or today's advanced Integrated Gate Communicated Thyristors (IGCT) or with Insulated Gate Bipolar Transistors (IGBT) based converter [15].

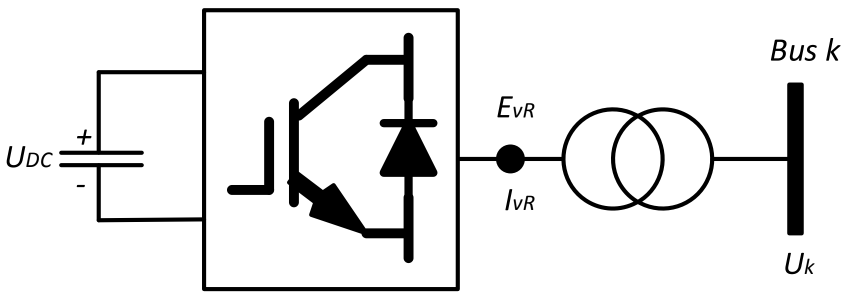
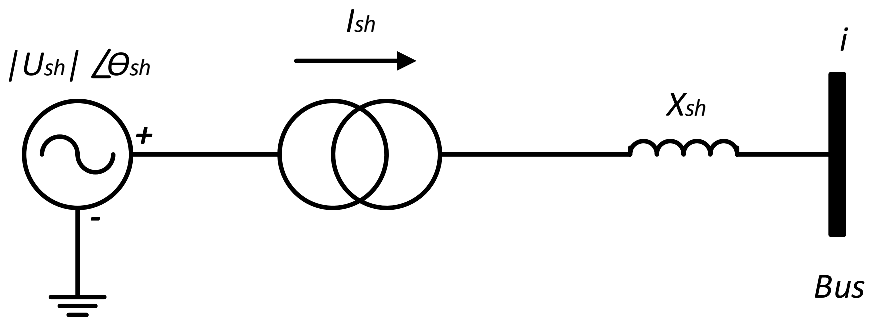


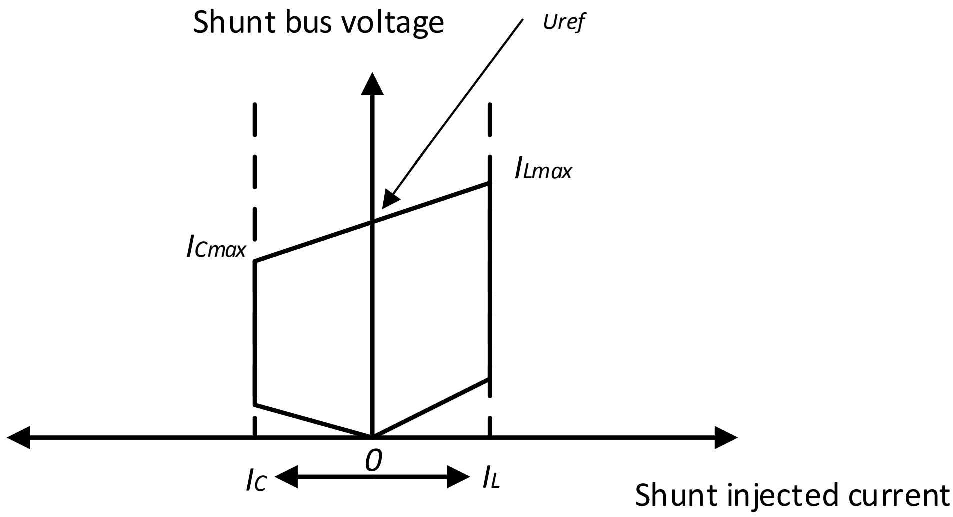
Figure 2.2: STATCOM schematic representation.

2.2.2 Operation principle

Traditionally, the STATCOM can be used as synchronous voltage source since its output voltage can be controlled as desired as presented in Figure 2.2. Here the assumption is that there is no exchange of active power between STATCOM and the grid, and the operation is lossless, so the voltage of the STATCOM controller and the grid voltage is in phase. The flow of current through the STATCOM is dependent on the voltage difference between the grid and the STATCOM. If the compensator voltage magnitude is smaller than the voltage at the connection point, reactive power will be consumed by the STATCOM. On the other hand, if the situation is opposite, reactive power will be delivered to the grid [15]. This principle is presented on the following Figure 2.3. A STATCOM injects reactive current



(a)



(b)

Figure 2.3: (a): STATCOM equivalent circuit. (b): A typical U-I characteristics of STATCOM.

to support the grid voltage in case of under voltage and behaves as an overexcited generator or capacitor. On the contrary, when the STATCOM is absorbing reactive current it decreases the grid voltage and STATCOM behaves as an under excited generator or inductor. The power flow constraints of STATCOM are given by the following equations.

$$P_{sh} = U_i^2 g_{sh} - U_i U_{sh}(g_{sh} cos(\theta_i - \theta_{sh}) + b_{sh} sin(\theta_i - \theta_{sh})) \tag{2.6}$$

$$Q_{sh} = -U_i^2 b_{sh} - U_i U_{sh}(g_{sh} sin(\theta_i - \theta_{sh}) - b_{sh} cos(\theta_i - \theta_{sh})) \tag{2.7}$$

in which U_i and θ_i are the voltage of the bus and the angle of the bus voltage to which the STATCOM is connected. U_{sh} and θ_{sh} are the voltage and the angle of the STATCOM and $g_{sh} + jb_{sh} = 1/Z_{sh}$.

2.2.3 Control modes

There are various control modes of STATCOM operation through which the control of reactive power flow is provided by STATCOM. The flow of reactive power control can be realized in one of the following control modes by the STATCOM.

- **Reactive power**

  This control method focuses on direct reactive power injection or absorption to the local bus, to which the STATCOM is connected according to the specified reference by the distribution operator [15]. This control mechanism can be expressed mathematically as follows:

  $$Q_{sh} - Q_{sh}^{Spec} = 0 \tag{2.8}$$

  in which the Q_{sh}^{Spec} is the reference signal for reactive power and Q_{sh} can be found from equation (2.7).

- **Voltage droop characteristics**

  This control strategy is based on voltage/reactive power slope characteristics and the setting of target voltage at Point of Common Coupling (PCC) is set by the distribution operator according to the grid code [15]. The voltage control is specified as follows:

  $$U_i - U_i^{Spec} = 0 \tag{2.9}$$

  in which the U_i^{Spec} is the reference voltage signal that has to maintained at PCC and U_i is the i_{th} bus voltage.

- **Power factor**

  This mode of control is the modification of power factor at the PCC in which the STATCOM is connected and the control constraint can be realized by the following equation [15].

$$Q_{ref} - Q_{PCC} = 0 \tag{2.10}$$

The Q_{ref} is the reference signal for reactive power that can be achieved by the following equation (2.11) and Q_{PCC} is the measured reactive power at PCC.

$$Q_{ref} = \sqrt{S^2 - P_{PCC}^2} = \sqrt{\frac{P_{PCC}^2}{cos^2\phi_{ref}} - P_{PCC}^2} \tag{2.11}$$

in which P_{PCC} is active power at the PCC and $cos\phi_{ref}$ is the desired reference power factor.

This thesis focuses on the voltage control by the STATCOM at the PCC in which the PV inverter is not capable anymore to maintain the voltage within the specified limit. Therefore, voltage droop characteristics control mode will be used to control the STATCOM. This control mode maintains a constant voltage at the PCC considering the error between the voltage reference and the measured voltage by providing the reactive power into the network. The details about the STATCOM control method modelling is discussed in the next chapter.

2.3 Grid codes

The European grid code EN 50160 is the standard that deals with the important grid requirements to provide quality power from supplier side to the customer side. One of the important requirements is to characterize the voltage parameters for the public distribution networks. According to standard EN 50160, there are several voltage parameters which needs to be fulfilled for the proper grid operation where *voltage magnitude variations, rapid voltage changes, supply voltage dips, flicker, supply interruptions* are the most important ones. However, according to this standard, the voltage magnitude variations at the customer's PCC in public LV and MV electricity distribution network have to be maintained within ±10%. However, in the appendix section A.1, the values for the allowed voltage limit for LV and MV grids are provided.

2.4 Test grid

The investigation of voltage instability is performed on the grid of Swedish municipality of Herrljunga. The grid consists of two MV networks and 338 LV networks. But the test grid considered for this study will focus on 252 nodes of one MV grid and one LV network under one node of the MV network. The generic single-line diagram of the test grid is shown in Figure 2.4. Finally, a coordinated voltage control method will be proposed by using two VAR compensation devices in the distribution network to overcome the voltage instability. One compensatator would be the existing PV inverter in the system and the other compensatator would be the STATCOM. Some information about the test grid parameters are summarized in the following Table 2.1.

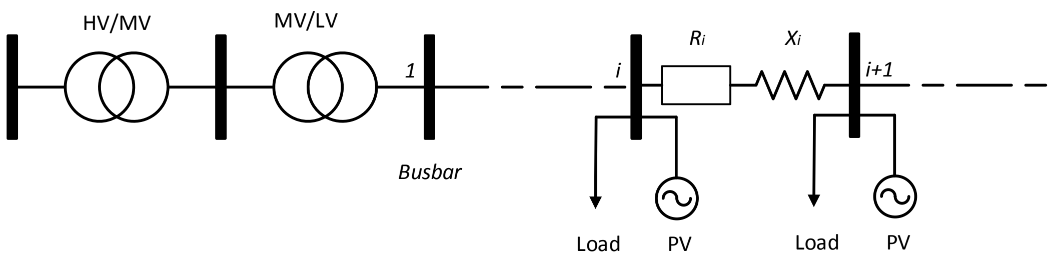


Figure 2.4: Generic single-line diagram of test grid.

Table 2.1: Summary of the test grid characteristics.

Test Grid (HERRLJUNGA) Characteristics		
	MV	**LV**
Voltage	10 KV	0.4 KV
Grid topology	mesh	radial
Number of buses*	-	93
Number of nodes**	252	-

** : grid bus of the LV network is the connection point where PV/STATCOM/load are connected, and there are 93 buses in total for the considered LV network.*

*** : node of the MV network is the connection point where LV network is connected, and there are 252 nodes in total of the considered one MV network.*

Chapter 3

Modelling of Reactive Power Control Methods and Proposed Coordinated Voltage Control Algorithm

Introduction

This chapter describes the modelling of reactive power control methods of the considered compensation devices which are PV inverter and STATCOM. It also presents the proposed coordinated voltage control algorithm for LV and MV network.

3.1 PV inverter control method - $Q(U)$

As already mentioned earlier, the reactive power capabilities of solar inverters can be used to maintain the voltage level within the specified limits. In chapter 2, several reactive power control methods for PV inverter has been mentioned, and in this thesis, we are going to implement the $Q(U)$ method that directly uses local voltage information that is a consequence of the power production and consumption. Therefore, the total reactive power absorption or generation of the inverters will be considerably reduced for voltage supporting compared with the other reactive power control methods such as fixed $cos\varphi$ and $cos\varphi(P)$ methods [4].

The following equation (3.1) can be easily implemented in the inverter controllers and be modified remotely to control the weak bus voltage by providing reactive power from the PV inverter [4]. The reactive power flow algorithm by PV inverter is developed based on the following equation (3.1). The general pattern of the reference reactive power absorption or generation for different voltage limit violations is shown in Figure 3.1 for $Q(U)$ method.

$$Q_{PV}^{ref} = \begin{cases} Q_{max} & U_{meas} < U_1 \\ \frac{Q_{max}}{U_1 - U_2}(U_{meas} - U_1) + Q_{max} & U_1 \leq U_{meas} \leq U_2 \\ 0 & U_2 \leq U_{meas} \leq U_3 \\ \frac{Q_{max}}{U_3 - U_4}(U_{meas} - U_3) & U_3 < U_{meas} \leq U_4 \\ -Q_{max} & U_{meas} > U_4 \end{cases} \tag{3.1}$$

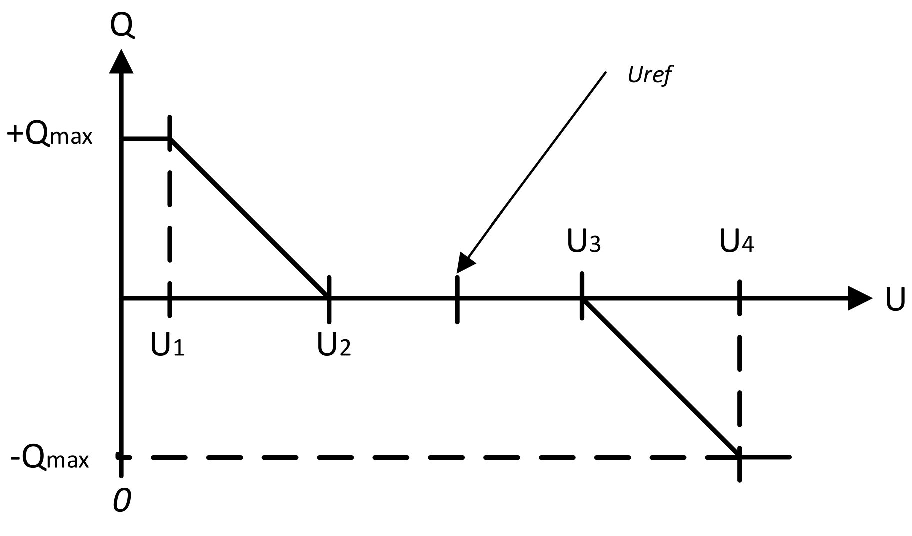


Figure 3.1: Standard reactive power methods- $Q(U)$.

