STUDY OF PV SOLAR FARM AS STATCOM FOR VOLTAGE REGULATION

DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
POWER SYSTEMS

Submitted by:

Vishal Varma
(2K14/PSY/20)

Under the supervision of

Dr. S. T. Nagarajan

DEPARTMENT OF ELECTRICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

2016

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CERTIFICATE

I, Vishal Varma, Roll No. 2K14/PSY/20 student of M. Tech. (Power System), hereby declare that the dissertation titled "**STUDY OF PV SOLAR FARM AS STATCOM FOR VOLTAGE REGULATION**" under the supervision of Dr. S. T. Nagarajan, Assistant Professor, Department of Electrical Engineering, Delhi Technological University in partial fulfillment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

Place: Delhi **VISHAL VARMA**

Date: 20.07.2016

Dr. S. T. NAGARAJAN

SUPERVISOR

Assistant Professor

Electrical Engineering Department

Delhi Technological University

Bawana Road, Delhi-110042

ABSTRACT

The integration of distributed generators (DGs) such as PV solar farms and wind farms in distribution networks is getting severely constrained due to problems of steady state voltage Rise, Voltage Flicker and Harmonic Injection etc. To mitigate these problems FACTS devices are used. One of these types of FACTS device is STATCOM which provides dynamic compensation of reactive power to improve transient performance.

A solar farm contains inverter as an essential part of it to convert DC power generated from PV modules into AC power. This thesis presents a strategy of PV solar farm control as a dynamic reactive power compensator (STATCOM) when large wind farm is connected to the grid and also load changes significantly. Using this control the voltage at PCC is regulated. The studies also conducted for the effect of this PV STATCOM when integrated at different location. The performance of this control strategy also studied when a 3LG fault occurred on load bus. Commercial grade software DIgSILENT PowerFactory is used to evaluate the steady state voltage profile and transient study.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to Dr. S T Nagarajan for his guidance and assistance in the thesis. The technical discussions with him were always been very insightful, and I will always be indebted to him for all the knowledge he shared with me. His prompt responses and availability despite his constantly busy schedule were truly appreciated. He always helped me in all the technical and non-technical issues during the production of this thesis. Without his consistent support, encouragement and valuable inputs, this project would not have become possible.

I would like to express my deep gratitude to Prof. Madhusudan Singh, Head, Department of Electrical Engineering for providing his support during my project.

I would also like to thank my batch-mates and friends who encouraged and helped me in completing the thesis work.

Finally, I express my deep sincere thanks to my Parents my brother and sister who motivated and encouraged me for higher studies, without which it wouldn't have been possible.

VISHAL VARMA

(2K14/PSY/20)

M.Tech. (Power System)

Delhi Technological University, Delhi

CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

DG	Distributed Generator
PV	Photo Voltaic
3LG	Three Phase Line To Ground
PCC	Point Of Common Coupling
STATCOM	Static Synchronous Compensator
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
PLL	Phase Locked Loop
PI	Proportional-Integral
MVA	Mega Volt Ampere
MVAR	Mega Volt Ampere Reactive
VSC	Voltage Source Converter
MW	Mega Watt
FACTS	Flexible AC Transmission System
TOV	Temporary Over Voltage
DC	Direct Current
AC	Alternating Current

CHAPTER 1

INTRODUCTION

1.1 RISE OF PV SOLAR POWER AND WIND POWER BASED DISTRIBUTED GENERATORS

Solar farms and wind farms are the most preferred distributed generators (DGs) that are being connected in world's most power distribution networks. As of the end of 2015, worldwide, total cumulative installed capacity of wind power reached to whooping 432,883 MW and increased by massive 17% compared to the previous year (369,553 MW). In 2015, China alone installed roughly half of the world's appended wind power installed capacity. Worlds wind power installations have raised by 63,330 MW, 51,447 MW and 35,467 MW in 2015, 2014 and 2013 respectively [1]. The total installed capacity of the world's Top 5 wind power producing countries is shown in Figure 1.1 while; the growth of wind power in India is given in Figure 1.2.

The governments of several countries provide various encouragement schemes. Due to this, small and medium scale wind and PV solar power farm installations are being increasingly installed worldwide. In India, Ministry Of New And Renewable Energy provides such schemes. The worldwide installations of PV solar power capacity are shown in Figure 1.3 while the same for India is charted in Figure 1.4 [2].

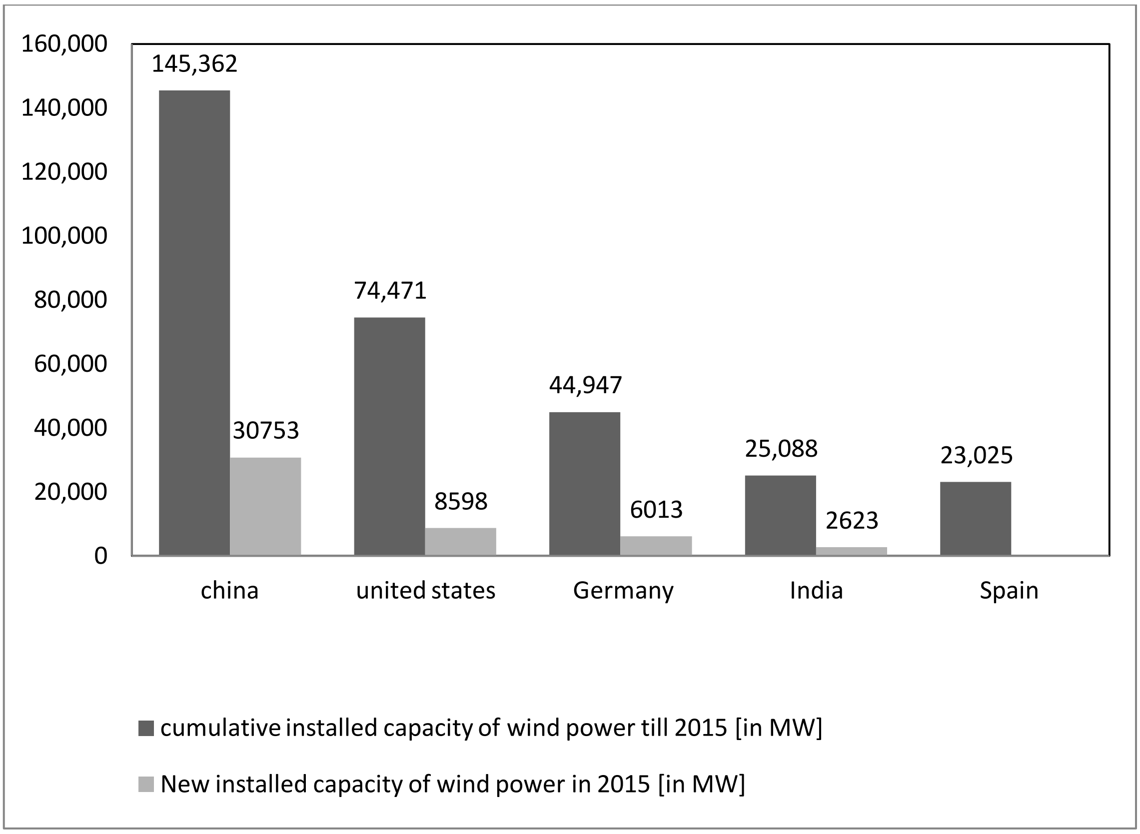

Figure 1.1 Total installed capacity of the world's major wind power producing countries (Source- GWEC, http://www.gwec.net)

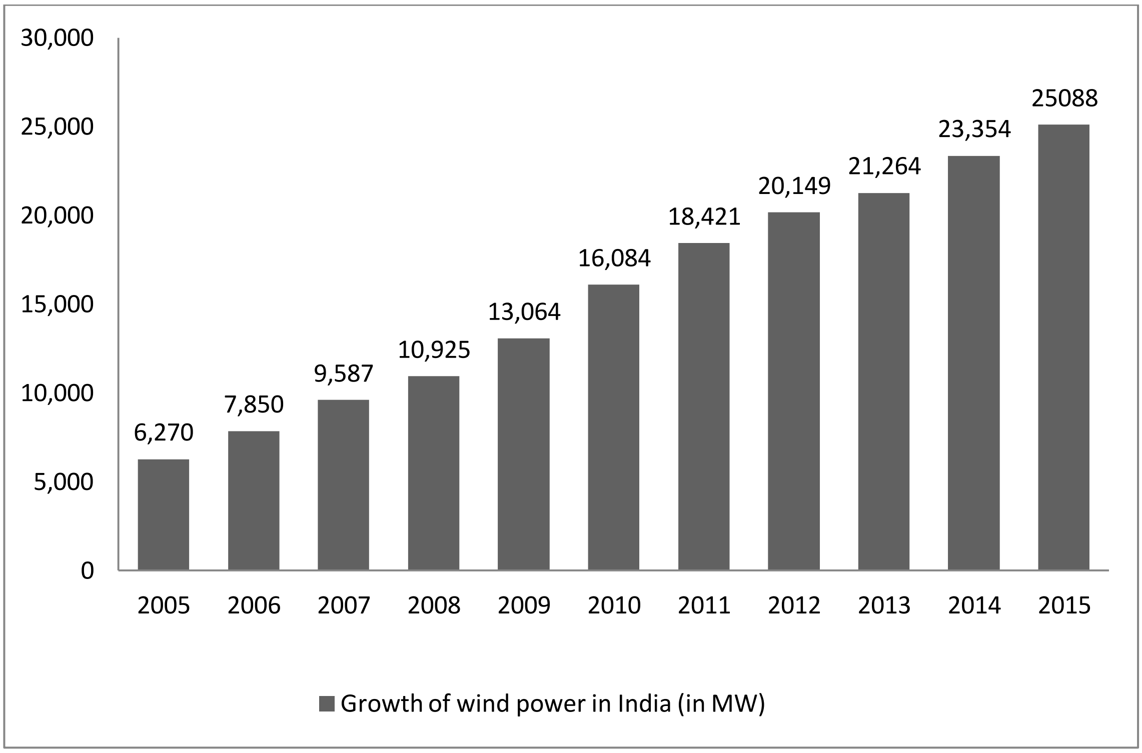

Figure 1.2 Growth of wind power in India (Source- GWEC, http://www.gwec.net)

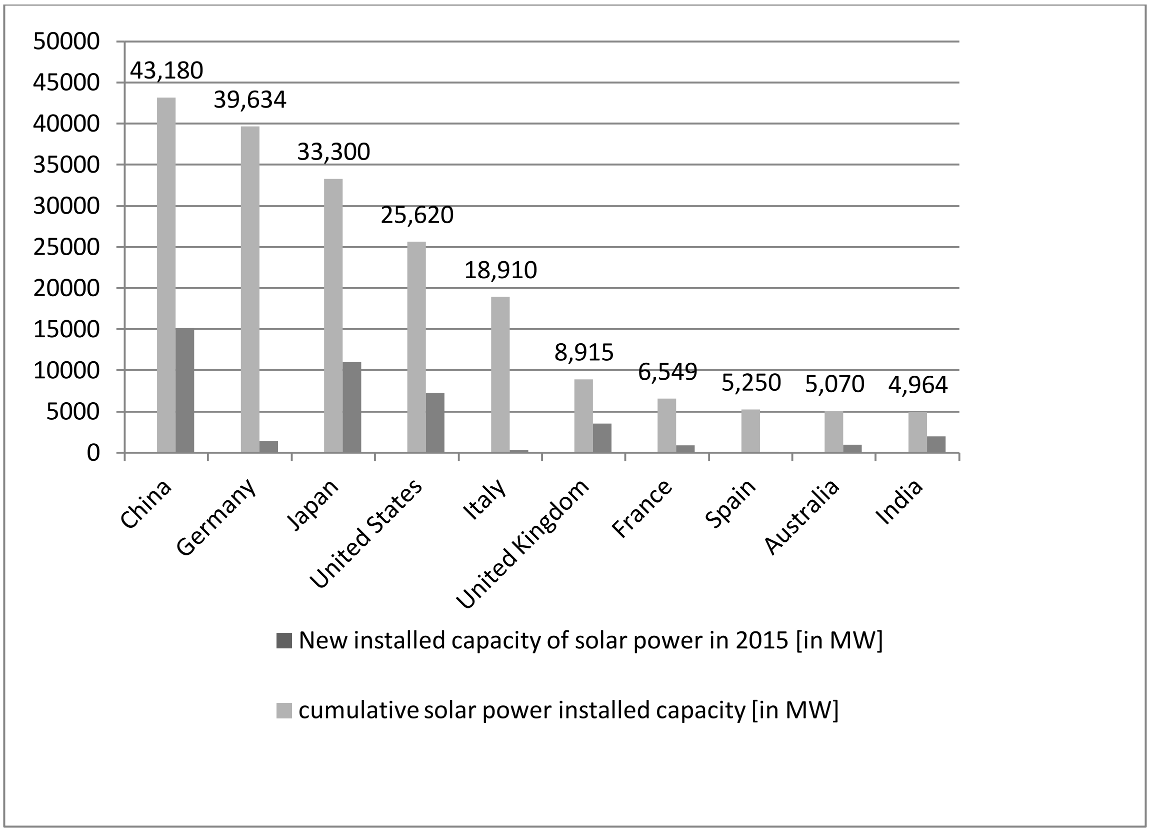

Figure 1.3 Total installed capacity of the world's major solar power producing countries (Source- IRENA, http://www.irena.org)