The reactive power reference is calculated using the value of the voltage variation at PCC found in equation (3.1). The droop curve in Figure 3.1 for $Q(U)$ method is normally provided by the grid operator. Therefore, at first, it is essential to specify the droop characteristic for the LV grid network. It can be seen from Figure 3.1 that the maximum value of voltage magnitude should not exceed U_4 during over voltage and at that moment the reactive power absorption is $-Q_{max}$. On the other hand, the minimum value of voltage magnitude should not drop below U_1 during under voltage and at that point the reactive power generation is $+Q_{max}$.

The start value for absorbing and generating the reactive power is chosen to be U_3 and U_2. Thereafter, the droop characteristics can be formed as Figure 3.1. The chosen values for the voltages $[U_1\ U_2\ U_3\ U_4]$ are provided in the next chapter in Table 4.1 and Table 4.3 respectively for summer and winter days. The equation for maximum reactive power is defined by

$$Q_{max} = tan(acos(cos\varphi)) \times P_n \tag{3.2}$$

in which P_n is the nominal PV power production capacity. The nominal active and maximum reactive power production capacity for the PVs are given in the appendix section A. The maximum reactive power is provided by PV inverter at power factor 0.85.

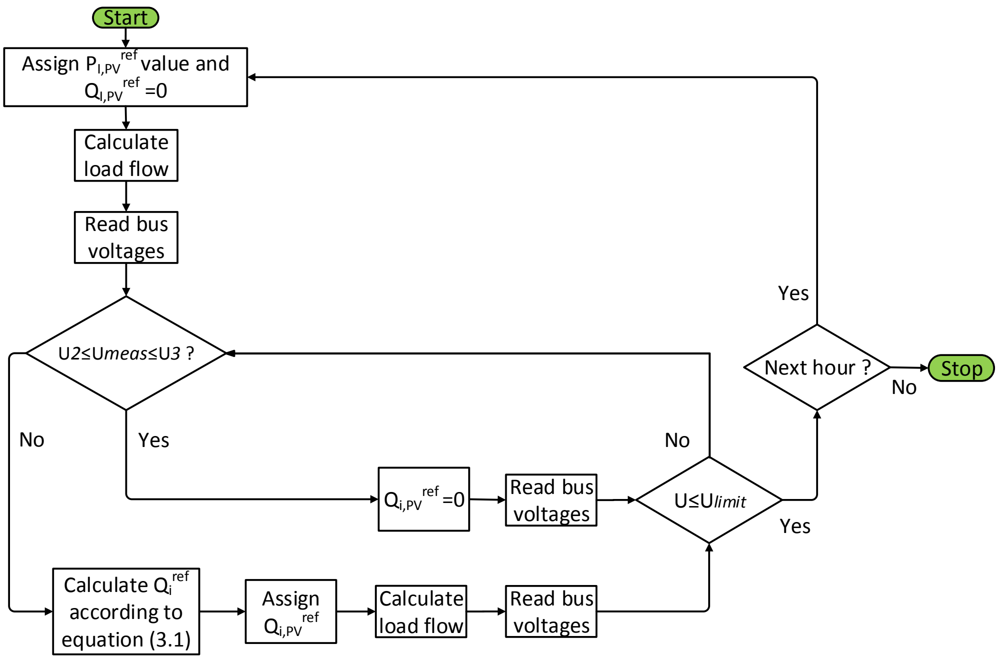


Figure 3.2: Flow chart with the implementation of the $Q(U)$ method.

The flow chart shown in Figure 3.2 presents the implementation of the $Q(U)$ method for PV inverter. For this purpose the Matlab/Simulink software was used for load flow analysis based on Newton-Raphson method. During each iteration two load flow analysis are performed. The effect of active power generation from the PV plant on the voltage magnitude is investigated initially. Then the reactive power Q_{PV}^{ref} is assigned individually from each PV based on the measured voltage value U_{meas}, and a new load flow analysis is performed in order to check if the problem has been mitigated.

3.2 STATCOM control method

It is already known from the previous chapter that the STATCOM can be designed to control the required amount of reactive power flow at the bus where it is connected to. Therefore, the control of reactive power flow and direction of flow from the STATCOM is controlled by the voltage difference between STATCOM output terminal voltage and the voltage at the bus. The following Figure 3.3 is showing the equivalent circuit of STATCOM. The reactive power flow exchange equation from

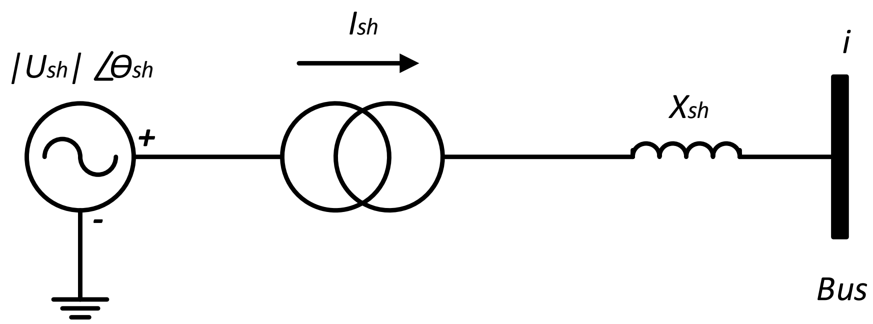


Figure 3.3: STATCOM equivalent circuit.

the STATCOM can be defined by

$$Q_{sh} = -|U_i|^2 b_{sh} - |U_i||U_{sh}|(g_{sh} sin(\theta_i - \theta_{sh}) - b_{sh} cos(\theta_i - \theta_{sh})) \tag{3.3}$$

To simply this equation, it is assumed that the STATCOM is lossless ($g_{sh} = 0$ and $\theta_i = \theta_{sh}$) and it is also assumed that the STATCOM is not providing any active power ($P_{sh} = 0$) into the grid. Then the final equation (3.3) for reactive power exchange becomes

$$Q_{sh} = -|U_i|^2 b_{sh} + |U_i||U_{sh}|b_{sh} \tag{3.4}$$

in which U_i is the measured bus voltage at bus i, U_{sh} is the voltage at the output of STATCOM, X_{sh} is the STATCOM reactance and Q_{sh} is the reactive power exchange for the STATCOM with the grid bus. The control flow chart for STATCOM reactive power control algorithm is mentioned in Figure 3.4.

The exchange of reactive power from the STATCOM is mainly based on the following two conditions:

- if $|U_i| < U_{sh}^{min}$, then the STATCOM generates reactive power Q_{stat}^{ref}.
- if $|U_i| > U_{sh}^{max}$, then the STATCOM absorbs reactive power Q_{stat}^{ref}.

The STATCOM parameters and maximum/minimum values of $|U_{sh}|$ are provided in the next chapter in Table 4.2 and Table 4.4 respectively for summer and winter days.

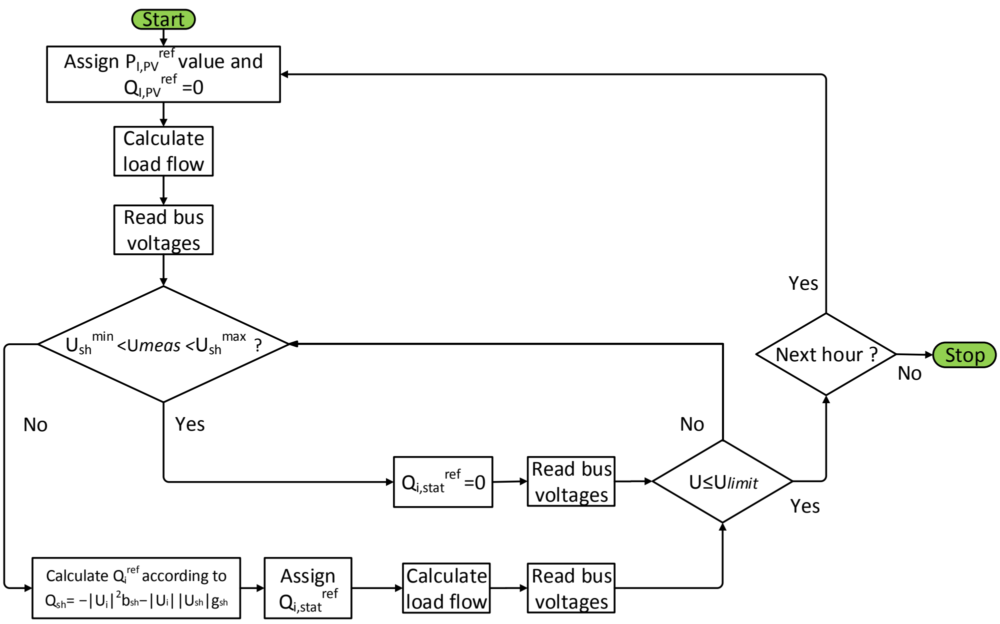


Figure 3.4: Flow chart with the implementation of the STATCOM control method.

3.3 Proposed coordinated voltage control algorithm

The proposed coordinated voltage control algorithm has been developed for controlling the voltages in the distribution grid. The methods have been developed to control the grid voltage for two different grid voltage levels: 1) voltage control for LV grid, and 2) voltage control for both the LV and MV grid together.

3.3.1 Scenario I : Voltage control algorithm for the Low Voltage (LV) grid

The voltage control algorithm for the Low Voltage (LV) grid is considered as a scenario I for simulation. It considers only the LV network's voltage control by means of PV inverter and STATCOM control devices. The reactive power control flow from these two devices (PV inverter and STATCOM) follows the hierarchical control modes. The coordinated control flow chart is shown in Figure 3.5. It shows that the voltage regulation starts with the PV inverter as a first layer of control action by injecting/absorbing the reactive power, and when this first layer of control action is not sufficient enough for voltage regulation, then the STATCOM comes as a second layer of control action. The STATCOM then injects/absorbs the reactive power to the corresponding bus of LV network to stabilize the bus voltage. The simulation results are shown in the next chapter.

3.3.2 Scenario II : Voltage control algorithm for the LV grid and Medium Voltage (MV) grid

The voltage control algorithm for the Low Voltage (LV) and Medium Voltage (MV) grid is considered as a scenario II. It considers both the LV and MV networks' voltage control where the MV network's control device is only the STATCOM and the LV network's control devices are PV inverter and STATCOM alike the scenario I. The reactive power control of these devices follows the hierarchical control modes. The coordinated control flow chart is shown in Figure 3.6. It shows that the voltage regulation starts from the LV side by means of the PV inverter and STATCOM

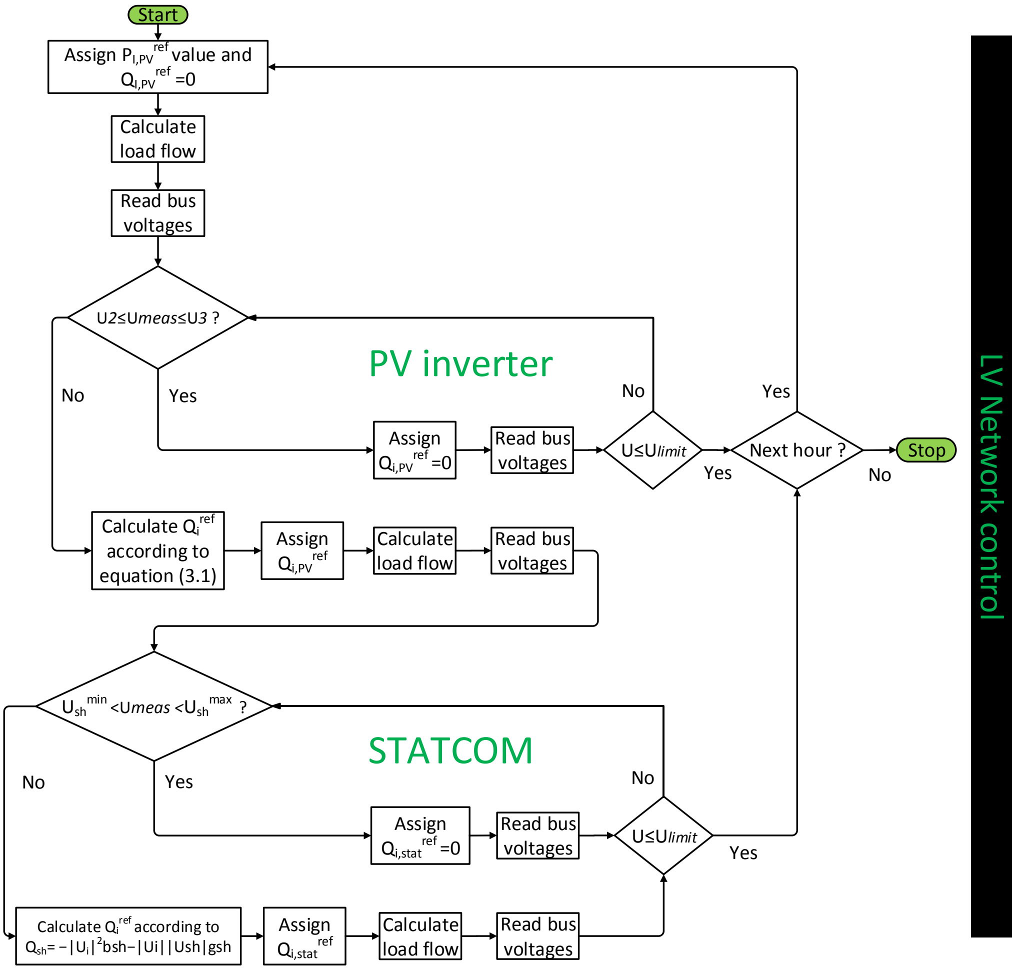


Figure 3.5: Control flow chart for the Low Voltage (LV) grid.

by injecting/absorbing reactive power into LV network to stabilize the voltage, and thereafter, the MV control action will take place.

However, it needs to be mentioned that the MV network control action is not that always the subsequent operation which only occurs after the LV network action. The MV network control can initiate its control action independently by activating the STATCOM to stabilize the voltage at the MV nodes. However, if only if there is a reactive power generation happened in the LV side, then the effect of this generation will be examined first on the MV grid side and then the MV network control will take control action depending upon the voltage situation. Otherwise, the LV network control and MV network control can take their control action independently to bring the voltage within specified limits. In the next chapter, the simulation and results are presented with the results analysis.

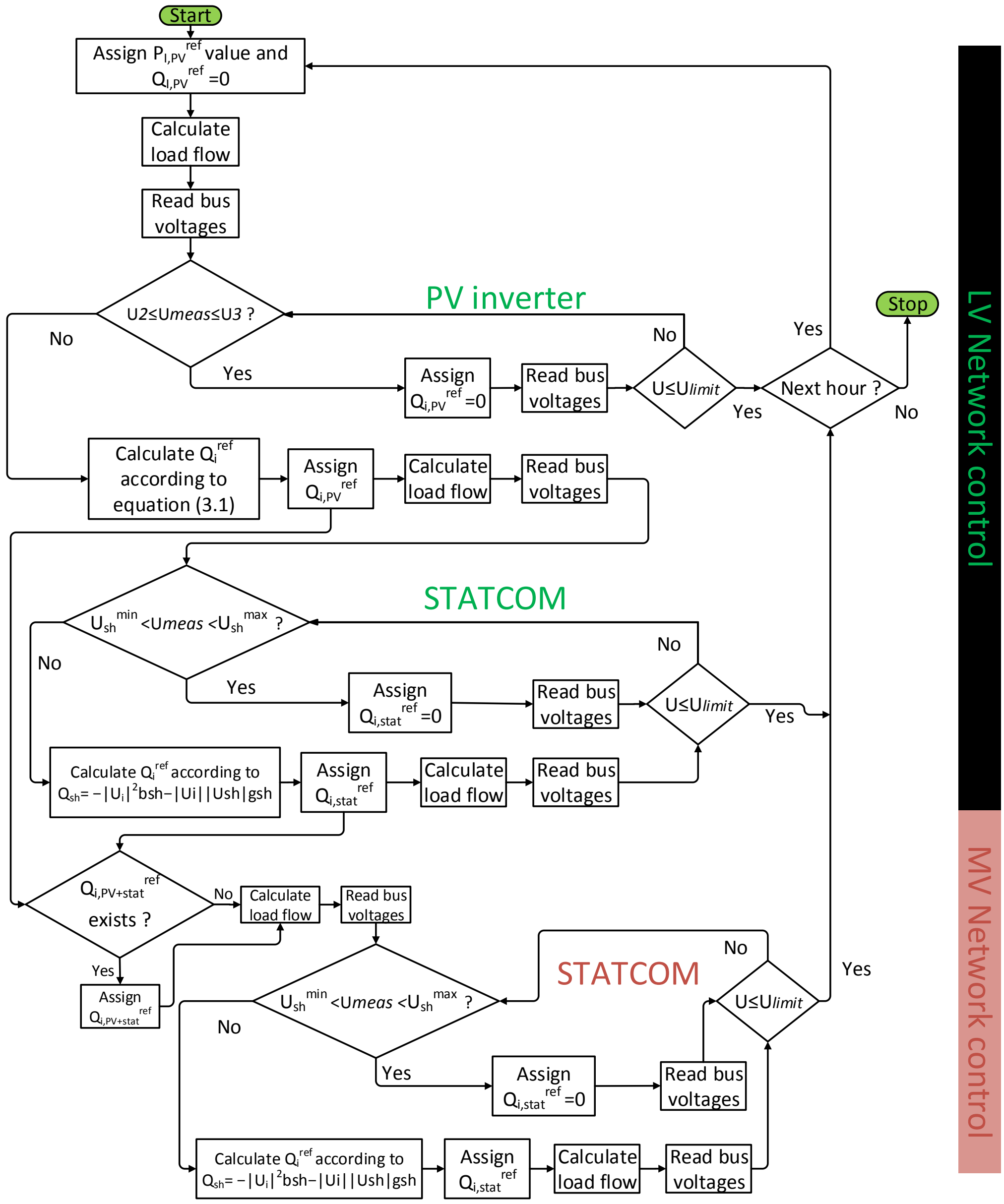


Figure 3.6: Control flow chart for the Low Voltage (LV) and Medium Voltage (MV) grid.

Chapter 4

Simulation and Results

Introduction

This chapter presents the grid simulation and results for two control scenarios I and II based on the proposed coordinated voltage control algorithm developed in the previous chapter.

4.1 Grid simulation for scenario I and II

The proposed coordinated voltage control algorithm with the help of reactive power flow would be tested and simulated on grid for two control scenarios. The two control areas are mentioned in the following Figure 4.1 and they are:

- Scenario I : Low Voltage (LV) network control
- Scenario II : LV network and Medium Voltage (MV) network control

The grid simulation for both scenarios will consider the following two situations to check the effectiveness of proposed algorithm:

- A summer day where the grid is imposed to over voltage situation due to high solar power production and low power consumption.
- A winter day where the grid is imposed to under voltage situation due to low solar power production and and high power consumption.

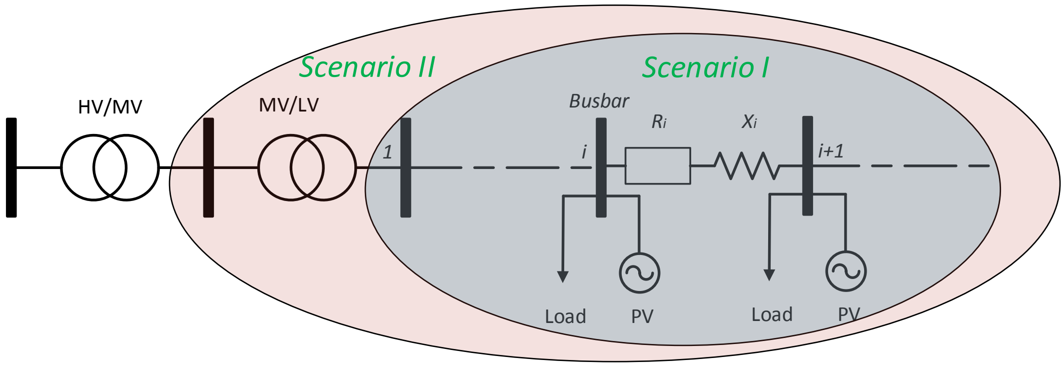


Figure 4.1: Two control scenarios.

4.1.1 Results for scenario I

The work of this part is programmed with the help of Matlab/Simulink software for the power flow simulation and simulating the developed reactive power control method onto control scenario I for the LV grid voltage regulation. As mentioned before, the proposed control method will be examined for one winter and one summer day to check the effectiveness of the algorithm.

Simulation for a summer day - over voltage situation:

The influence of high solar PV power production and low power consumption are considered during a summer day when LV grid buses suffer from the over voltage situation. Figure 4.2 depicts all the buses voltage for 24 hours in a summer day. All the buses except one are within the specified voltage limit of 440 V, indicated by the green line in Figure 4.2. The bus number 48 is found to be the the most critical bus out of total 93 buses in the studied LV grid with respect to the upper voltage limit violation. The total number of hours that the bus 48 stays over the specified limit is 10 hours.

Table 4.1: Summer settings for PV inverter control for LV network.

$Q(U)$ **method**
$[U_1\ \ U_2\ \ U_3\ \ U_4] = [355\ \ 364\ \ 436\ \ 445]$ V
Q_{max} production at power factor $= 0.85$

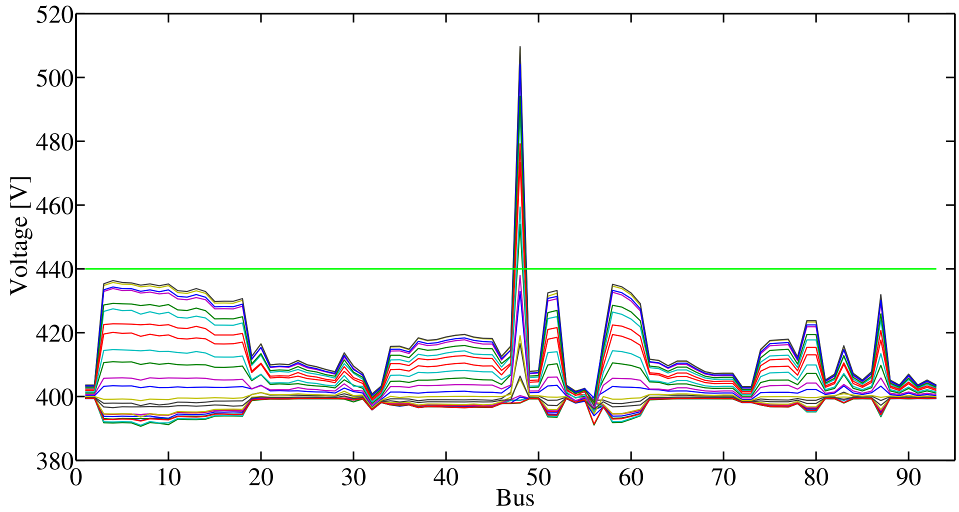


Figure 4.2: Voltage in the LV grid buses before applying the voltage control. Total number of buses 93 and each line represents the hourly buses voltage.

The voltage variations of bus 48 at different hours in a day can be seen from Figure 4.3 where the voltage has crossed the voltage upper limit 440 V due to high amount of PV power production and low load demand in that bus. So, the voltage of this bus needs to be controlled in this situation.

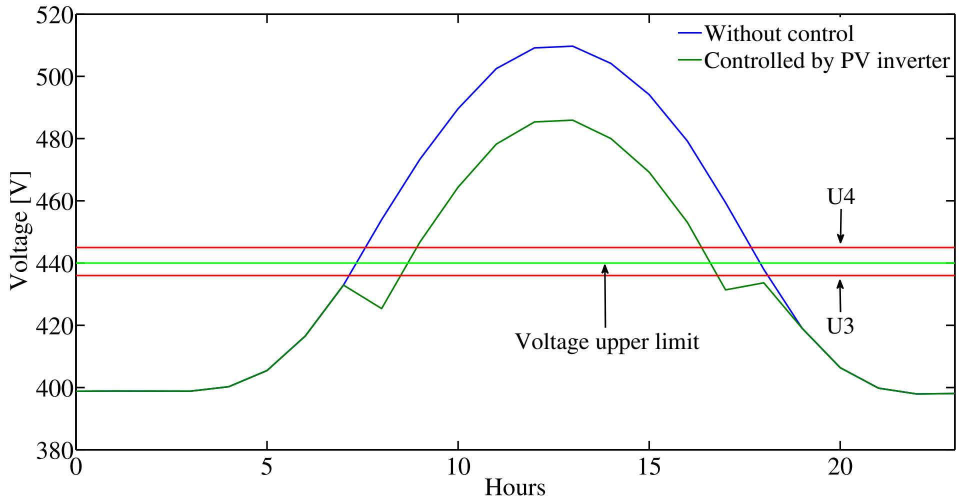


Figure 4.3: Voltage in the critical grid bus 48 after applying the voltage control by the PV inverter.