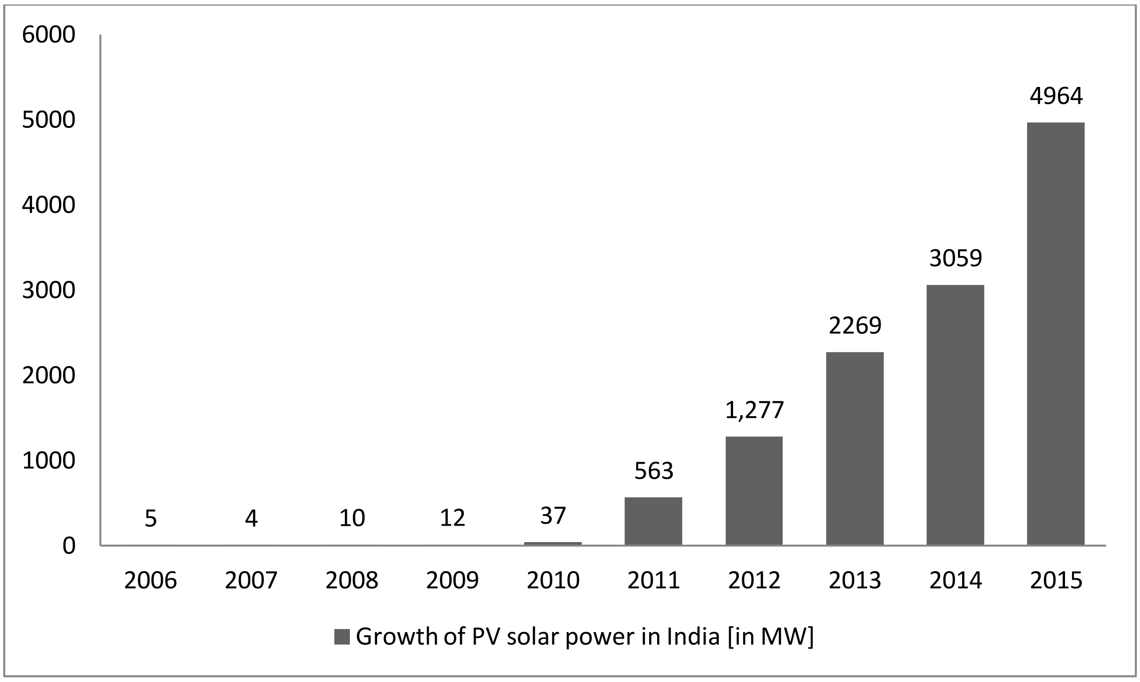

Figure 1.4 Growth of PV solar power in India (Source- IRENA, http://www.irena.org)

1.2 PROBLEMS DUE TO GRID INTEGRATION OF DGs

Traditionally, power grids are fed from big centralized generating stations mainly based on hydro, thermal and nuclear generation technologies. The integrated power grids are characterized by large generation, bulk transmission and end use by distribution network. However, the distributed nature of renewable energy resources like solar energy and wind energy have transformed this traditional integrated network with presence of a large number of small scale distributed generators (DGs) [3]. These distributed generators are generally connected to the medium voltage (MV) and low voltage (LV) distribution networks.

The interconnection of DGs in distribution network gives additional benefits in the network. With the development of solar farm and wind farm in medium voltage distribution network, the increase in the demand can be locally supplied reducing the cost of transmission network expansion. It also helps to decrease the transmission congestion in existing network. The transmission and distribution losses are reduced hence increasing the system efficiency. However, these advantages come along with new challenges to the system operator. The major problem encountered by the medium voltage distribution with the integration of distributed generation include steady state voltage rise, increased temporary overvoltage (TOV), increase in voltage flicker and harmonic components, and restrictions on operation of existing grid protection system [3] – [5] .

1.2.1 Steady State Voltage Rise

Connecting the DGs towards the receiving end of radial distribution system may initiate reverse power flow during the light load condition (off-peak load during nighttime). In this situation, the distribution line, traditionally operated to carry particular amount of power from the source end towards the load end, is likely to have increased voltage at the receiving end due to reverse power flow [4]. A typical scenario of reverse power flow can be occur when DG output is greater than the load for the distribution network, shown in Figure 1.5

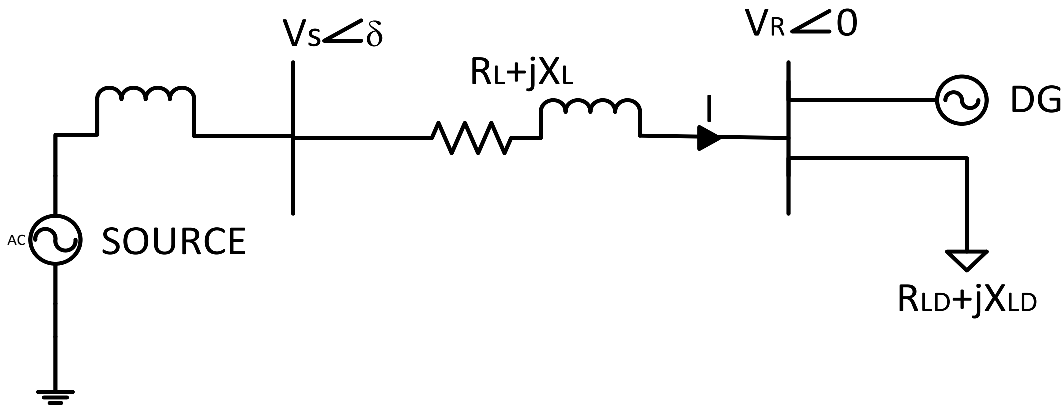

Figure 1.5 Radial distribution system with DG

For this network, the receiving end voltage is given by:

$$V_R = V_S - I.(R_L + jX_L) \qquad (1.1)$$

Where, $I = (P_{LD} - jQ_{LD})/V_R$

V_R= receiving end voltage

V_S=sending end voltage

R_L=line resistance

X_L=line reactance

P_{LD}=load active power

Q_{LD}=load reactive power

$$V_R = V_S - [\frac{P_{LD} - jQ_{LD}}{V_R}].(R_L + jX_L) \qquad (1.2)$$

The approximate expression for receiving end voltage will be

$$V_R \cong V_S - (P_{LD}.R_L + Q_{LD}.X_L)/V_R \qquad (1.3)$$

For the DG in the receiving end with active power injection of P_{DG} at unity power factor, the receiving end voltage is given by:

$$V_R \cong V_S - [(P_{LD} - P_{DG}).R_L + Q_{LD}.X_L]/V_R \qquad (1.4)$$

From this expression we can say that the receiving end voltage will increase depending on the reverse power flow created by the difference between load and distributed generation at receiving end and the line resistance. For a distribution system with low *X/R* ratio (i.e. high line resistance *R*), the rise in voltage can be in substantial amount.

1.2.2 Voltage Flicker

In the distribution grids, the most frequent cause of a voltage flicker is continuous and rapid variation of the load current. An example of a cause of continuous load current changes is the tower effect of a fixed speed wind turbine. This effect occurs in three blade wind turbine due to the wind shielding effect of each blade when it passes the tower. When the blade passes the tower, the electrical power provided by the wind turbine decreases, which has an effect on the grid voltage [6]. The tower effect produces a power oscillation having a frequency of three times the turbine revolving speed and hence voltages flicker with the same frequency. Conversely, some DG schemes contribute significant amount to the fault level which decreases the network impedance. As a result, the changing load current caused by a changing load or tower effect will lead to a smaller voltage variation and hence improved power quality [7].

1.2.3 Harmonics and Resonances

Inverter connected DG units might inject harmonics in the grid. The magnitude and the order of the harmonic currents depend on the technology of the converter used and its mode of operation [8]. The injection of harmonic currents can distort the voltage waveform of inverter which can propagate throughout the distribution grid. Also the small voltage distortions can cause large harmonic currents at series resonance conditions of the cable capacitance and the supply inductance (transformer leakage and cable inductance) and have to be prevented. Especially for inverter interfaced DG, like PV systems, parallel resonance of the parallel network capacitance (output capacitance of the inverter and the cable capacitance) and the supply inductance can produce high-voltage distortion at the connection point [9]. These types of resonances are also found in [9] where practical measurements were performed on low-voltage networks having a large number of PV systems. The measurements especially shows that parallel resonances occur which can trip the inverters due to a distorted supply voltage. A way to reduce the harmonic current injection is filtering process of the output current. Modern power electronic converters are able to filter out the injected current hence decreases the injected harmonics in the grid.

1.2.4 Temporary Overvoltage

In medium voltage networks, unbalanced faults, such as single line to ground fault (SLGF) in the network make temporary overvoltages (TOV) on the healthy phases of the network feeder [10], [11]. Overvoltages between one phase and ground or between two phases are classified based on the shape of the voltage, percentage increase from nominal value and time duration of application. Temporary overvoltages (TOV) originating from switching or system faults (e.g. load rejection, unbalanced faults etc.) or from nonlinearities (ferroresonance effects, harmonics) are generally undamped or weakly damped [12].

Integration of distributed generators originates changes in fault level, fault current distribution and voltage profile in the distribution line. TOV in the distribution line mainly depends on pre-fault voltage, type of fault, resistance of fault, etc. The types of distributed generator and configuration of its interconnection transformer play an important role in the temporary overvoltage.

1.2.5 Grid Protection problem

Distribution grid protection consists of generally a simple overcurrent protection scheme since there is only one source of supply and the power flow and its direction is defined. The connection of the DG to the distribution grid creates multiple sources of the fault current which can affect the detection of faults and disturbances. The contribution of the DG to the fault current depends on the type of the DG units and the scheme by which DG unit is connected to the distribution grid. As stated earlier, the converter equipped DG hardly contributes to the fault current. In [13], [14], potential problems to the distribution grid protection are discussed. The main problems identified are:

- Prohibition of automatic reclosing;
- Unsynchronized reclosing;
- Fuse-recloser coordination;
- Islanding problems;
- Blinding of protection;
- False tripping.

1.3 CONVENTIONAL METHODS TO ELIMINATE VOLTAGE ISSUES

In any power network, voltages at various system buses change regularly according to the variation in demand, switching of lines or transformers, and system contingencies. It's the responsibility of Power system operators to ensure system voltages within permissible limits in all operating conditions. Typically, on load tap changing (OLTC) transformers are employed to maintain voltages in medium voltage distribution network.

1.3.1 Voltage Regulation

Voltage control is achieved by installing voltage regulators [15] at various locations in power network. Most of the existing voltage regulators used in the distribution network are implemented for unidirectional power flow from source to the load ends. Increased DG output during off-peak load hours may create reverse power flows. The upstream voltage regulators are affected by these reverse power flow [15]. Modification of the controller has been proposed for the upstream line voltage regulators if DGs are connected to the system. Multiple line drop compensation based voltage regulators are very effective to regulate the system voltage even with high penetration of distributed generators [16]. In the traditional distribution system, the system voltage is maintained by installing upstream voltage regulators and the load end reactive power compensators. The DGs themselves are not allowed to regulate the bus voltages in grid.

1.3.2 Reactive Power Compensation

Traditionally, shunt compensation can be used to provide reactive power compensation locally at load buses. Conventional shunt capacitors or shunt inductors are employed for this purpose. Capacitive reactive power compensation is provided to increase the system voltage to desired level where as inductive compensation is used to decrease the voltage during light load (off-peak) situations. The terminal characteristic (I-V characteristic) for fixed capacitor and inductor is drawn in Figure 1.6.

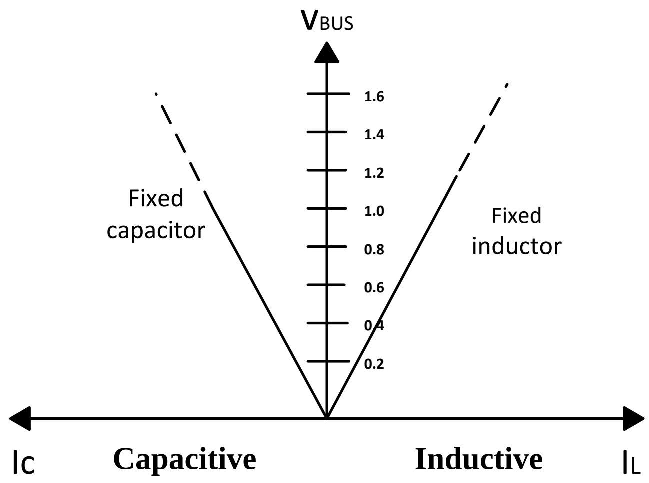

Figure 1.6 Terminal characteristic of fixed Capacitor/Inductor

Shunt capacitors and inductors provide fixed compensation to the grid whereas variable compensation is implemented by switching appropriate combination of capacitors or inductors. Different types of distributed generation resources used and requirement of dynamic reactive power support make these conventional devices less effective in resolving voltage issues created by DGs. Synchronous condensers can provide continuously controlled reactive power output from inductive to capacitive region [17], However, such devices have slow response and are generally not employed in distribution systems due to their high cost.

1.4 FACTS CONTROLLER BASED METHODS TO ELIMINATE VOLTAGE ISSUES

Flexible AC Transmission System (FACTS) is defined as the AC transmission systems incorporating power electronics based and other static controllers to enhance controllability and increase power transfer capability of the grid [18]. The FACTS Controllers have the following benefits to the electric power network:

- Provides reactive power compensation
- Provides voltage regulation
- Improves steady-state stability and transient stability
- Damps power system oscillations
- Improves voltage stability
- Increases power transfer capability

In medium voltage distribution networks, shunt FACTS devices are generally used to provide very fast and continuous reactive power support. It helps to improve system power factor and regulate the system voltage within specified limits. Due to their fast response and dynamic reactive power support capability, FACTS Controllers are most suitable to decrease voltage fluctuation created by the solar and wind power integration to the grid [19]. Mostly, Static Var Compensator (SVC) – a thyristor based FACTS Controller [17], [20] and Static Synchronous Compensator (STATCOM) – a voltage source converter based FACTS Controller are used in medium voltage distribution network to provide reactive power compensation. STATCOM is discussed in the next chapter

1.5 LITERATURE REVIEW

Grid integration of DGs are increasing worldwide. Power Utilities are currently facing huge challenges when it comes to the grid integration of renewable-energy-based distributed generators (DGs) while ensuring voltage regulation, stability, power quality etc. During night time loads decreases in greater amount as compared to daytime, while the wind farms may produce more power due to rise in wind speeds. These events causes reverse power flow from the point of common coupling (PCC) towards the main grid which further causes rise of feeder voltages above permissible limits, typically +/-5%. To integrate more DGs in grid, power utilities need to install costly voltage regulating devices (e.g., voltage regulators, static var compensator (SVC), static synchronous compensator (STATCOM), etc.).

For PV solar farms, Voltage-source inverters are essential which convert solar power into electricity during daytime (normal operation). Though, during nighttime PV Solar Farm are practically inactive and do not generate any real power output. The new strategy is to control the existing Solar Farm inverter as a STATCOM during nighttime to regulate voltage variations at the PCC due to increased and intermittent WF power and/or by load variations.

The use of Flexible AC transmission system (FACTS) controllers to boost up the existing power transfer limits/capacity of presently installed transmission lines growing worldwide. New control scheme has been implemented on the nighttime usage of a dormant photovoltaic (PV) solar farm inverter to improve system performance and to increase grid connectivity of other DGs like wind farm etc without the need of installation of voltage regulating devices. This control scheme can also be implemented to improve the power transmission capacity. A full converter-based wind turbine generator has recently installed with FACTS capabilities to improve performance during faults and fault ride through capabilities

CHAPTER 2

PV SOLAR FARM AND
STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

2.1 STATCOM

The Static Synchronous Compensator (STATCOM) is a FACTS device used at the transmission and distribution level [18], and as a custom power device at end users electrical installations and system [21]. The major applications of STATCOM in these contexts include voltage regulation, power factor correction, damping out power oscillations, and load balancing.

2.1.1 Principle of Operation

Static synchronous compensator (STATCOM) is a voltage sourced converter (VSC) based on controllable semiconductor switches. A STATCOM is a shunt connected device that provides rapid reactive power support in the network. STATCOM, which injects sinusoidal current at the point of common coupling, can emulate itself as inductive or capacitive reactive power source by aligning the injected current almost in quadrature with line voltage thus behaves like inductor or capacitor [22], [23]. A STATCOM with proper control strategy can be effectively used to mitigate the voltage fluctuation problem in the network [24], [25]

The STATCOM is connected to the AC bus terminal by a coupling transformer. The terminal characteristic for this type of STATCOM is shown in Figure

2.1.By seeing this characteristic we can observe that the STATCOM can provide rated capacitive current at very low voltages. This feature is very useful in case of fault at the bus where STATCOM is connected to provide voltage regulation. Pulse Width Modulation (PWM) controlled techniques is used to provide the firing pulses to the converter switches to achieve the control on active and reactive power flow to or from the STATCOM. A 6-pulse, three phase converter is modeled as Static Synchronous Compensator (STATCOM) in this thesis.

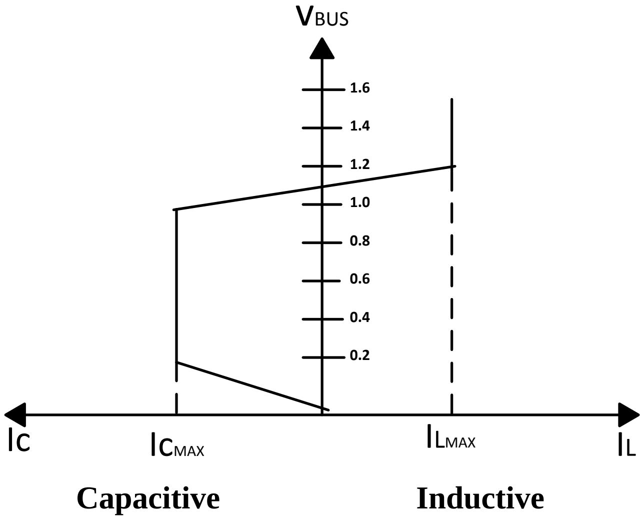

Figure 2.1 Terminal characteristic of a STATCOM

The single line diagram given in Figure 2.2 represents the grid connected with the STATCOM. A STATCOM basically generates a set of balanced 3-phase sinusoidal voltages at fundamental frequency with fast voltage magnitude and phase angle control capability. The active and reactive power transfer between the STATCOM and the grid (flow from STATCOM terminal to grid side terminal) can be represented by the following expressions [17]:

$$P = \frac{V_{BUS} \cdot V_{STATCOM}}{X_L} . \sin \delta \qquad (2.1)$$

$$Q = \frac{{V_{STATCOM}}^2 - V_{BUS} \cdot V_{STATCOM} \cdot \cos \delta}{X_L} \qquad (2.2)$$

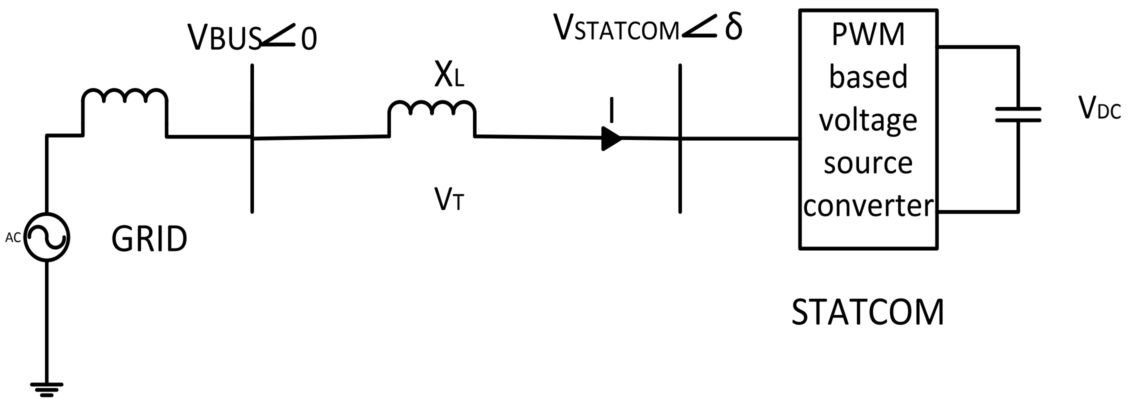

Figure 2.2 Single line representation of STATCOM terminal connected to the grid

From equation (2.1), it is clear that the real power transfer is dependent on the power angle δ between STATCOM terminal and grid side terminal for rated values of voltage magnitudes. Similarly from equation (2.2) it can be depicted that for small power angle δ, the reactive power exchange depends on STATCOM terminal voltage compared to grid terminal voltage magnitude. Hence various combinations of active and reactive power transfer to and from STATCOM can be possible. The four possible combinations of active and reactive power transfer are elaborated with the help of phasor diagrams. The transfer of reactive power to and from the STATCOM is given in Figure 2.3. The STATCOM will absorb reactive power in inductive mode of operation if $V_{STATCOM} < V_{BUS}$ and will supply reactive power in capacitive mode of operation if $V_{STATCOM} > V_{BUS}$. Similarly, the transfer of active power is shown in Figure 2.4. Active power will flow from AC side (Grid) to DC side (STATCOM) when power angle δ is negative. This will raise the DC bus voltage. When power angle δ is positive, active power will flow from DC side to the AC side and the DC bus voltage will decrease.

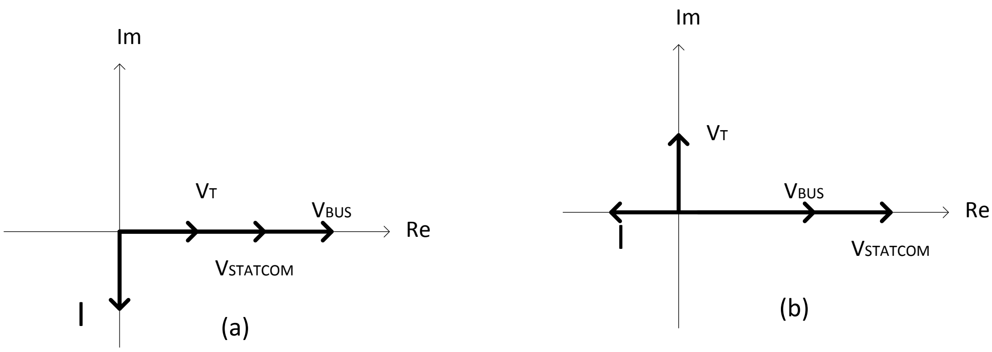

Figure 2.3 Phasor diagram of reactive power control by STATCOM,
(a) Reactive power absorbed by STATCOM (Inductive mode), and
(b) Reactive power supplied by STATCOM (Capacitive mode)

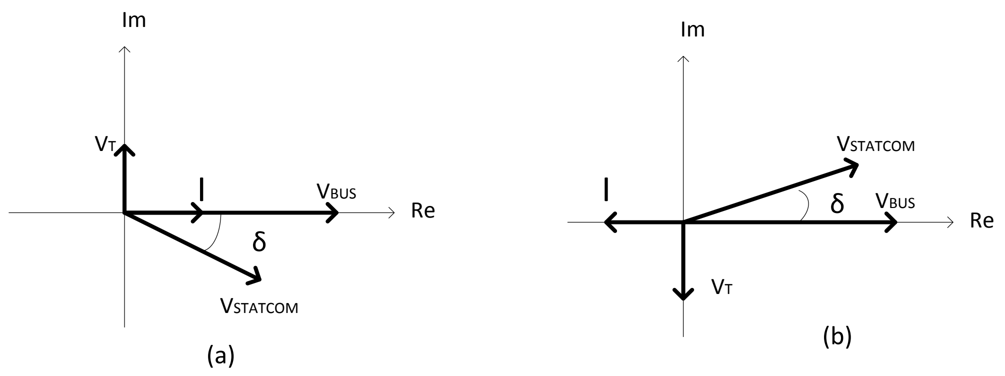

Figure 2.4 Phasor diagram of active power control by STATCOM -
(a) Active power consumed by STATCOM (Power flow from AC side to DC side)
(b) Active power supplied by STATCOM (Power flow from DC side to AC side)

2.1.2 STATCOM Controller

Based on the above discussed analysis, a phase angle regulator and a voltage magnitude regulator can be used to control the exchange of active power and reactive power respectively between the grid and the STATCOM. Therefore STATCOM can provide control on voltage magnitude and phase angle at its terminal. Voltage Sourced Converters implement either fundamental frequency switching or pulse width modulation switching strategies. In fundamental frequency switching technique switching loss is less because it works on low switching frequency. However, this switching technique injects more harmonics in the connected power system. Generally, Gate Turnoff Thyristors (GTO's) are employed as controllable switches at fundamental frequency and multi-level voltage switching is used to decrease the harmonic components. Alternatively, pulse width modulation (PWM) technique can also be used to eliminate lower order harmonics and decrease the total harmonic distortion (THD) due to converters. Preferably Insulated Gate Bipolar Transistors (IGBT's) are mostly used as controlled switches to decrease switching losses in PWM converters. In sinusoidal pulse width modulation (SPWM), which is the most preferred PWM technique, the magnitude and frequency of the sinusoidal fundamental component are controlled by pulse width modulation. In such type of converters, by increasing the switching frequency, the quality of the resulting waveform greatly increase and we required small size of filter capacitor and inductors to eliminate harmonics. In PWM technique, the shape of the fundamental component of the output voltage is attached (modulated) in the widths of the output voltage pulses. The output low-pass filter (LC filters), is required to demodulate the signal. Filters separate the switching harmonics from the fundamental component, or in the inductive load, where the pulsed voltage waveform is converted to a sinusoidal current at the fundamental frequency. The Sinusoidal Pulse Width Modulation known as SPWM is based on generation of sinusoidal modulating signal and the triangular carrier signal. The sinusoidal modulating signal is compared with a triangular carrier signal of constant maximum amplitude and frequency to generate the gate pulses for the converter switches. For three phase PWM inverter, the AC voltage magnitude is calculated by the following equation:

$$V_{LL} = \frac{\sqrt{3}}{2\sqrt{2}}.m_a.V_{DC} = 0.6124.m_a.V_{DC} \quad (2.3)$$