To do that, the first control action according to control flow diagram described in Figure 3.5 will come from the corresponding PV inverter of that bus by absorbing the reactive power from the grid.

Figure 4.3 depicts that the voltage at the grid bus 48 is reduced by approximately 4.6% for those hours where the bus voltage crossed the upper voltage limit. The PV inverter connected to bus 48 is absorbing the reactive power to bring the voltage down and the amount of reactive power absorption is shown in Figure 4.4.

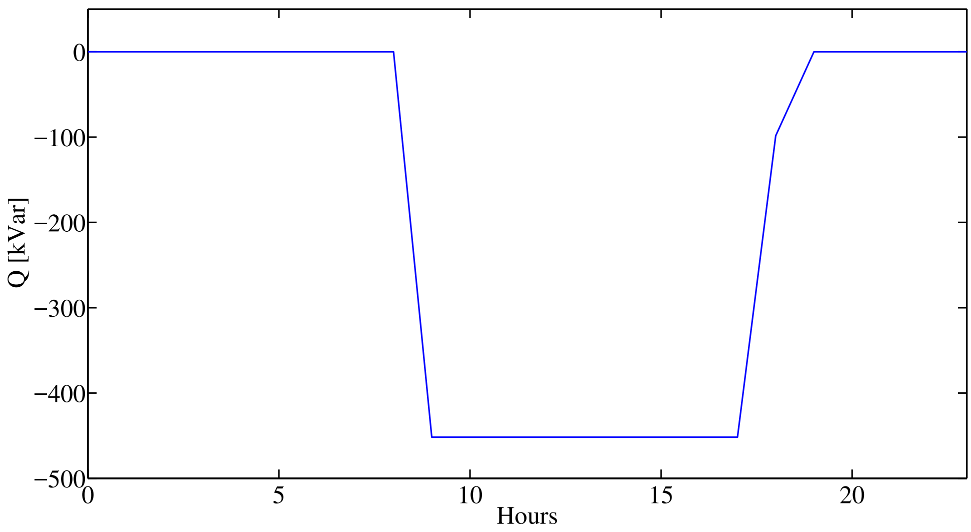


Figure 4.4: Reactive power absorption at bus 48 by the PV inverter.

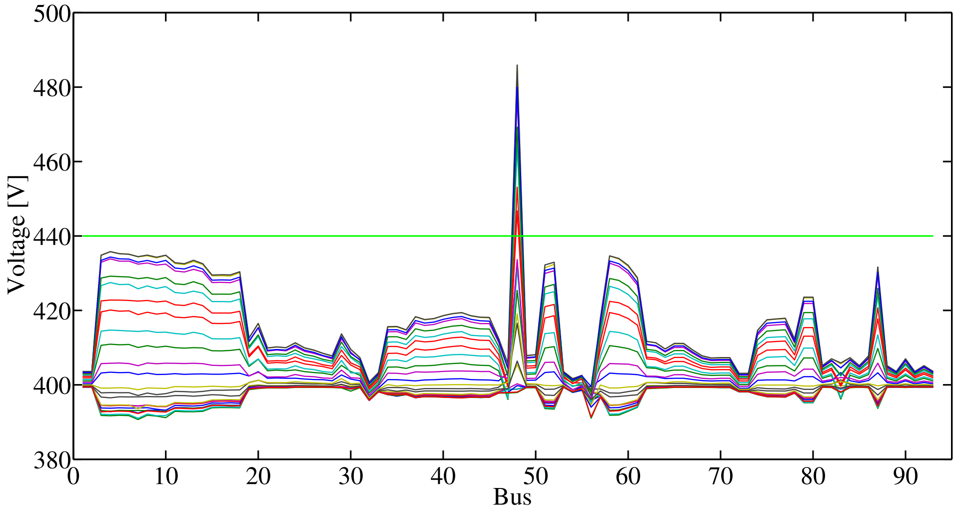


Figure 4.5: Voltage in the grid buses after applying the voltage control by PV inverter. Each line represents the hourly buses voltage.

The voltages for all of the buses after reactive power support by the PV inverter are shown in Figure 4.5. However, the voltage at the grid bus 48 is still exceeding the upper voltage limit of 440 V. The PV inverter provides the maximum Q support by consuming reactive power that is available at those hours without curtailing any power; but that is not sufficient enough to bring the voltage down to or below the upper limit.

Hence, according to control flow diagram described in Figure 3.5, the next or second layer of control action will come from the STATCOM. However, the optimal placement of the STATCOM is one of the important factors where it benefits the system most in order to keep the voltage stable. It can be observed from Figure 4.5 that the grid bus 48 would be the best place for compensation because there it requires more reactive power support. Therefore, the STATCOM is placed at the grid bus 48. The susceptance value in Table 4.2 for the STATCOM has been decided empirically.

Table 4.2: Summer settings for STATCOM control for LV network.

STATCOM
$[U_{stat}^{max}\ \ U_{stat}^{min}] = [440\ \ 360]$ V
Susceptance, $b_{sh} = 23.9901$ s

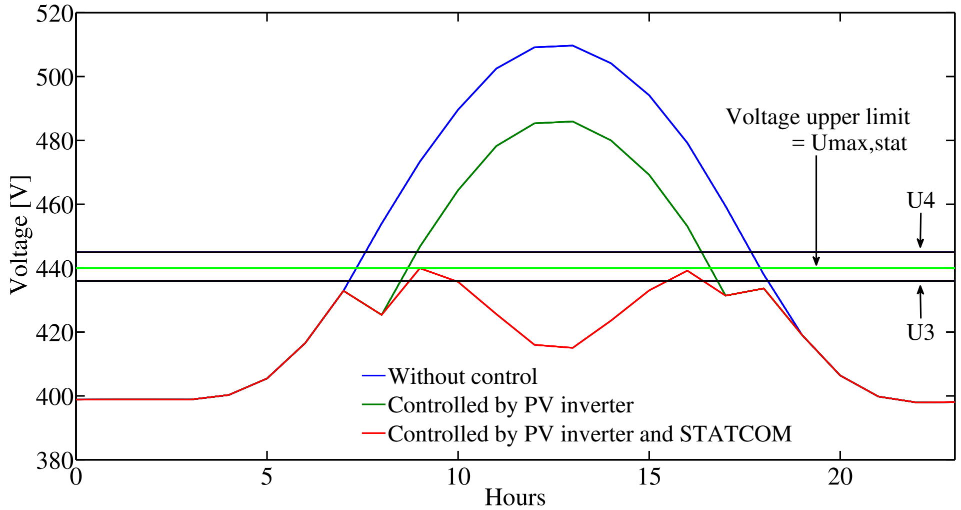


Figure 4.6: Voltage in the grid bus 48 after applying the voltage control by the PV inverter and STATCOM.

The STATCOM connected to bus 48 is now supporting the bus 48 by absorbing the reactive power to bring the voltage down or equal to the specified upper limit according to the control logic described in Figure 3.5. The voltage and amount of reactive power absorption by STATCOM at bus 48 are shown in Figure 4.6 and Figure 4.7 respectively.

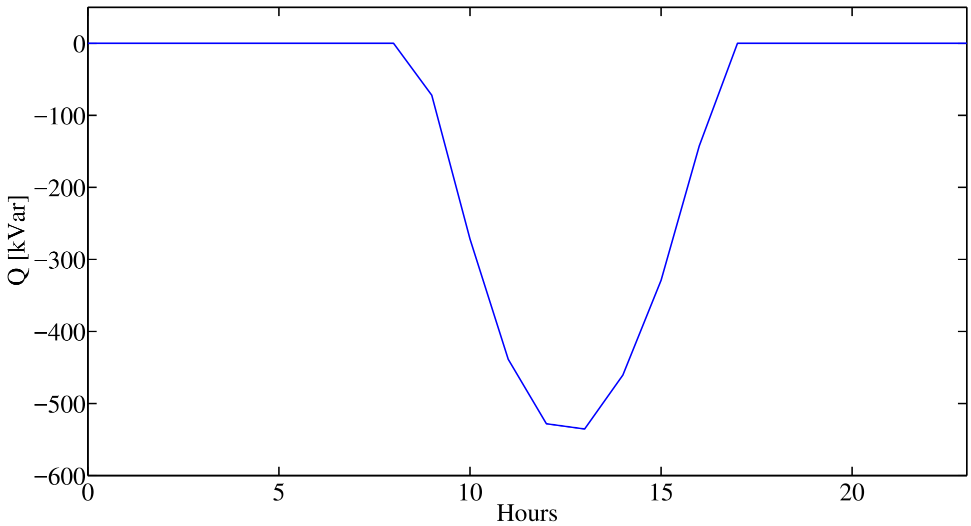


Figure 4.7: Reactive power absorption by the STATCOM.

Finally, Figure 4.8 is depicting the voltages for all of the buses after being controlled by the proposed control method and Figure 4.9 is showing the total amount of reactive power absorption by the PV inverter and STATCOM.

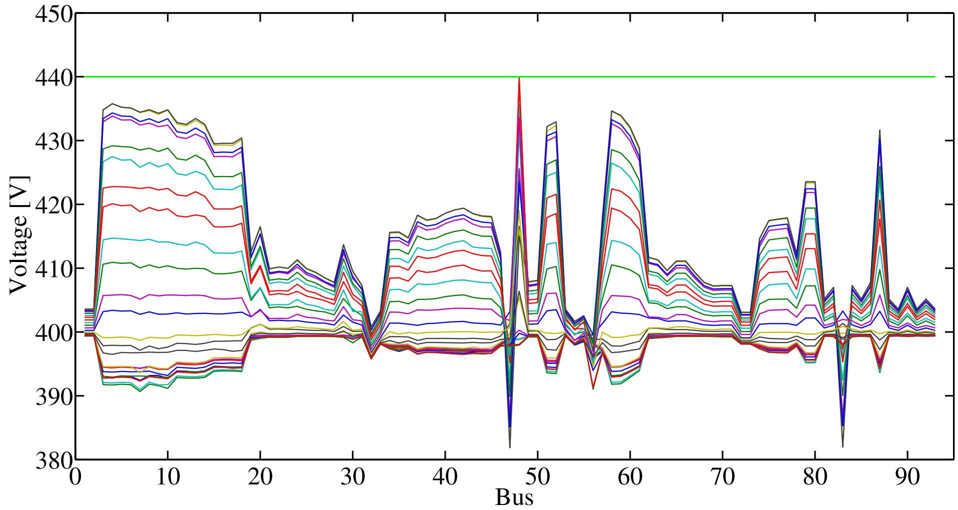


Figure 4.8: Voltage in the grid buses after applying the voltage control by the PV inverter and STATCOM. Each line represents the hourly buses voltage.

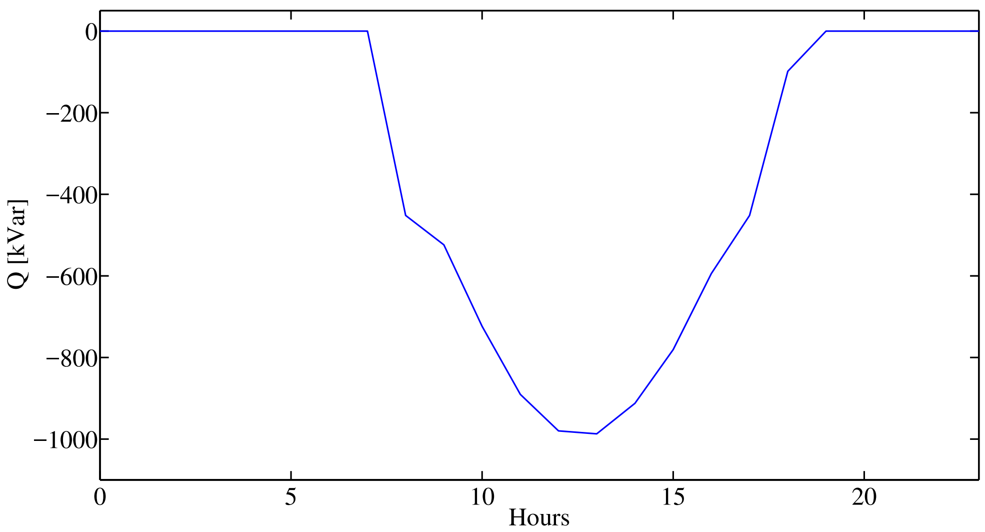


Figure 4.9: Total reactive power absorption by the PV inverter and STATCOM.