V_{LL}= Line voltage of AC side of converter

V_{DC}= DC link voltage of converter

m_a= Modulation index

m_a= (peak value of sinusoidal modulating signal)/(peak value of triangular carrier signal)

2.1.3 PV Solar Farm based STATCOM (PV-STATCOM)

Solar farms are installed with grid tied inverters to facilitate the conversion of DC power generated from photovoltaic modules to the power grid. These inverters has a voltage sourced converters with pulse width modulated (PWM) switching techniques and well designed filter and/or interconnection transformer between the converter and the power grid. PV solar farms are completely idle in the nighttime and only partially utilized during early morning and late evening hours of the day. A novel control of PV solar farm inverter as STATCOM (termed PV-STATCOM) was proposed by Varma [26] The PV-STATCOM can provide dynamic reactive power compensation using the entire inverter capacity during nighttime. It can also provide reactive power compensation during daytime by remaining inverter capacity after real power generation [26], [27]. Assuming the inverter capacity S to be the same as the peak output power capacity of the photovoltaic modules, the active power P and reactive power $Q = \sqrt{S^2 - P^2}$ of the PV-STATCOM is shown is Figure 2.5. It can be seen that the PV-STATCOM can deliver up to 66% of reactive power when it is producing 75% of rated real power during day time. Therefore significant amount of reactive power can be provided even with large amount of production of active power makes such PV-

STATCOM control very effective in reactive power compensation techniques. The detailed modeling and control of solar farm converter as STATCOM is presented in Chapter 3.

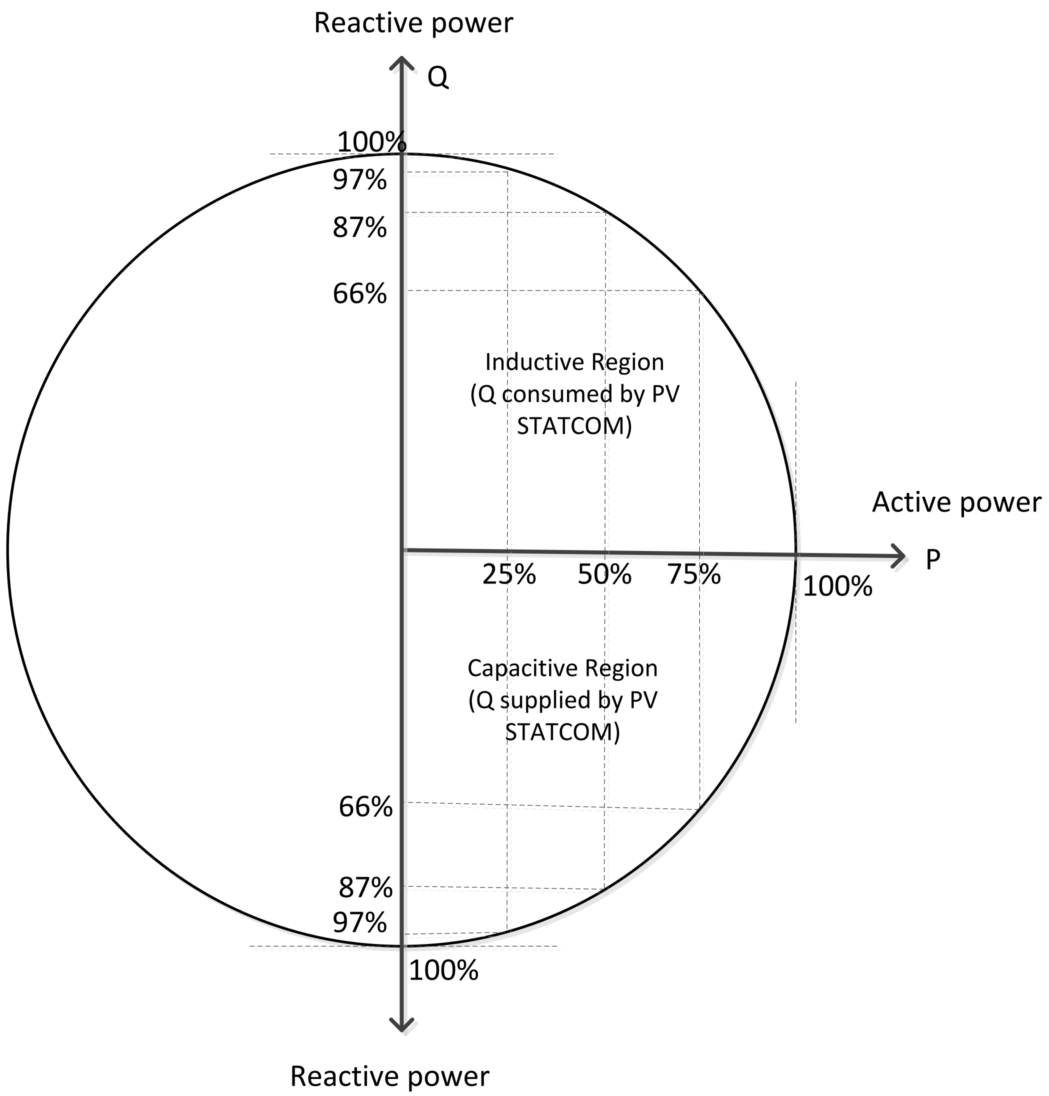

Figure 2.5 Active and reactive power capability curve for PV-STATCOM

2.2 PV SOLAR FARM

A PV Solar Farm is a large-scale photovoltaic system (PV system) designed for the supply of merchant power into the electricity grid. They can be differentiated from most building mounted and other decentralized solar power systems because they supply power at the utility level, rather than to a local user or users. They are mostly sited in agricultural areas. The generic term utility-scale solar is sometimes used to describe this type of system. The solar farm contains following component

1. PV Solar Panel/Module
2. PV Inverter
3. DC link Capacitor

2.2.1 PV Solar Panel/Module

A photovoltaic (PV) system directly converts sunlight into electricity. The basic device of a PV system is the PV cell. Cells may be grouped to form panels or arrays. A photovoltaic cell is basically a semiconductor diode whose *p*–*n* junction is exposed to light. The incidence of light on the cell generates charge carriers that originate an electric current if the cell is short circuited. The current versus voltage (I-V) characteristic of the PV cell, and thereby the PV module, is not linear.

2.2.2 PV Inverter

PV solar inverter is used to convert the DC power generated by PV modules to the AC power so that it can be supplied to the electric grid.

2.2.3 DC Link Capacitor

In a PV solar system the main role of the DC link capacitor, in addition to holding a constant DC voltage, is to maintain the power quality at the DC side which ultimately influences the power quality at the AC side. For smooth operation of the inverter, a comparatively ripple free DC current and voltage is required at the input of the inverter.

The complete solar farm modeling and its integration with the distribution feeder is thoroughly discussed in the CHAPTER 3

CHAPTER 3

SYSTEM MODEL

3.1 INTRODUCTION

In this chapter a detailed modeling of a realistic medium voltage radial distribution feeder connected with a PV solar farm, a wind farm along with loads are presented. The system model implemented in DIgSILENT PowerFactory software is used for steady state analysis, electromechanical (RMS values) and electromagnetic transient (instantaneous values) analyses.

3.2 STUDY SYSTEM

A realistic medium-voltage distribution system shown in Figure 3.1 is considered as the study system in this thesis. The system data corresponds to an actual Hydro One feeder in Ontario. The study system consists of 45 *km* of 27.6 *kV* radial distribution network connected to a supply substation through 115*kV*/27.6*kV* transformer. The load is approximated as lumped a load at bus no. 5 at the end of the radial network. Here load is considered as 4.82 *MW* active and 2.19 *Mvar* reactive (5.3 *MVA* at 0.91 lagging power factor). A PV solar farm of 5 *MW* capacity is located at bus no. 3 at a distance of 10.0 *km* from the load bus. A brief description of the five buses considered in the network is given in Table 3.1. The parameters for the study system and various components are provided in Appendix.

.

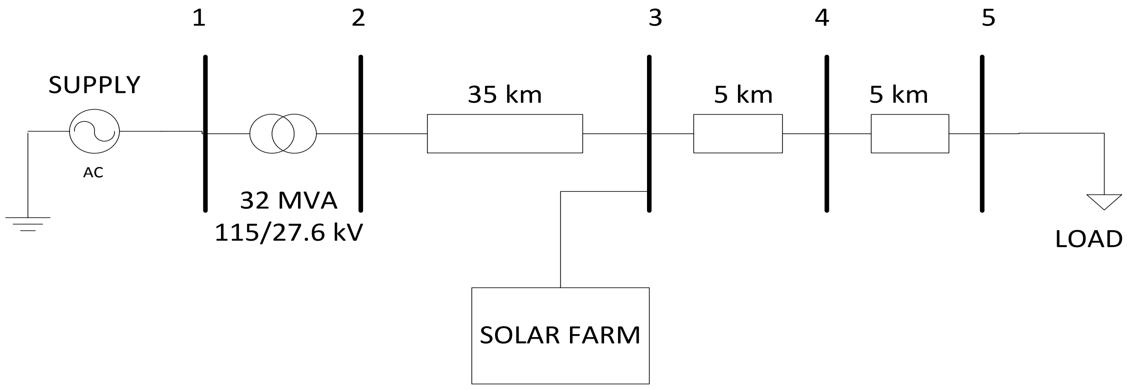

Figure 3.1 Study system

Bus No.	Description
1	Supply end bus (primary side of transformer)
2	Secondary side of transformer
3	PV solar farm connection bus (Point of Common Coupling – PCC bus for solar farm
5	Load bus (Lumped load)

Table 3.1 Bus description

Figure 3.2 is complete modeling of test feeder implemented in DIgSILENT PowerFactory software

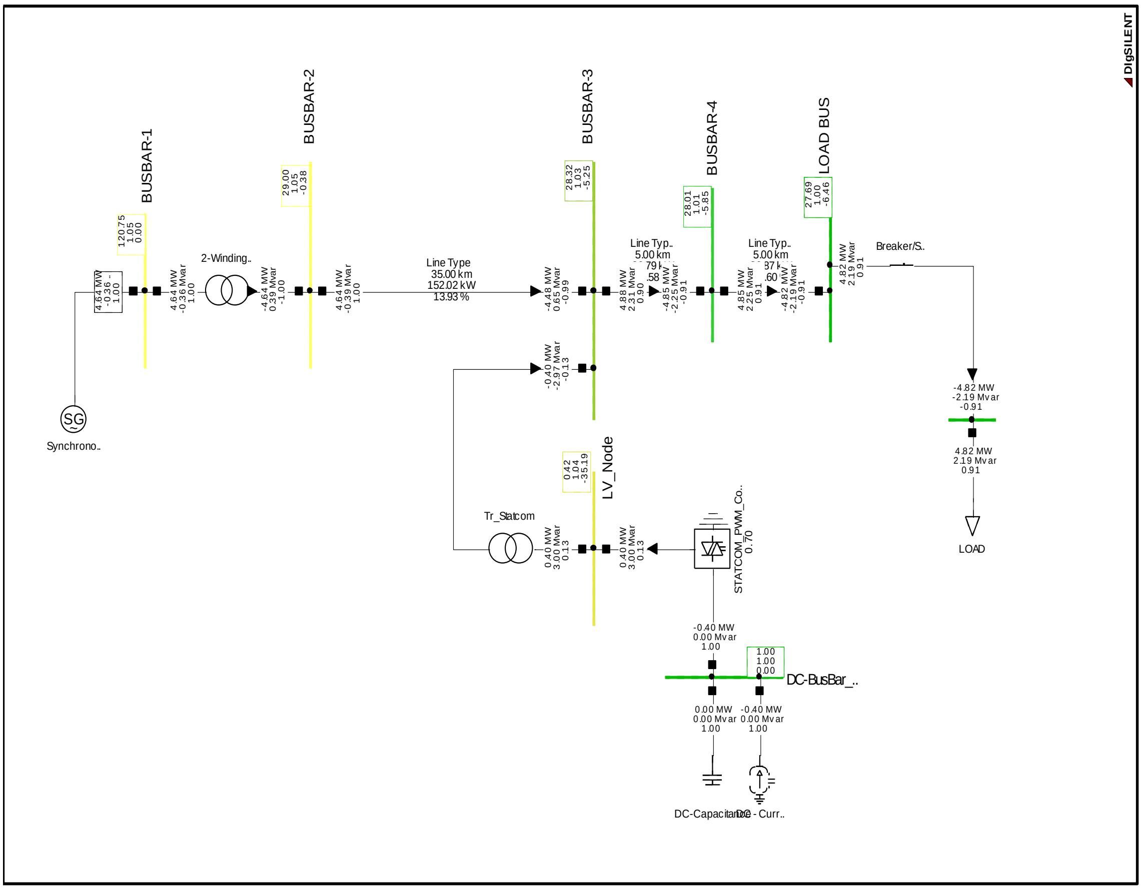

Figure 3.2 study system model in DIgSILENT PowerFactory

3.3 NETWORK AND LOAD MODEL

3.3.1 Grid Model

For steady-state and transient analysis, the grid is represented by a slack bus/infinite bus capable of supplying the required power at specified bus voltage. The generator considered as slack bus can supply the active power (including total system loss and load) required by the distribution network or it can also have ability absorb the excess active power in case of reverse power flow due to distributed generators. Also, such generators can supply or absorb reactive power at specified voltage as required by the feeder. Synchronous machine model of DIgSILENT PowerFactory is used in this thesis

3.3.2 Transformer Model

Electric power grid mainly consists of generation, transmission and distribution systems which generally exist at different voltage levels. In such type of power grids, transformers are widely employed to connect the systems at different voltage levels. The transformer is typically represented by series and shunt parameters. The series parameters, which contain the series resistance and reactance represents the copper loss and the leakage flux of the windings, respectively. The copper loss and the leakage flux for both the primary and secondary windings depend on how much the transformer is loaded. The net established flux that links the transformer windings and the iron loss (hysteresis loss and eddy current loss) are fixed for a transformer with nominal voltage and does not depend on the transformer loading condition. Shunt parameters, called as shunt resistance and reactance are used to represent such fixed loss and flux in the transformer. The shunt resistance and reactance are very high therefore their effect in the system is neglected in complete system analysis. Also, copper loss in the transformer windings is very low compared to the network losses and hence a loss less transformer is used for the study system.

3.3.3 Line Model

Electrical parameters of a transmission line in power system are based on size of conductors and their geometrical configuration. An overhead transmission line is represented by series parameters (series resistance, R, and reactance, X) and shunt parameters (shunt conductance, G, and susceptance, B).these parameters are entered as per km basis in line model.

For the medium voltage overhead feeder, these distributed line parameters are represented as lumped model both for steady-state and transient analyses study. The series parameters are represented by equivalent resistance, R and equivalent reactance, X. The shunt conductance, G is negligible for the overhead lines and half of capacitive susceptance ($Y/2$) is used to represent shunt parameters on each terminal of the feeder.

3.3.4 Load Model

The loads in a distribution network have various types like heating, lighting and motor loads. Individual loads have their individual performance characteristic. The equivalent characteristic of the load seen from the medium voltage side (secondary of the feeder transformer) will be obtained by the net effect of the individual loads in network. The net active power and reactive power of a given load are affected by the terminal voltage and the system frequency from the network side.

For the study requirements, the load models can be broadly classified into two categories: static load models and dynamic load models. Static load models used in load flow studies are indicated as steady state active and reactive powers as function of bus voltage and system frequency.

In this thesis constant power static load models (General load model of PowerFactory) are used for load flow studies as well as transient (fault) studies. The load is considered as lumped at the receiving end (*Bus 5*) of the study system. In this thesis, constant power load with power factor of 0.91 lagging is considered for both steady state and transient analysis studies.

3.4 WIND FARM MODELING

The wind farm model used in this thesis is a standard static generator model of DIgSILENT PowerFactory library. The Static Generator (ElmGenstat) is an easy-to-use model to represent any kind of non-rotating generators. The common characteristic of these generators is that they are all connected to the grid through a static converter and hence the name static generator. Typical applications are:

- Photovoltaic Generators
- Fuel Cells
- Storage devices
- HVDC Terminals
- Reactive Power Compensations

Wind generators, which are connected with a full-size converter to the grid, can be modeled as a static generator as well, because the behavior of the plant (from the view of the grid side) is determined by the converter

3.5 PV SYSTEM MODELING

PV solar system basically consists of photovoltaic modules that produce DC electricity, an inverter that converts DC to AC and a coupling transformer that connects AC side of the PV system to one voltage level to the point of common coupling (PCC) to another voltage level at grid. The DC side voltage, V_{DC} and AC side Active and Reactive power are used as input to the inverter controller which generates gate drive pulse signal to operate inverter switches. A schematic diagram of PV system is shown in Figure 3.3.

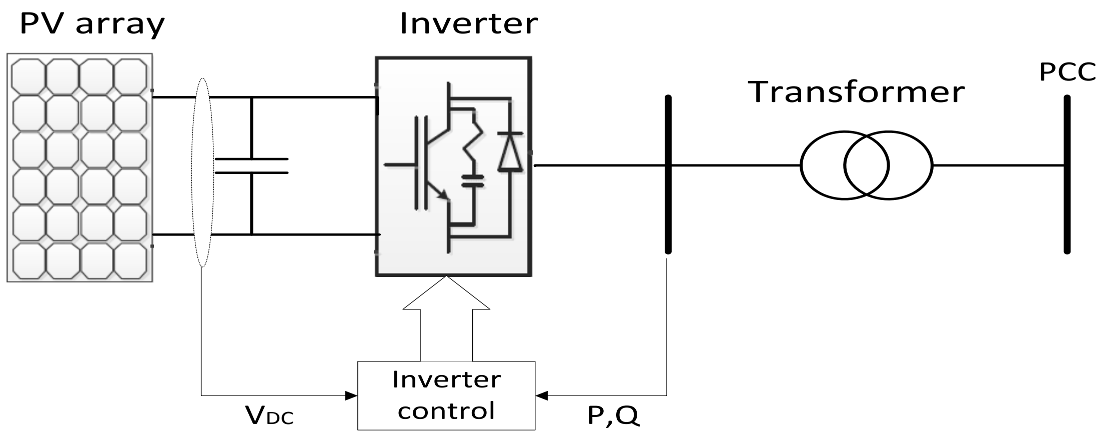

Figure 3.3 PV Solar System

Figure 3.4 is the complete PV system modeling composite frame in DIgSILENT PowerFactory which is used in the PWM converter controlling model. The given frame contains following blocks

1. V_{DC} controller block
2. Active and reactive power controller block
3. Inbuilt current controller (In converter block)
4. VDC measurement block
5. PQ measurement block
6. PLL block

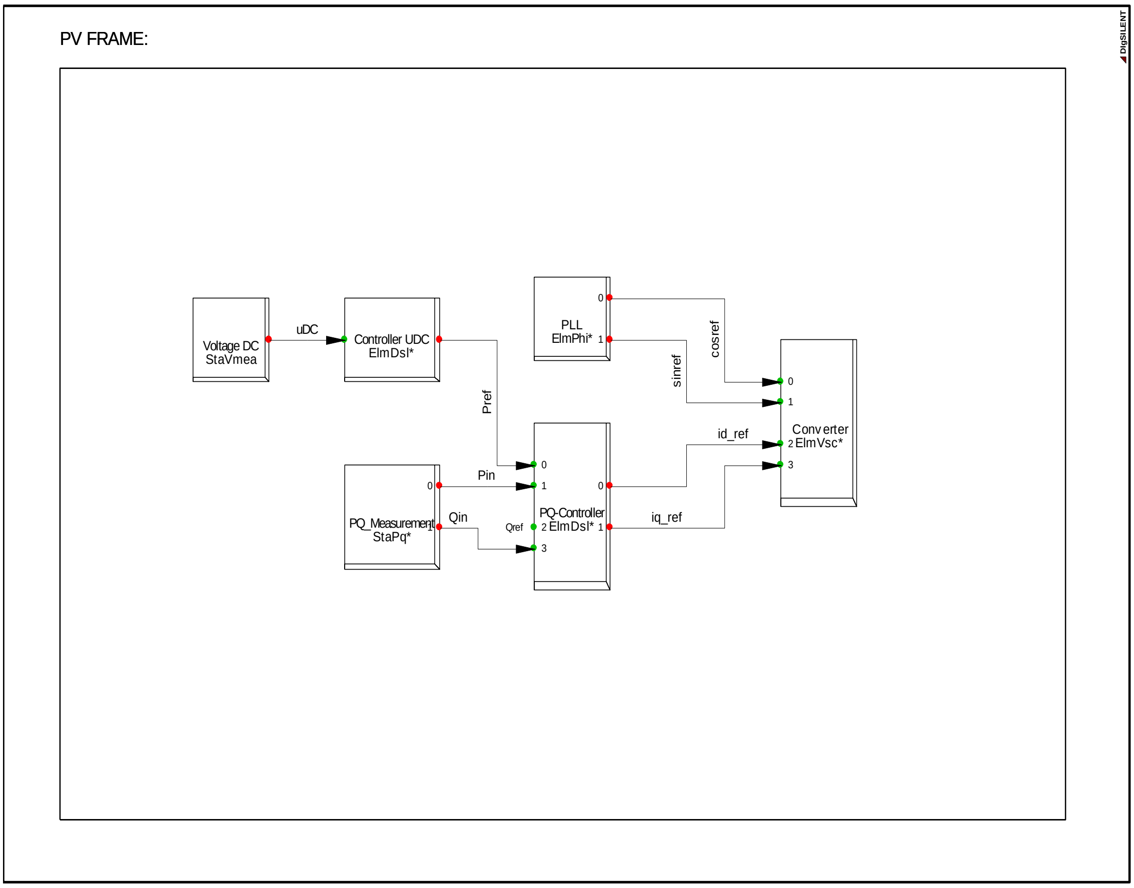

Figure 3.4 PV system composite model used in PWM inverter

3.5.1 Photovoltaic Array

Photovoltaic cell, which consists of semiconductor material, is the basic unit of a PV solar system. A photovoltaic cell is basically a semiconductor diode whose *p–n* junction is exposed to light. Photo voltaic cells are made of several types of semiconductors using different manufacturing processes. The incidence of light on the cell generates charge carriers that originate an electric current if the cell is short circuited. The equivalent circuit of PV cell is shown in Figure 3.5. In the above diagram the PV cell is represented by a current source in parallel with diode. R_{SE} and R_{SH} represent series and parallel resistance respectively. The output current and voltage from PV cell are represented by I and V.

The basic units of photovoltaic technology referred as PV cells are connected in a combination of series and parallel connection to increase the voltage and current available from the photovoltaic cells. Such combination of cells is referred as PV solar module. Typical solar module consists of 36 to 72 cells and ranges from 75 *W* to 350 *W* in peak output power (W_p). A PV array is the combination of PV modules connected in series and parallel to match the requirement of inverter for grid integration. A PV solar farm may consist of a number of solar arrays based on its capacity.

Based on this equivalent circuit, the relationship between the terminal voltage of solar module and the current delivered to the load is:

$$I = I_{ph} - I_0 \left[e^{\left(\frac{V+I.R_{SE}}{N_S V_t}\right)} - 1 \right] - \left[\frac{V+I.R_{SE}}{R_{SH}} \right] \tag{3.1}$$

$Where$

$I_{ph} = PHOTO\ generated\ current \begin{pmatrix} depends\ upon\ solar\ radiation \\ and\ module\ temprature \end{pmatrix}$

$I_0 = Reverse\ saturation\ current (depends\ on\ module\ temprature)$

$V = Terminal\ voltage\ of\ pv\ module$

$I = Output\ current\ of\ module$

$N_S = Number\ of\ PV\ modules\ in\ series$

$V_t = Junction\ thermal\ voltage$

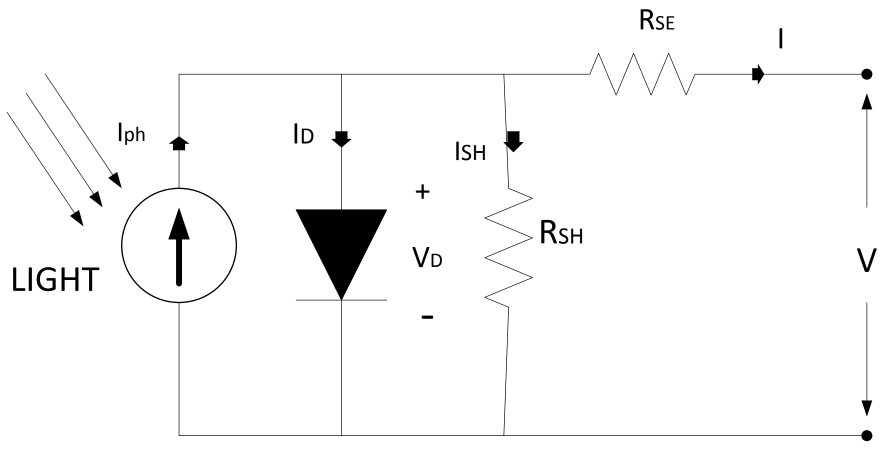

Figure 3.5 Equivalent circuit of PV solar cell

3.5.2 Coupling Transformer

Medium to large scale three-phase grid-integrated PV inverters use coupling transformer to match the voltage on AC side of the inverter and the grid side voltage. It also helps to maintain electrical isolation between the PV system and the grid. Various configurations of 3-phase transformer windings are used to connect PV solar output to the grid. The transformer selection is based on the guidelines provided in Hydro One's DG technical interconnection requirements. Star-Delta configuration as shown in Figure 2.8 is used for PV solar farm integration at Bus-3 of the study system. For simulation studies, the transformer is represented by ideal transformer in series with leakage reactance.