Therefore, the coordination has happened effectively in control hierarchy between the PV inverter and STATCOM to provide the reactive power support for the critical bus within a LV network for over voltage suppression in a summer day.

Simulation for a winter day - under voltage situation:

The influence of low solar PV power production and high power consumption are considered during a winter day when the LV grid buses suffer from the under voltage situation. Figure 4.10 depicts all the buses voltage for 24 hours in one winter day. All the buses except some of the buses are within the specified voltage limit of 360 V, indicated by the green line in Figure 4.10. The total number of buses with respect to the voltage limit violation are 11. These buses are found to be the weak buses out of total 93 buses in the studied LV grid.

The bus number $3-10$, 12 and 58, 59 are the weak buses respectively. The Figure 4.11 shows only the voltages for those weak buses where the control action is required. The voltage has crossed the lower voltage limit 360 V due to low amount of PV power production and high load demand in a winter day. So, the voltage of those buses need to be controlled in this situation. To do that, the first control action according to control flow diagram described in Figure 3.5 will come from the corresponding PV inverter of those buses by injecting the reactive power into the

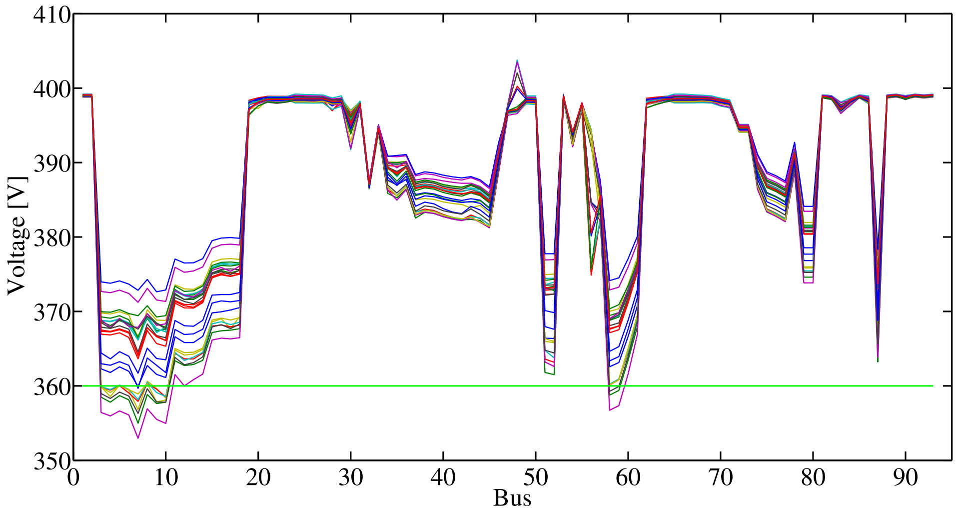


Figure 4.10: Voltage at all the grid buses before applying the control. Each line represents the hourly buses voltage.

grid. It is important to note that the buses 58 and 59 have no PV system. The total number of hours that the each weak bus stays below the specified limit are given below.

- The bus 3 stays for 7 hours
- The bus 4 stays for 7 hours
- The bus 5 stays for 3 hours
- The bus 6 stays for 7 hours
- The bus 7 stays for 9 hours
- The bus 8 stays for 3 hours
- The bus 9 stays for 7 hours
- The bus 10 stays for 7 hours
- The bus 12 stays for 1 hour
- The bus 58 stays for 3 hours
- The bus 59 stays for 3 hours

Table 4.3: Winter settings for PV inverter control for LV network.

$Q(U)$ **method**
$[U_1\ \ U_2\ \ U_3\ \ U_4] = [355\ \ 364\ \ 436\ \ 445]$ V
Q_{max} production at power factor $= 0.85$

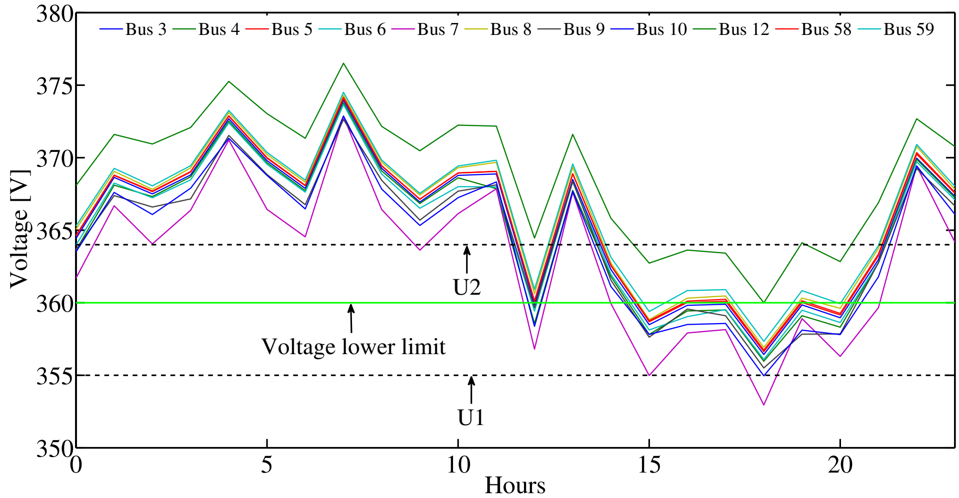


Figure 4.11: Voltage at all the weak grid buses before applying the voltage control. Each line represents the each bus voltage.

Figure 4.12 shows the voltages at the weak grid buses $3 - 10$, 12 and 58, 59 and the voltages are increased for those hours where the bus voltage's crossed the lower voltage limit. The PV inverter connected to these buses are injecting the reactive power into the grid to raise the voltage above the lower voltage limit. The amount of reactive power injection is shown in Figure 4.13. The voltages for all of the buses after reactive power support by the PV inverter are shown in Figure 4.14.

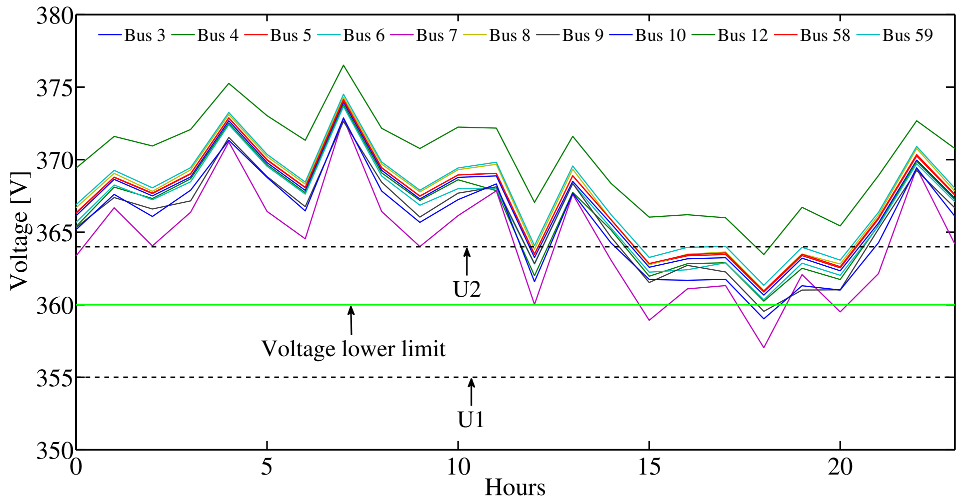


Figure 4.12: Voltage at all the weak grid buses after applying the voltage control by the PV inverter. Each line represents the each bus voltage.

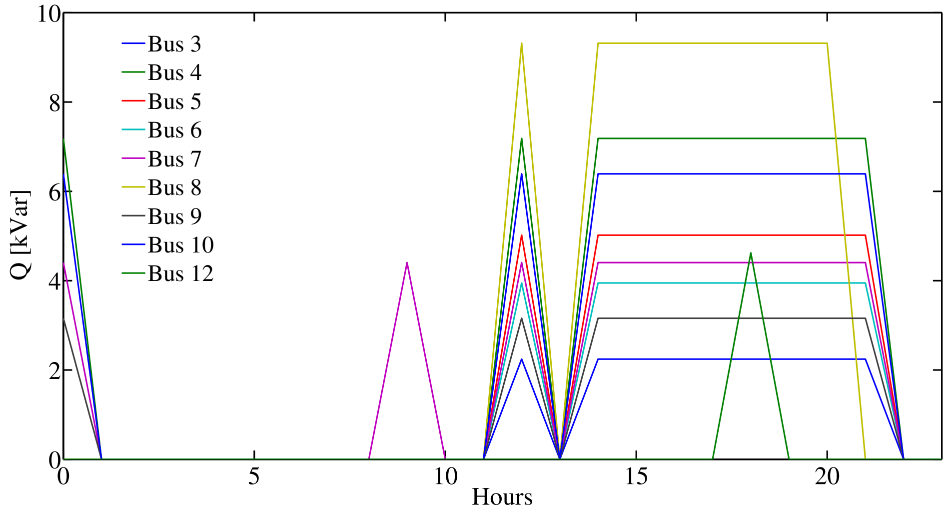


Figure 4.13: Reactive power injection by the PV inverter.

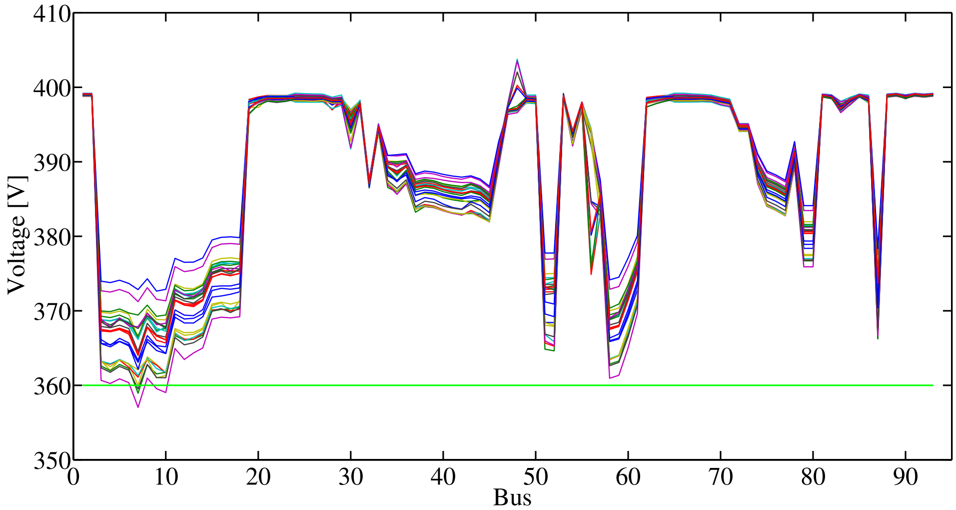


Figure 4.14: Voltage at all the grid buses after applying the voltage control by PV inverters. Each line represents the hourly buses voltage.

However, the voltage at the weak grid buses are still exceeding the voltage limit of 360 V. The PV inverters provide the maximum Q support by producing reactive power that is available at those hours without curtailing any power; even inverters continue supporting independently when the active/real power generation is zero at night. The reactive power support at night or during zero real power generation will be discussed later in this chapter. However, this is not yet sufficient enough to bring the voltage up to or above the lower limit for all of the weak buses.

Hence, according to control flow diagram described in Figure 3.5, the next or second layer of control action will come from the STATCOM. However, the optimal placement of the STATCOM is one of the important factors where it benefits the system most in order to keep the voltage stable. It can be observed from Figure 4.14 that the grid buses 7, 9 and 10 require more reactive power support becuase these three buses have been found to be the weakest buses among the 11 weak buses.

Table 4.4: Winter settings for three STATCOMs' control for LV network.

STATCOM
$[U_{stat}^{max} \;\; U_{stat}^{min}] = [440 \;\; 360]$ V
Susceptance, $b_{sh} = 29.9901$ s

Therefore, these three places would be the best place for STATCOM for effective compensation and voltage regulation. So, three STATCOMs are placed at the LV grid buses 7, 9 and 10. The susceptance value in Table 4.4 for the STATCOM has been decided empirically. The three STATCOMs have the identical settings of their parameters.