3.5.3 PV Solar Inverter

PV solar inverter is used to convert the DC power generated by PV modules to the AC power so that it can be supplied to the electric grid. These inverters are interfaced to the grid voltage and designed so that maximum power transfer available from the PV modules based on the solar irradiance and the cell temperature. Typically, a 3- phase, 2-level, 6-pulse voltage sourced converter (VSC) is used to convert DC to AC in the PV inverters. Such PV inverters that convert DC to AC are made possible with the development of high power switches like Gate Turn-off Thyristors (GTO). A GTO can be turned ON or turned OFF with gate pulses (turned ON by positive polarity pulse and turned OFF by negative polarity pulse on gate terminal). However, these devices produce high loss for high switching frequency applications. The switching losses are significantly minimized in Insulated Gate Bipolar Transistor (IGBT) with fully controlled capability. Sinusoidal pulse width modulation (SPWM) gate pulses are generated based on the DC terminal voltage and current as well as the grid side voltage and output current of the inverter.

Following controller are used in the PWM Inverter

3.5.3.1. V_{DC} controller:

To maintain DC side voltage of Inverter following model is implemented in DIgSILENT PowerFactory. The difference of VDC and VDC_{ref} called error signal is passed through PI controller to generate the P_{ref}

Input signals- V_{DC} , V_{DC}ref

Output signal- P_{ref}

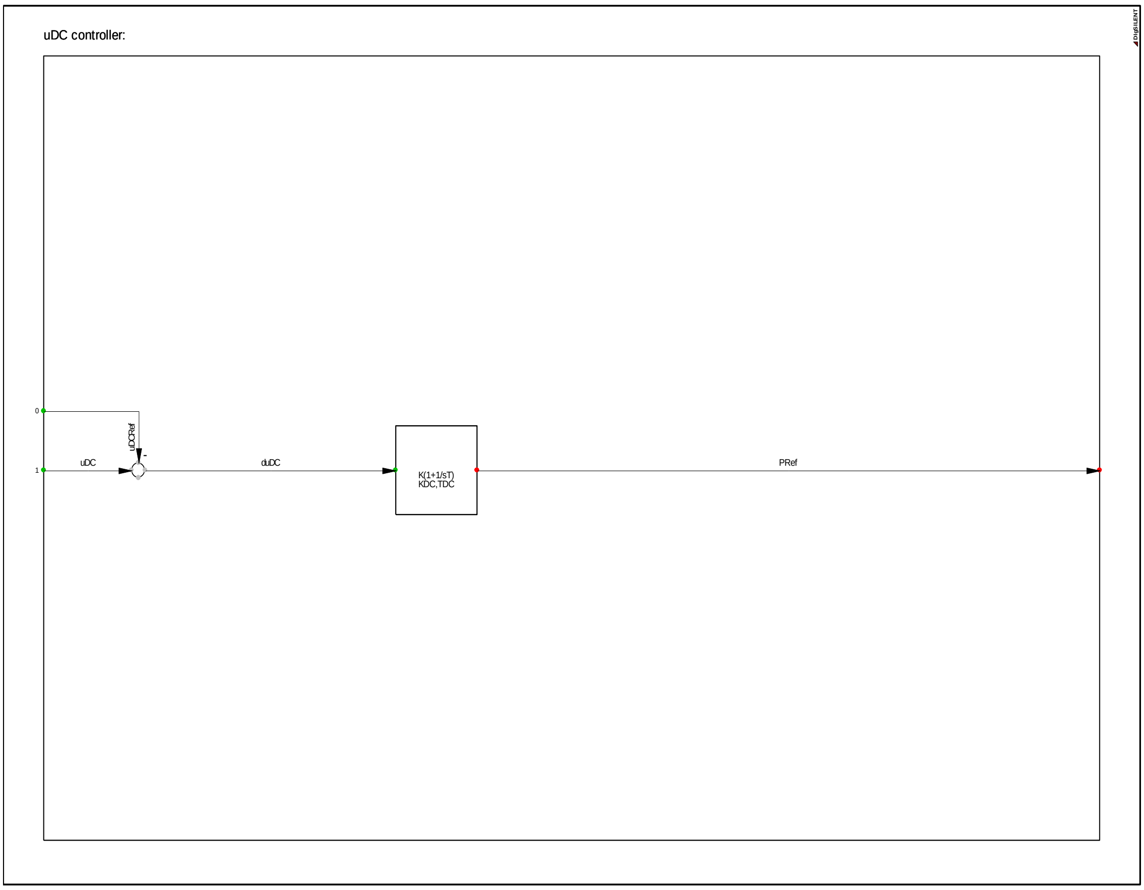

Figure 3.6 Model of dc voltage controller

3.5.3.2. PQ controller

This controller is used to control the active and reactive power transfer between the inverter and grid. The difference of p_{in} and p_{ref} is passed through PI controller, similarly difference between q_{in} and q_{ref} is passed through PI controller. Output of PI controller is further passed through magnitude limiter. Magnitude limiter will provide id_ref and iq_ref to inbuilt current controller of PWM converter to generate the firing pulses.

Input signals- P_{in} , P_{ref} , Q_{in} , Q_{ref}

Output signals- id_ref , iq_ref

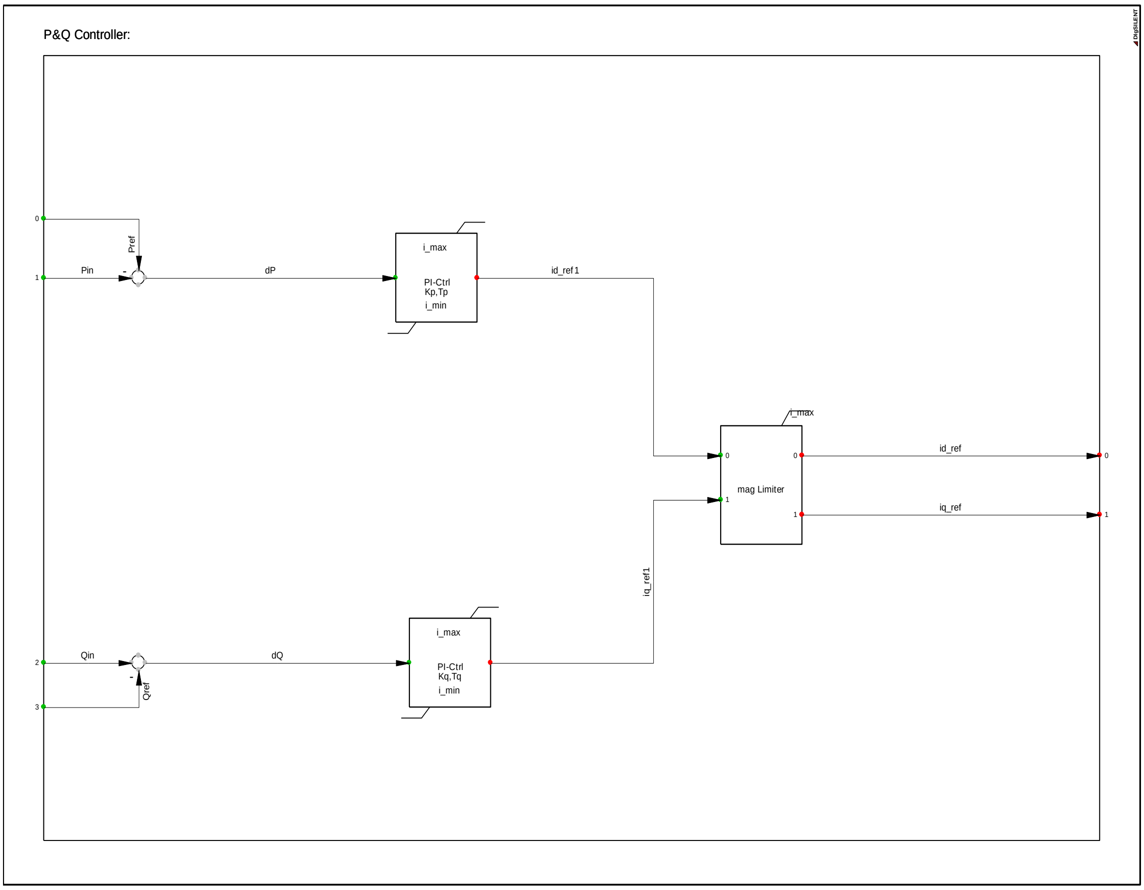

Figure 3.7 Active and Reactive power controller

3.5.3.3. Inbuilt current controller

The PWM inverter of DIgSILENT PowerFactory contains an inbuilt current controller. Enabling the flag “Use Integrated Current Controller” enables the built-in controller according to block diagram shown in Figure 3.8. The input currents to the controller are the converter’s AC-currents expressed in a reference frame (id, iq) that is defined by the input signals cosref, sinref. The output signals Pmd and Pmq are defined in the same reference frame and transformed back to a global reference frame using the same reference angle.

The current-references id_ref and iq_ref are available as additional input signals to the PWM converter model. If the parameters of the built-in current controllers are all set to zero (Kp=0, Tp=0s, Kq=0,Tq=0s), the controller is disabled and the converter output currents id and iq are set equal to the input variables id_ref and iq_ref. hence the PWM converter is operating as a current source.

Input signal- id , id_ref , iq , iq_ref

Output signal – Pmd , Pmq

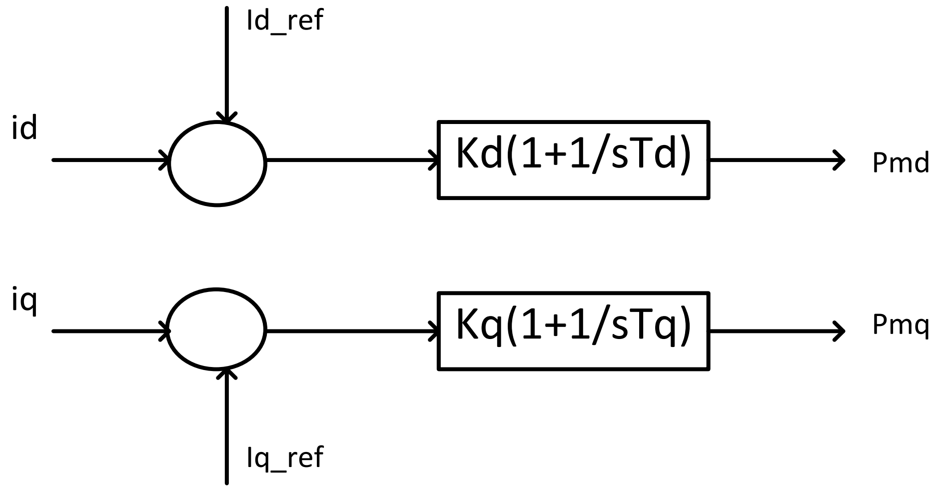

Figure 3.8 Built In current controller of PWM converter

3.5.4 MODEL OF PV SOLAR INVERTER AS STATCOM (PV STATCOM)

Fig. 3.10 shows the block diagram of the control scheme implemented to obtain the proposed concept. The controller is consist of two proportional integral (PI) based voltage-regulation loops. One loop regulates the PCC voltage (V_{PCC}), while the other maintains the dc link voltage (V_{DC}) across Solar Farm inverter capacitor at its nominal value (constant).

The PCC voltage is regulated by providing leading or lagging reactive power during bus voltage drop and rise, respectively. Here 5.0% droop characteristic is employed to increase the range of voltage control available and improve the dynamic performance of the converter. A Proportional-Integral (PI) controller is used to reduce the steady state error as well to obtain a good transient response characteristic i.e. faster response with small overshoot and minimum settling time. A phase-locked loop (PLL) based control approach is used to maintain synchronization with PCC voltage as shown in figure 3.9..

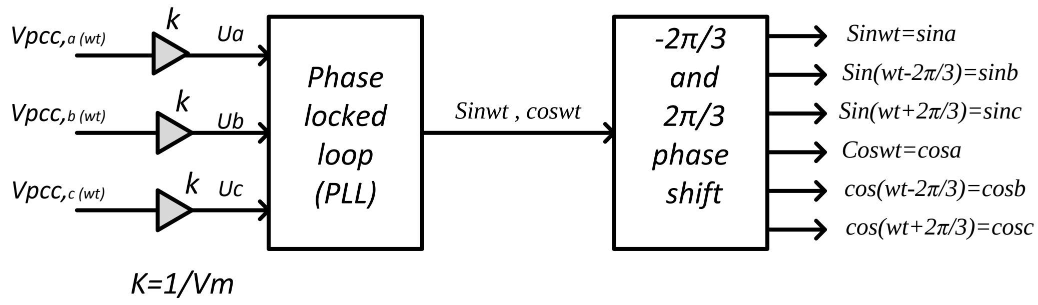

Figure 3.9 Synchronization signal produced by PLL

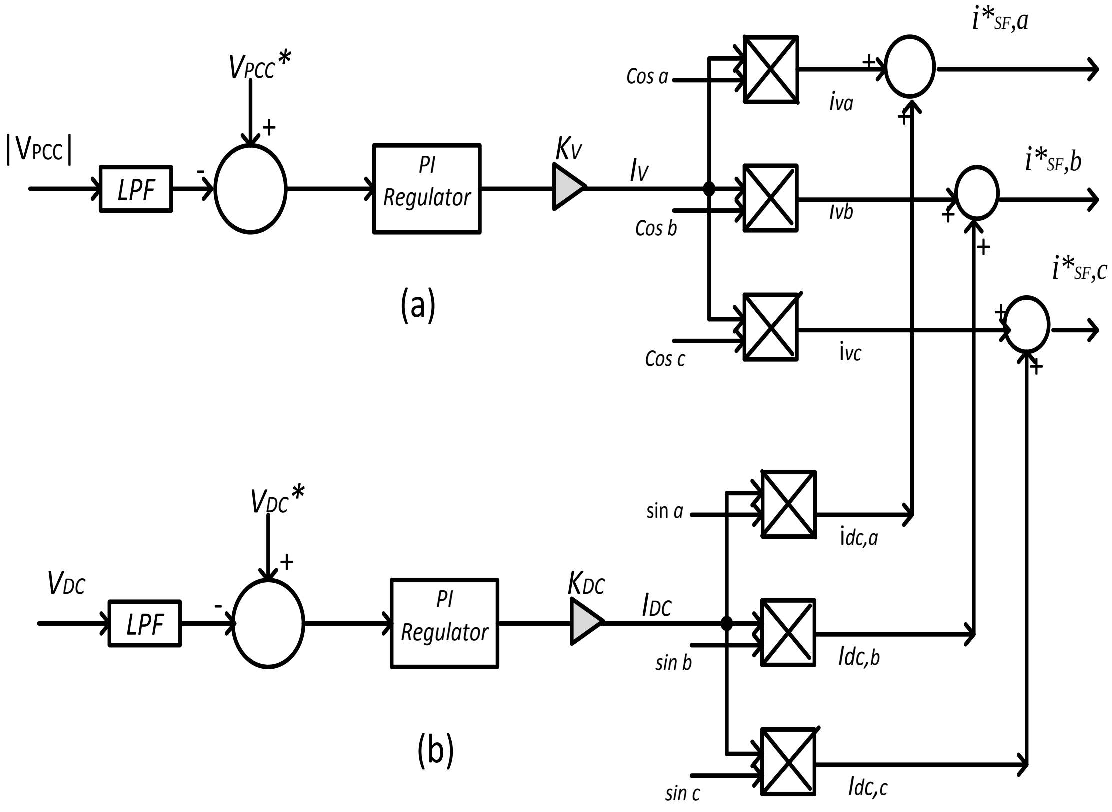

Figure 3.10 controller diagram. (a) PCC voltage regulation loop. (b) DC bus voltage regulation loop.

Figure 3.11 shows the statcom controller implemented in DIgSILENT PowerFactory. The output of this controller provides id_ref and iq_ref to built in current controller which is discussed in the section 3.5.

Input signal- vdc , vdc_ref ,vac and vac_ref

Output signal- id_ref and iq_ref

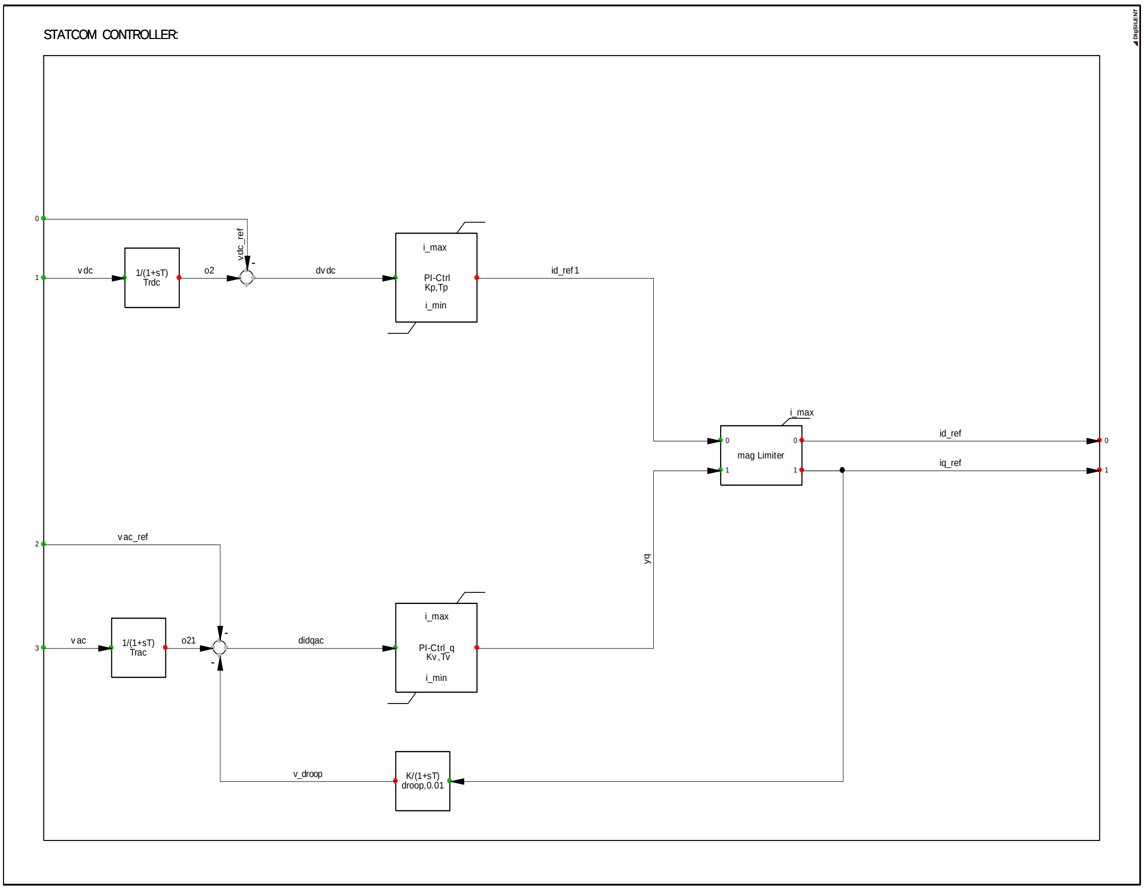

Figure 3.11 STATCOM Controller in DIgSILENT

Figure 3.12 shows the frame of STATCOM model which is used in the PWM inverter to control the firing pulse generated by it. It contains following block

1. vdc measurement block
2. vac measurement block
3. statcom controller block
4. PWM Inverter block (Built in current controller)
5. PLL

The block ext controller shown in statcom frame contains the controller which is shown in Figure 3.11

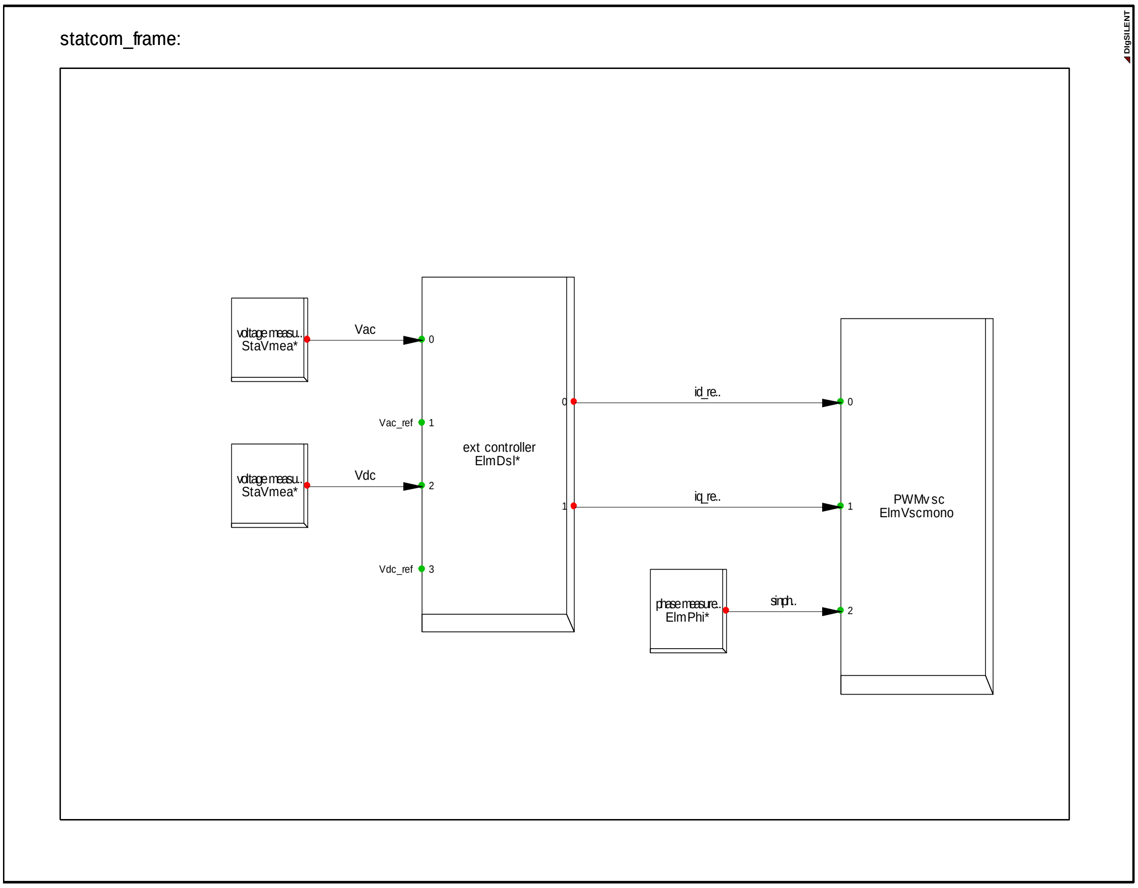

Figure 3.12 STATCOM model used in PWM inverter of DIgSILENT

CHAPTER 4

SIMULATION OF STUDY SYSTEM AND DISCUSSION

4.1 TRANSIENT STUDY OF PV SOLAR FARM

Transient study of PV solar farm conducted for the following cases

1. Cloudiness disturbance

2. Three phase symmetrical fault at load bus

The study is conducted by Electromechanical transient stability simulation (RMS values) of DIgSILENT PowerFactory software. The fault transient simulation (EMT) is also used to get the instantaneous three phase values of the output current and voltage during 3LG fault. The study system is already described in the chapter 3

4.1.1 Cloudiness disturbance

When cloud blocks the sun, the irradiation suddenly reduces sustaining for 2s. This event happened at the time instant 0.1 sec to 2.1 sec. The graph shown in Figure 4.1 have the following curve- (a) PV array current in pu, (b) output active power of PV in MW, (c) output reactive power in Mvar, (d) output current in kA and (e) DC bus voltage in pu. From the graphs it can be observed that output power, output current and DC bus voltage have the same recovery curve. Output power and current stabilizes after some time of disturbance.