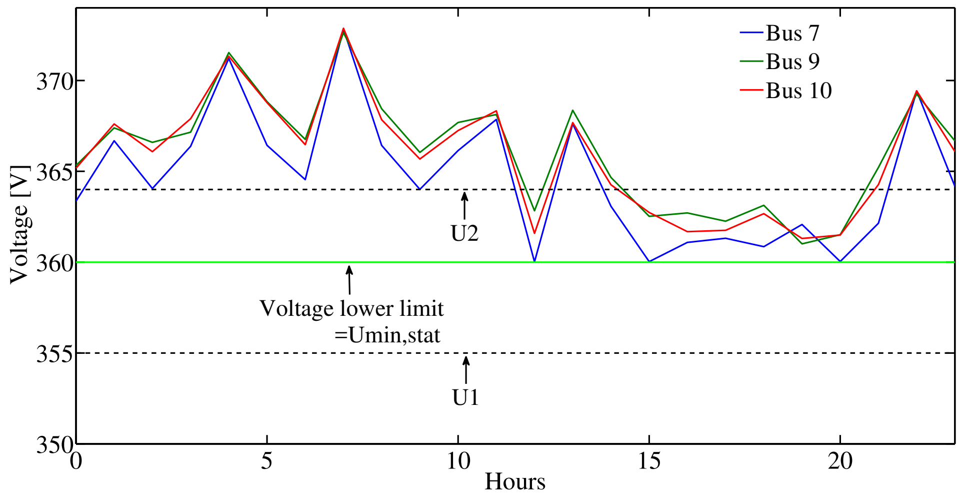


Figure 4.15: Voltage at the weak grid buses 7, 9 and 10 after applying the voltage control by the PV inverter and STATCOM. Each line represents the each bus voltage.

Now, the STATCOM connected to buses 7, 9 and 10 are now supporting the bus 7, 9 and 10 by injecting the reactive power to bring the voltage up to or equal to the specified voltage lower limit according to the control logic described in Figure 3.5.

The voltage and amount of reactive power injection by STATCOM at buses 7, 9 and 10 are shown in Figure 4.15 and Figure 4.16 respectively.

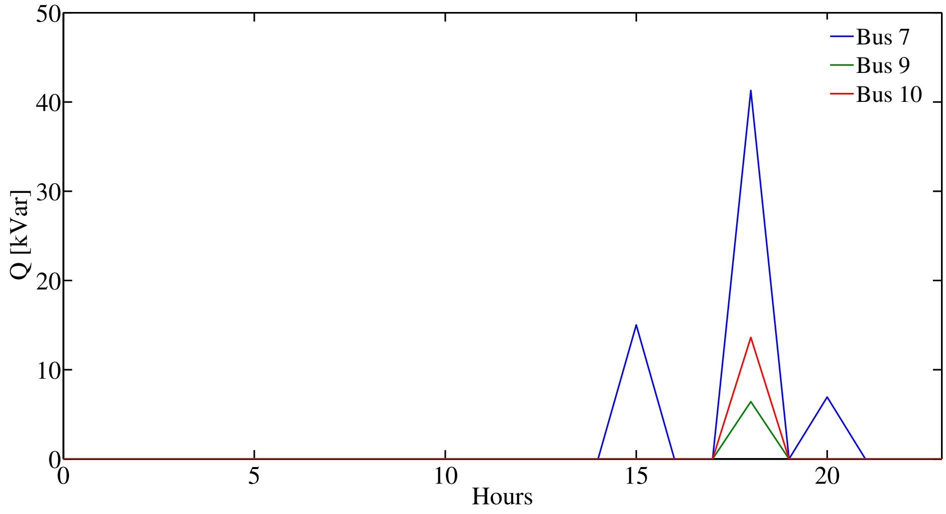


Figure 4.16: Reactive power generation by the STATCOM.

Finally, Figure 4.17 is depicting the voltages for all of the buses after being controlled by the proposed control method and Figure 4.18 is showing the total amount of reactive power injection by the PV inverter and STATCOM.

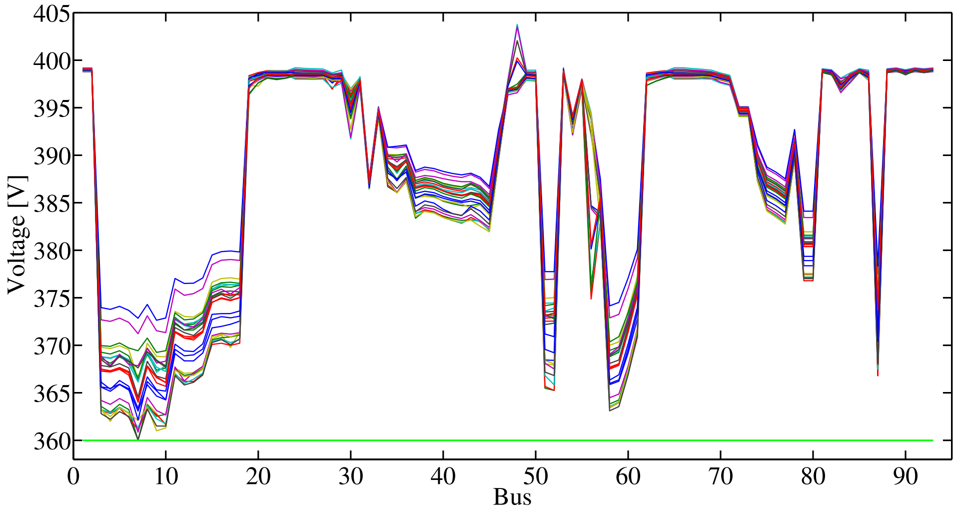


Figure 4.17: Voltage at all the grid buses after applying the voltage control by the PV inverter and STATCOM. Each line represents the hourly buses voltage.

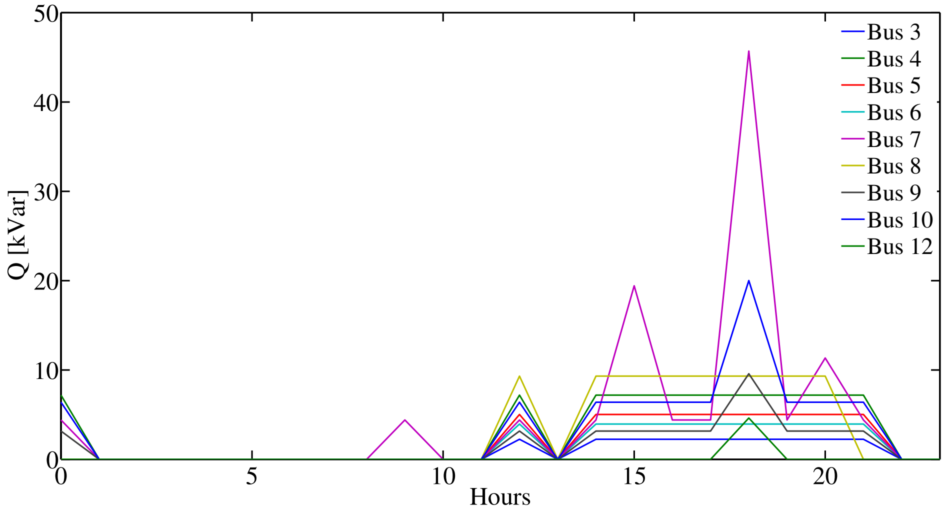


Figure 4.18: Total reactive power injection by the PV inverter and STATCOM.

Therefore, the coordination has happened effectively in control hierarchy between the PV inverter and STATCOM to provide the reactive power support for the critical bus within a LV network for voltage regulation in a winter day.

4.1.2 Results for scenario II

Due to high or low PV power generation in the LV network, the MV network is also affected in terms of voltage instability. Additionally, the MV network is affected by the reactive power generation or absorption in the LV network, and it just happened in scenario I to control the LV side's voltage. Now, in terms of impact from these situations, the MV node's voltage needs to be examined to check whether the voltage is within the specified limit according to EN 50160 or not. Depending upon the voltage at MV node the control action will take place hierarchically which is clearly shown in Figure 3.6. If the voltage at the MV node violates the specified upper or lower voltage limit then the MV controller will activate the STATCOM along with the LV network control system to bring the MV node voltage within allowed limit.

The simulation here will focus only on the MV network control part and LV network control has already shown in the previous section. The control area is shown in Figure 4.19. Here, this part will apply the proposed control algorithm according to Figure 3.6, and the control here is the control of MV node voltage.

This observation is also both for the summer and winter days.

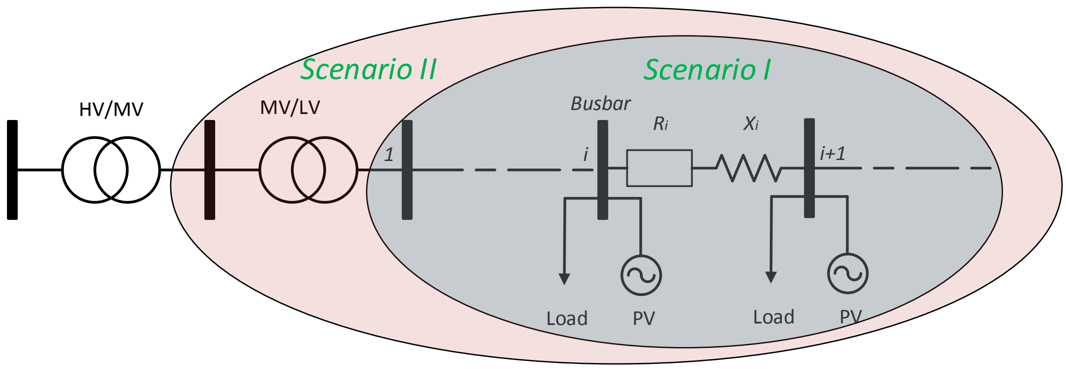


Figure 4.19: Two control scenarios.

Simulation for a summer day - over voltage situation:

The simulation for a over voltage situation has already been observed and discussed above, and the LV network was controlled by the PV inverter and STATCOM by means of reactive power absorption. The following Figure 4.20 is showing the voltage at the MV node when no control action was applied at the LV network. The nominal voltage for the MV node is 10 KV and the voltage magnitude variations limit according to the EN 50160 is ±10%.

The over voltage limit is for MV node would be 11 KV. It is also observed from Figure 4.20 that the MV node voltage is already within a upper voltage limit over the period even when there was no LV network control in action. So, the control action for MV network's voltage control is not necessary by means of STATCOM according to Figure 3.6 as the MV node voltage is within a upper voltage limit over the period.

However, the voltage at the MV node in Figure 4.20 is slightly affected during the period when the LV network control came into control action to support the voltage of LV network buses. It happened because of the reactive power absorption in the LV network by the PV inverter and STATCOM. Moreover, it is also observed from Figure 4.20 that the voltage at the MV node got impact positively, and the direction of the voltage change towards to the nominal voltage 10 KV.

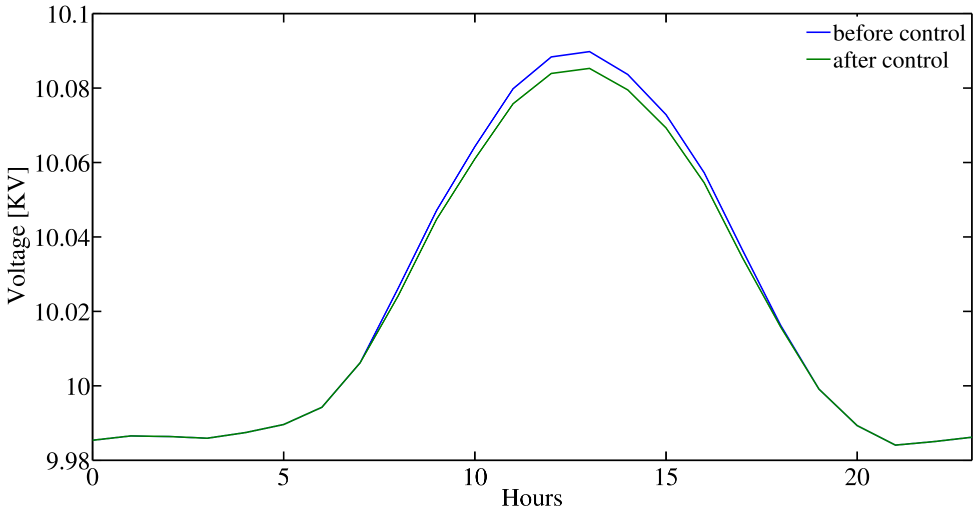


Figure 4.20: Voltage at the MV node before and after the LV network control action.

Simulation for a winter day - under voltage situation:

The simulation for a under voltage situation has already been observed and discussed above, and the LV network was controlled by the PV inverter and STATCOM by means of reactive power injection. The following Figure 4.21 is showing the voltage at the MV node when no control action was applied at the LV network.

The lower voltage limit is for MV node is 9 KV according to grid codes. So, from Figure 4.21, it is observed that the MV node voltage is already within a lower voltage limit over the period even when there was no LV network control in action. So, the control action for MV network's voltage control is not necessary by means of STATCOM according to Figure 3.6 as the MV node voltage is within a lower voltage limit over the period.

However, the voltage at the MV node in Figure 4.21 is slightly affected during the period when the LV network control came into control action to support the voltage of LV network. It happened because of the reactive power injection in the LV network by the PV inverters and STATCOMs. Moreover, it is observed from Figure 4.21 that the voltage at the MV node got impact positively, and the direction of the voltage change towards to the nominal voltage 10 KV.

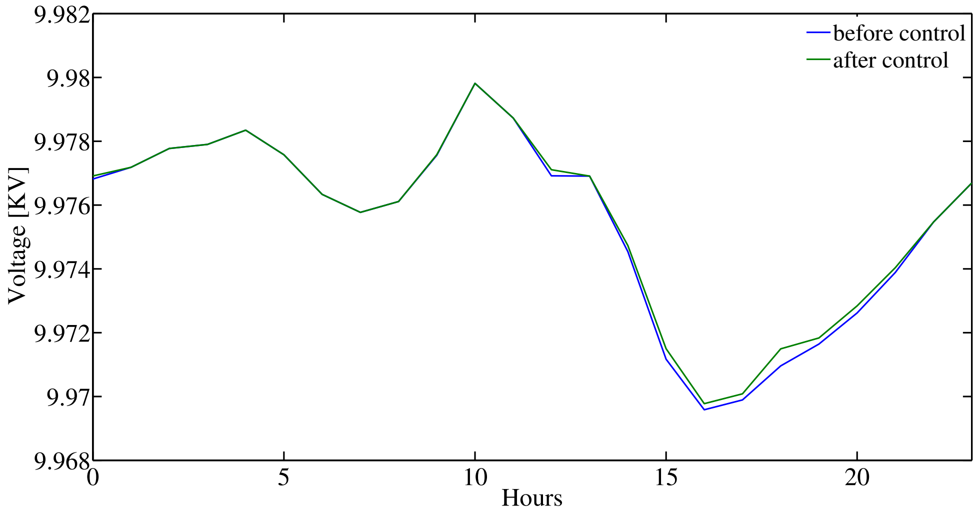


Figure 4.21: Voltage at the MV node after the LV network control action.

Nevertheless, if it is required to control the voltage at the MV node, then the control action will be taking place for controlling the MV node voltage according to Figure 3.6. In the following paragraph, an additional simulation work is presented for the MV network's node voltage control and it considers only the over voltage situation.

Simulation for 252 MV nodes of the MV network - over voltage situation:

This section has considered all the 252 nodes of MV network and it will present the results of control action from the MV network control according to Figure 3.6 for an over voltage situation during one summer day. The parameter settings for STATCOM is provided in Table 4.5 and decided empirically.

Firstly, one node of the MV network from the Herrljunga municipality distribution network has been presented. Figure 4.22 shows that due to high PV power production the voltage at the MV node has crossed the specified voltage limit of 11 KV indicated by the red line. Then this over voltage situation is completely suppressed by the STATCOM control action where the STATCOM absorbed the reactive power from the grid. The amount of reactive power consumption is shown in Figure 4.23. It can be observed that the switching of the STATCOM for reactive power consumption happened only for an hour and actively supporting the MV node when the MV node is suffering from the over voltage situation.

Table 4.5: Parameter settings used for STATCOM control during summer for MV network.

STATCOM	
$[U_{stat}^{max} \;\; U_{stat}^{min}]$	[11 9] KV
Susceptance, b_{sh}	23.9901 s

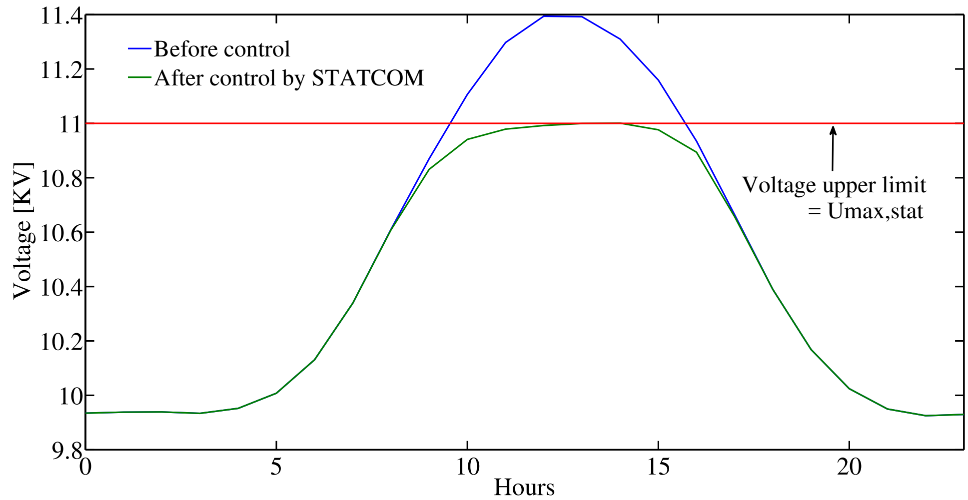


Figure 4.22: Voltage at one MV node before and after applying the MV network control.

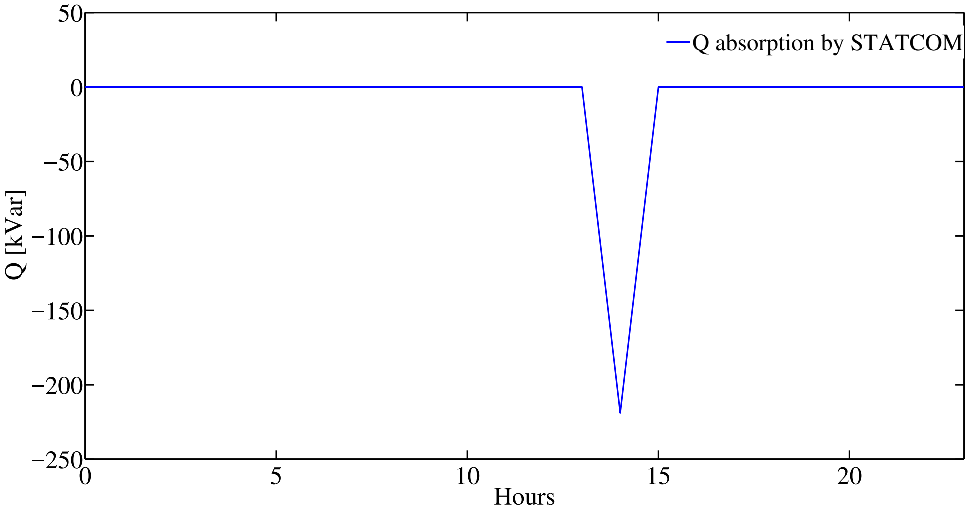


Figure 4.23: Q absorption by the STATCOM at one MV node.

Secondly, the voltage at all the 252 nodes of MV network is shown in Figure 4.24 and it shows the voltage for an hour for all the MV nodes before and after applying the MV network control. The Figure 4.25 shows the corresponding Q absorption by the STATCOMs.

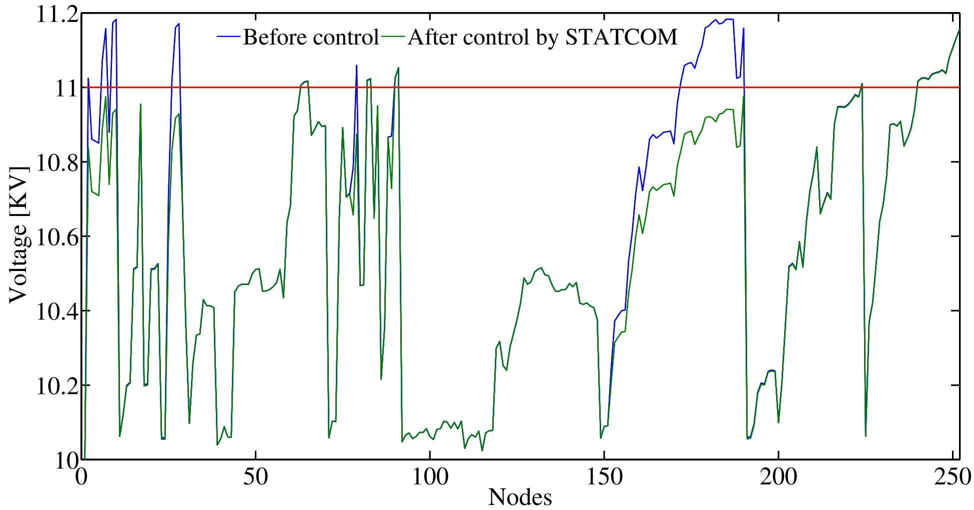


Figure 4.24: Voltage at all MV nodes before and after applying the MV network control.

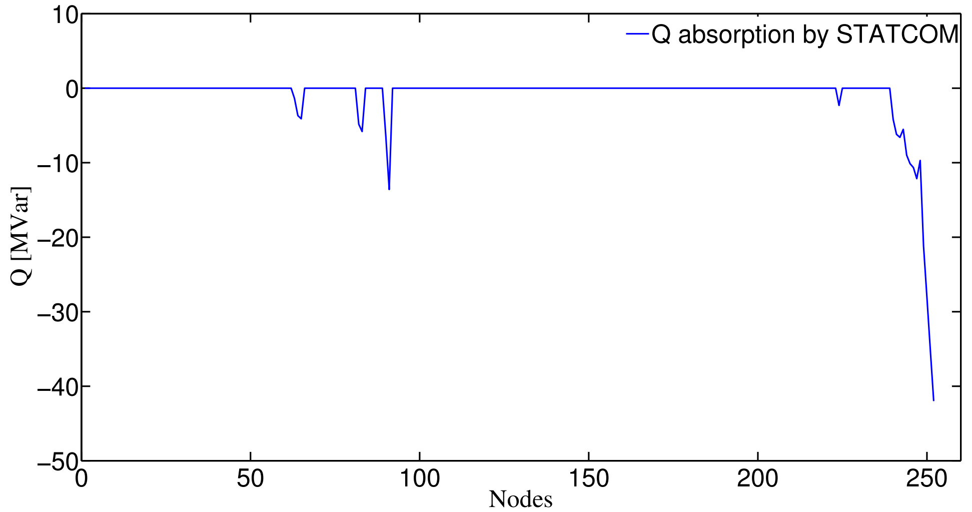


Figure 4.25: Q absorption at all MV nodes by the STATCOM.

The results also show that most of the the MV nodes are under specified voltage limit by the control action of STATCOMs. For some nodes STATCOM control action is not sufficient enough to suppress this situation, especially when the PV power production is very high. The nodes 63 − 65 , 82, 83, 90, 91, 224, and 240 − 252 are not under specified voltage limit. In this case the control algorithm needs to be modified with one the following two actions. One of these two actions might work to resolve this problem: 1) by increasing the capacity of STATCOM at these nodes, 2) changing the primary side voltage of the HV/MV transformer at first layer of control for those MV nodes. This modification in control algorithm could be the part of the future work.

However, it is observed from the results that the proposed algorithm for MV network control has shown satisfactory performance in terms of voltage regulation for most of the nodes of MV network among all the 252 nodes. The rest of the nodes would also be controllable if one of the above mentioned methods could apply in the MV network control algorithm.

4.2 PV inverter - reactive power (Q) support at night

The reactive power support during night is one of the prominent features of today's smart PV inverter [16]. When the PV system does not generate any real power during night, the inverters remain idle which reduces the effective utilization of inverters. It is already known that the PV inverters can be used as VAR compensators for the voltage regulation. Therefore, reactive power support during night would increase the effective utilization of PV inverters which will reduce the need of other expensive way of compensation.

The Q support at night have been used in the under voltage situation. Figure 4.26 shows the PV power production maximum capacity, reactive power production maximum capacity, power generation from PV during a winter day, reactive power generation during the winter day, real power demand and reactive power demand for the LV grid bus 3.

It is observed that the load demand is high during night and the PV power generation is low and because of this the voltage at this bus is lower than the allowed lower voltage limit shown in Figure 4.27. Now, the way of voltage profile improve-

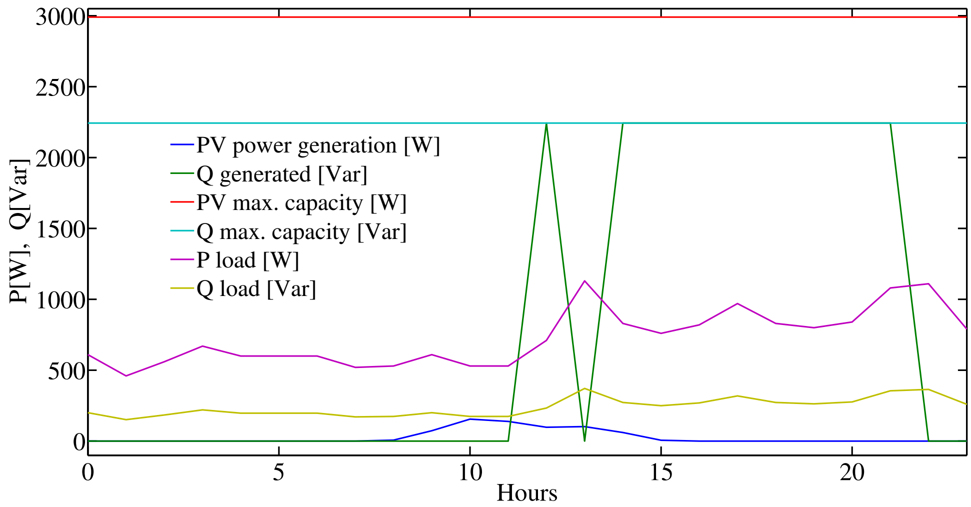


Figure 4.26: P and Q scenarios for the LV grid bus 3.

ment is through supplying Q power from the PV inverter and it can be observed from Figure 4.27 that the voltage profile has been improved by approximately 1.2%.

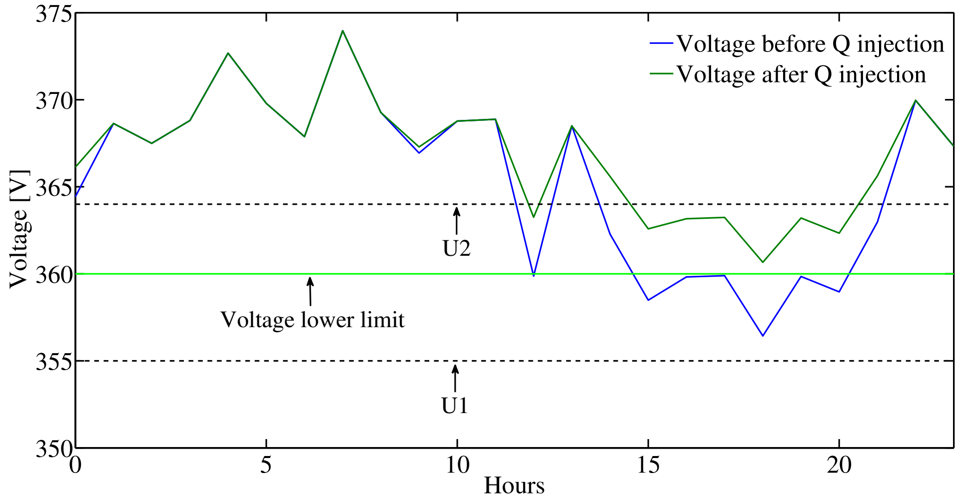


Figure 4.27: Voltage at the LV grid bus 3 before and after Q compensation by the PV inverter.

So, the bus voltage is completely under allowed voltage limit through the reactive power compensation technique, and by utilizing only the PV inverter's available Q capacity during night. Finally, the appendix section A.2 will collectively present the summary on seasonal parameter settings for both the PV inverter and STATCOM. Additionally, the appendix section A.3 will provide the details on the PV systems data that have been used throughout the simulation.

Chapter 5

Discussion

This chapter provides an overall discussion on methodology, input data, system effects due to high PV power production, compensation techniques to overcome the effects.

5.1 Methodology and input data

Voltage management by means of reactive power compensation with the accurate reactive power control model can be used to fulfill the grid codes in distribution grids with a large PV penetration. Therefore, in this thesis work, the reactive power control for voltage stability has been considered by proposing effective coordinated voltage control methods.

The used methods for coordinated voltage control have two layers of control actions. The first layer of control action used in this thesis is directly provided by the PV inverter with a $Q(U)$ voltage control method. Thereafter, the second layer of control action is provided by the STATCOM based on voltage droop characteristics. The control model for the PV inverter, STATCOM, coordinated reactive power control method and load flow model are implemented in a house built program in Matlab/Simulink that enables to design, modify and analyze the control model to fit the specific grid requirements.

The coordinated control method has been tested upon for two scenarios where seasonal variations of PV power and load demand are considered. The control response in terms of voltage stability for both winter and summer from the proposed coordinated voltage control method has shown the potential use of both the control algorithm and combination of PV inverter and STATCOM. However, the criteria to use this method requires accurate settings of PV inverter and STATCOM control parameters. It is one of the observations that one setting for one LV network and one MV node does not work for other networks or nodes, especially for those networks or nodes where PV power production is very high.

It is also observed that the networks suffering most in terms of voltage instability due to very high PV power production requires modification of proposed control algorithms. However, I had applied the developed LV network control algorithm for some other LV networks as well which are under different MV nodes to check the generality of the developed algorithm. It is observed from the simulation that for some LV networks the voltage profile collapsed especially for those LV networks where all the LV grid buses are extremely violating the voltage limit. On the other hand, the proposed algorithm worked for some other LV voltage networks where not every LV grid buses are violating the voltage limit or the violation is not extreme. So, I only presented the simulation results in this thesis for one LV network out of other LV networks that worked. It is obvious from the simulation results that the proposed algorithm is applicable for specific grid structure and situation.

Nevertheless, to generalize the developed algorithm for the other LV networks, it requires modification in the proposed algorithm. The modification in control flow algorithm demands that the first layer of control action should come from the MV distribution side by changing the primary voltage of MV/LV transformer (node voltage of MV) and thereafter, the second layer of control action would be provided by the LV network control as presented in Figure 3.5.

This is also true for controlling the voltage of 252 nodes of MV network. The first layer of control action should control the primary voltage of HV/MV transformer and then the second layer of control action will be activated by the MV network control as presented in Figure 3.6. However, other solutions might include power curtailment, peak shaving by the energy storage or distribution line reinforcement.

In the simulation the input data for the reactive power load demand has been produced from the available real active power demand of the Swedish municipality of Herrljunga by assuming that all the loads are operating at 0.95 power factor. It would probably be more realistic if the real reactive power load demand was found. However, it was not a big problem from technical point of view for control method designing. The data for each PV inverter maximum capacity was determined by taking the day of the maximum generation in a year.

5.2 System effects and compensation techniques

The fast growing penetration PV power into the distribution grid is a present and future scenario in the energy system. But the system effects from the variable nature of PV power production is the challenge in terms of voltage stability to the distribution grid operators, although it is not the case for Sweden yet. In this study the reactive power support by two compensation devices (PV inverters and STATCOM) has been considered to overcome this voltage instability issues.

The main advantage of using the PV inverter as a way of first control implies that the grid system can be benefited technically by importing/exporting instant reactive power locally from the cheap and already existing PV inverter than installing expensive way of other compensation devices. Moreover, the results show that even if the PV system does not produce any real power, the PV inverter still yields the reactive power during night for voltage regulation. Thereafter, the STATCOM has shown the benefit to remove the voltage instability from the weakest buses by providing reactive power.

Therefore, in combination with the PV inverter and STATCOM, and their coordinated control have presented the effective way of voltage regulation for both the over- and undervoltage situations.

Chapter 6

Conclusion and Future Work

This chapter highlights the main conclusions of the study presented in this thesis and summarizes the ideas for future research work.

6.1 Conclusion

This thesis has been an attempt to address the importance of reactive power compensation for large scale PV systems integration into power distribution grids. In this regard, the role and impact of having PV inverter and STATCOM for reactive power compensation are analyzed with the chosen grid codes. The voltage profile control in a distribution grid - via the reactive power contribution of PV inverter and STATCOM- is based on the indirect voltage control when the reactive power regulation is direct.

The overall conclusions of this thesis are (***i***) the proposed approach efficiently regulates the bus voltages of LV and MV networks to the steady-state voltage limit according to the grid codes for both the over- and undervoltage situations, (***ii***) the STATCOM, coupled with the existing PV inverter, has shown both the reliability for effective reactive power compensation as well as the potential of ensuring compliance with the grid codes in terms of voltage stability, (***iii***) results from the simulation indicated that the Q supply from PV inverter at night can efficiently be utilized for the grid voltage stability, and (***iv***) the proposed algorithm has shown satisfactory performance in terms of voltage regulation.

6.2 Future work

As future work, a number of points can be paid attention to, in order to further demonstrate the benefits of STATCOM and PV inverter devices in grid voltage management. The future work might include the following points:

- Different PV inverter control strategies such as $Q(P)$ and $Q(P, U)$ methods can be examined and compared with the used $Q(U)$ mehtod in this thesis.
- Voltage control algorithm might be extended to adapt the other grid networks as well.
- Including an energy storage in the algorithm to shape the peak power during high PV power generation.
- The economical analysis would be interesting for the feasibility analysis.

Chapter 7

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MD. Shakib Hasan

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Appendix A

System data

A.1 Grid code data

Table A.1: Allowed voltage limit in steady-state for both MV and LV network.

EN 50160 standard		
Nominal voltage	10 KV	400 V
Voltage upper limit	11 KV	440 V
Voltage lower limit	9 KV	360 V

A.2 Summary on parameter settings for compensators

Table A.2: Parameter settings used seasonally for PV inverters and STATCOMs for LV and MV network control.

Compensator	**Parameter**	**Season**	**LV**	**MV**
STATCOM	Susceptance, b_{sh}	Summer	23.9901 s	23.9901 s
		Winter	29.9901 s	-
	$[U_{stat}^{max} \ \ U_{stat}^{min}]$	Summer	[440 360] V	[11 9] KV
		Winter	[440 360] V	-
PV inverter	Power factor, $cos\varphi$ up to	Summer	0.85	-
		Winter	0.85	-
	$[U_1 \ \ U_2 \ \ U_3 \ \ U_4]$	Summer	[355 364 436 445] V	-
		Winter	[355 364 436 445] V	-

A.3 PV system data

Bus Number	P_{max} (W)	Q_{max} (Var)	Bus Number	P_{max} (W)	Q_{max} (Var)	Bus Number	P_{max} (W)	Q_{max} (Var)
1	0	0	**41**	8738,293	6553,719	81	0	0
2	0	0	**42**	6955,882	5216,912	82	0	0
3*	2990,727	2243,045	**43**	12672,85	9504,639	83	0	0
4*	9578,797	7184,098	**44**	6015,167	4511,375	84	0	0
5*	6691,194	5018,395	**45**	5036,784	3777,588	85	0	0
6*	5263,625	3947,718	**46**	4084,398	3063,299	86	0	0
7*	5872,86	4404,645	**47**	0	0	87	0	0
8*	12421,71	9316,285	**48***	451782,7	602376,9	88	0	0
9*	4210,452	3157,839	**49**	4943,407	3707,555	89	0	0
10*	8522,583	6391,937	**50**	3751,718	2813,789	90	0	0
11	10920,91	8190,684	**51**	5928,865	4446,649	91	0	0
12*	6163,453	4622,59	**52**	14322,79	10742,1	92	0	0
13	12137,74	9103,305	**53**	0	0	93	0	0
14	9955,438	7466,578	**54**	0	0			
15	13727,8	10295,85	**55**	0	0			
16	9757,248	7317,936	**56**	4953,351	3715,013			
17	4976,019	3732,014	**57**	0	0			
18	12958,84	9719,127	**58***	0	0			
19	6637,538	4978,154	**59***	0	0			
20	34356,46	25767,35	**60**	0	0			
21	18290,68	13718,01	**61**	0	0			
22	4480,077	3360,058	**62**	0	0			
23	15355,16	11516,37	**63**	0	0			
24	55659,98	41744,99	**64**	0	0			
25	19103,47	14327,6	**65**	0	0			
26	0	0	**66**	0	0			
27	9174,322	6880,741	**67**	0	0			
28	0	0	**68**	0	0			
29	62467,37	46850,53	**69**	0	0			
30	7085,456	5314,092	**70**	0	0			
31	0	0	**71**	0	0			
32	0	0	**72**	0	0			
33	7462,985	5597,239	**73**	0	0			
34	5859,827	4394,87	**74**	0	0			
35	5301,891	3976,418	**75**	0	0			
36	6073,256	4554,942	**76**	0	0			
37	10679,66	8009,746	**77**	0	0			
38	4824,822	3618,616	**78**	0	0			
39	5286,696	3965,022	**79**	0	0			
40	7341,678	5506,259	**80**	0	0			

The buses containing P_{max} and Q_{max} values are the PV connected buses.

P_{max} = PV nominal power capacity

Q_{max} = PV maximum reactive power generation capacity

'*' = The weak and critical buses

Figure A.1: PV systems' P and Q capacity information.