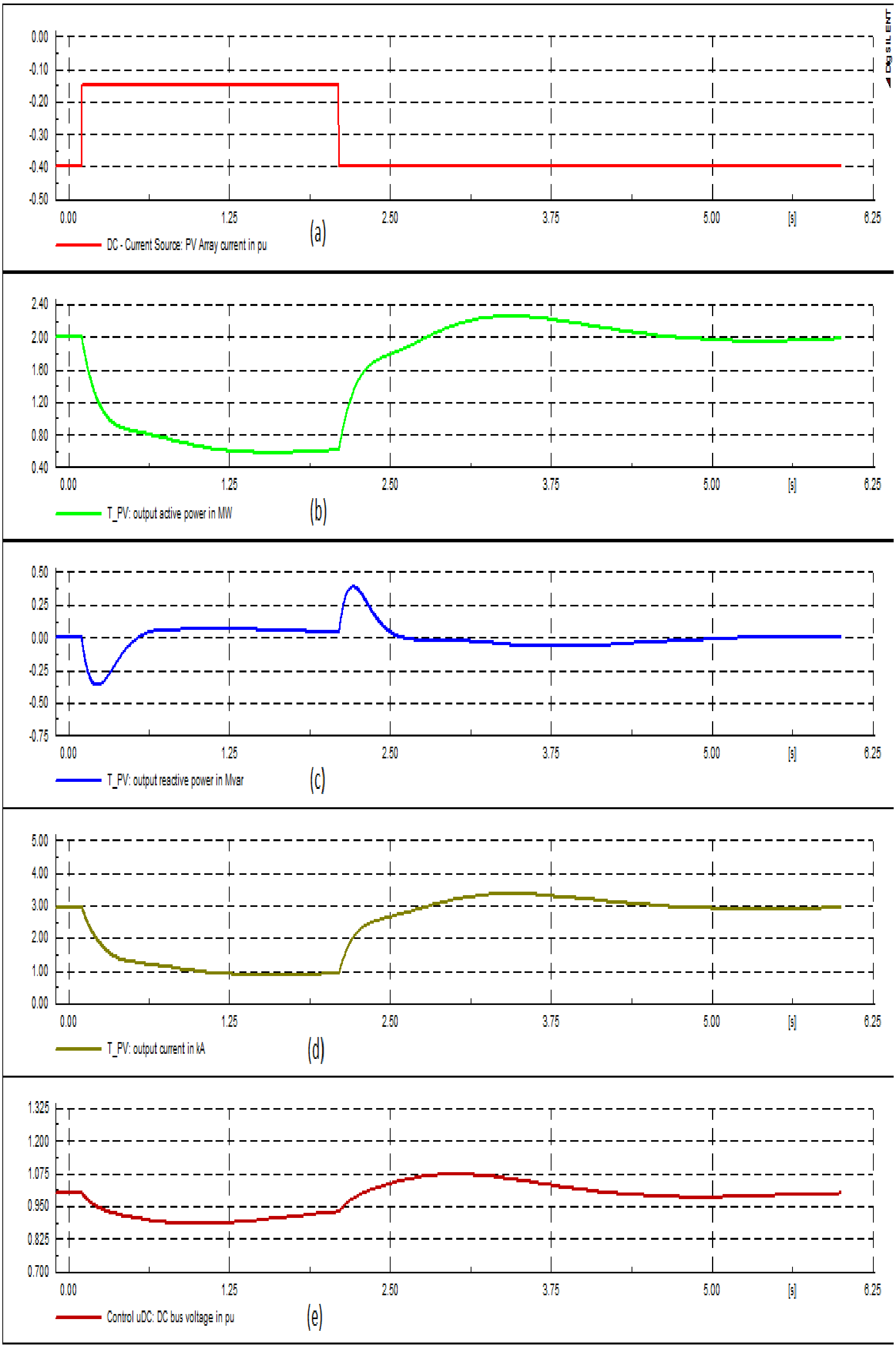

Figure 4.1 Transient results during cloudiness disturbance

4.2.2 Three phase symmetrical fault at load bus

A three-phase short circuit voltage sag fault with reactance 10 ohm is simulated on the load bus and the short circuit is cleared after 0.2s. The time instant at which fault occurred is 0.0 sec and cleared at 0.2 sec.

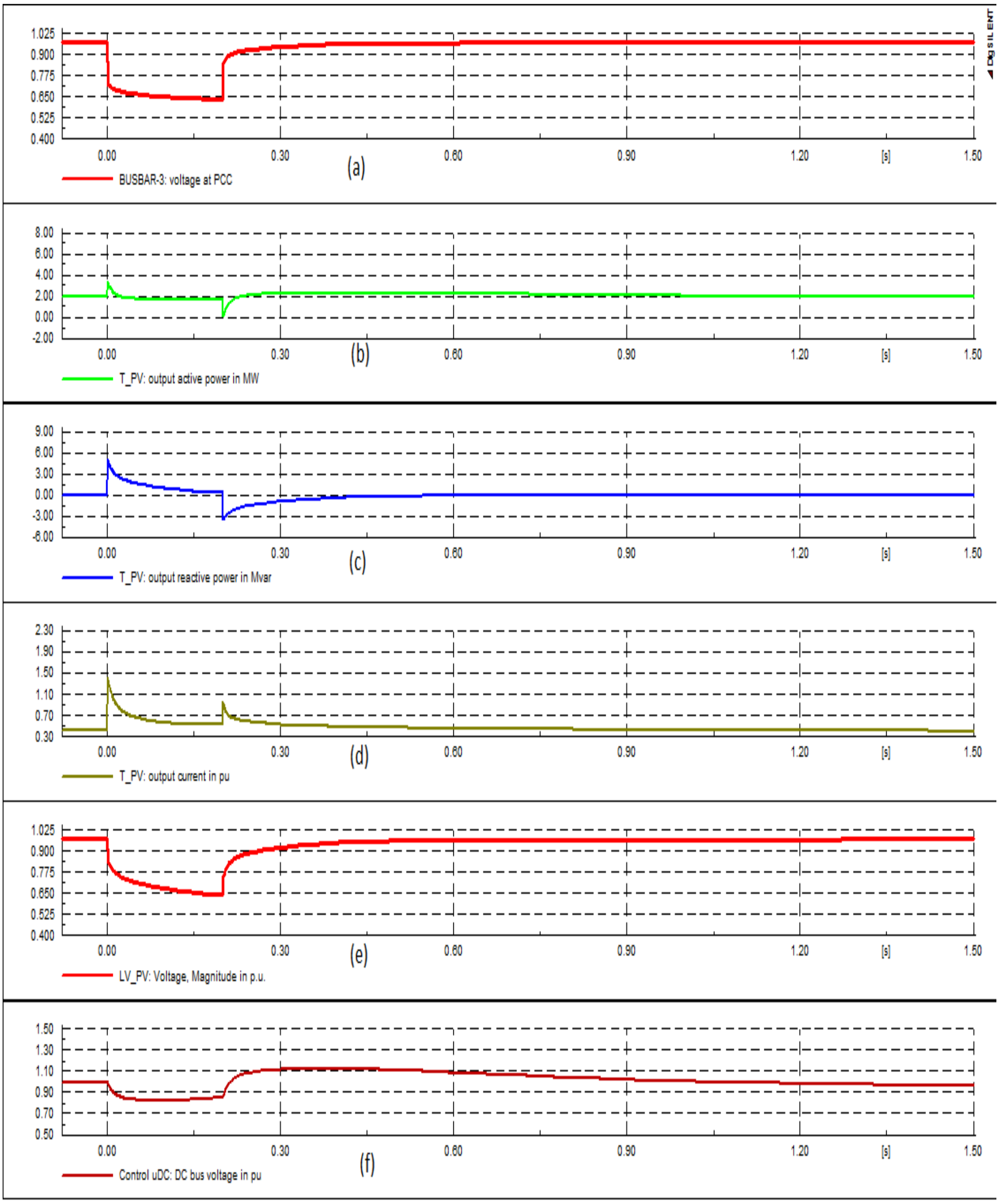

Figure 4.2 Transient results during 3LG fault

Figure 4.2 have following transient curves- (a) voltage of PCC in pu (b) active power output in MW (c) reactive power output in Mvar (d) output current of PV in pu (e) output voltage of PV in pu (f) DC bus voltage in pu. From the curves it is cleared that PV system modelled in digsilent powerfactory can recoverd from three phase fault succesfully.

The instantaneous values of output voltage and current during three phase fault are also shown in Figure 4.3. This curve is plotted using electromagnetic transient (EMT) simulation of powerfactory in Figure.The curves shows the failure free operation.

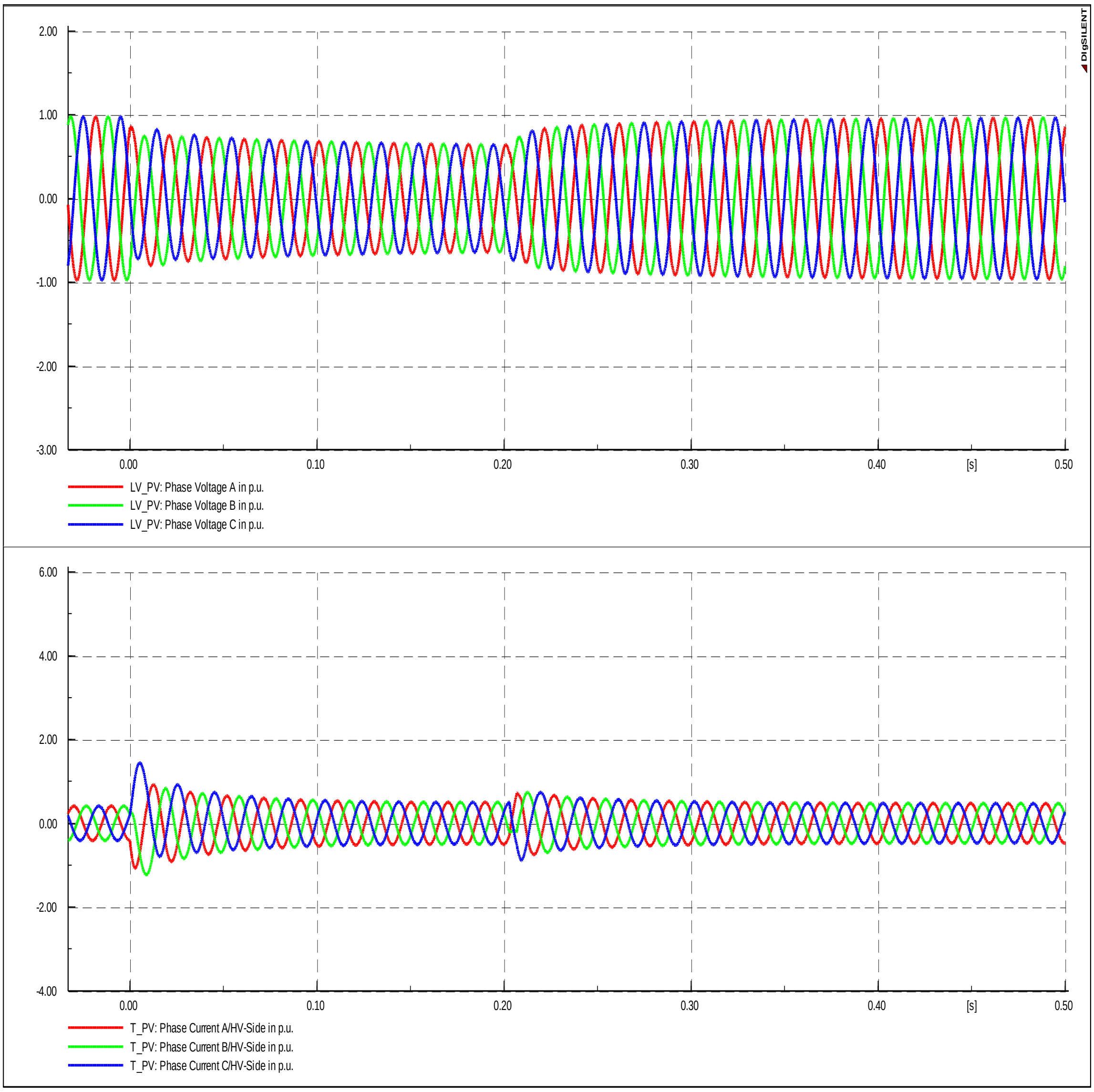

Figure 4.3 Output voltage and current of PV solar farm during 3LG fault

4.2 PV SOLAR FARM AS STATCOM

4.2.1 Voltage Regulation of PCC on Load Changes and Wind Farm Connection

DIgSILENT PowerFactory simulation results for the study system during steady-state and transient conditions are depicted in Figure 4.4. Three different time instant of interest are

(1) When a wind farm of 3 MW output power is connected at bus 4 at time instant 0.1 s

(2) When a wind farm of 12 MW output power is connected at bus 4 at time instant 0.2 s

(3) When load is reduced by 80% at time instant 0.3 s

In steady state condition output at bus 3 (PCC) was 0.96 pu. After time instant (1), (2), (3) it raises to 0.983 pu, 1.038 pu, 1.093 pu respectively which is shown in Figure 4.4 (a) in blue line. When solar farm inverter is controlled as STATCOM, the voltage at PCC regulated to 0.994 pu, 1.014 pu, 1.032 pu respectively shown in Red line in same Figure, which is under permissible limit of +/- 5%.

In Figure 4.4 (b) reactive power compensation provided by PV STATCOM is shown. After time instant (1) when wind farm is attached to system PV STATCOM provides reactive power compensation of 0.530 Mvar to regulate the voltage near to 1 pu. After time instant (2) and (3) reactive power is absorbed by PV STATCOM because voltages are increased above 1 pu due to reverse power flow.

Figure 4.4 (c) shows the active power provided by wind farm at different instants. It shows the wind farm integration to the distribution feeder at time instant 0.1 sec and 0.2 sec.

Figure 4.4 (d) shows the load active and reactive power. It shows that at time instant 0.3 load decreases by 80% to its previous value.

Figure 4.4 (e) shows the DC link voltage regulated by STATCOM which is within the permissible limit.

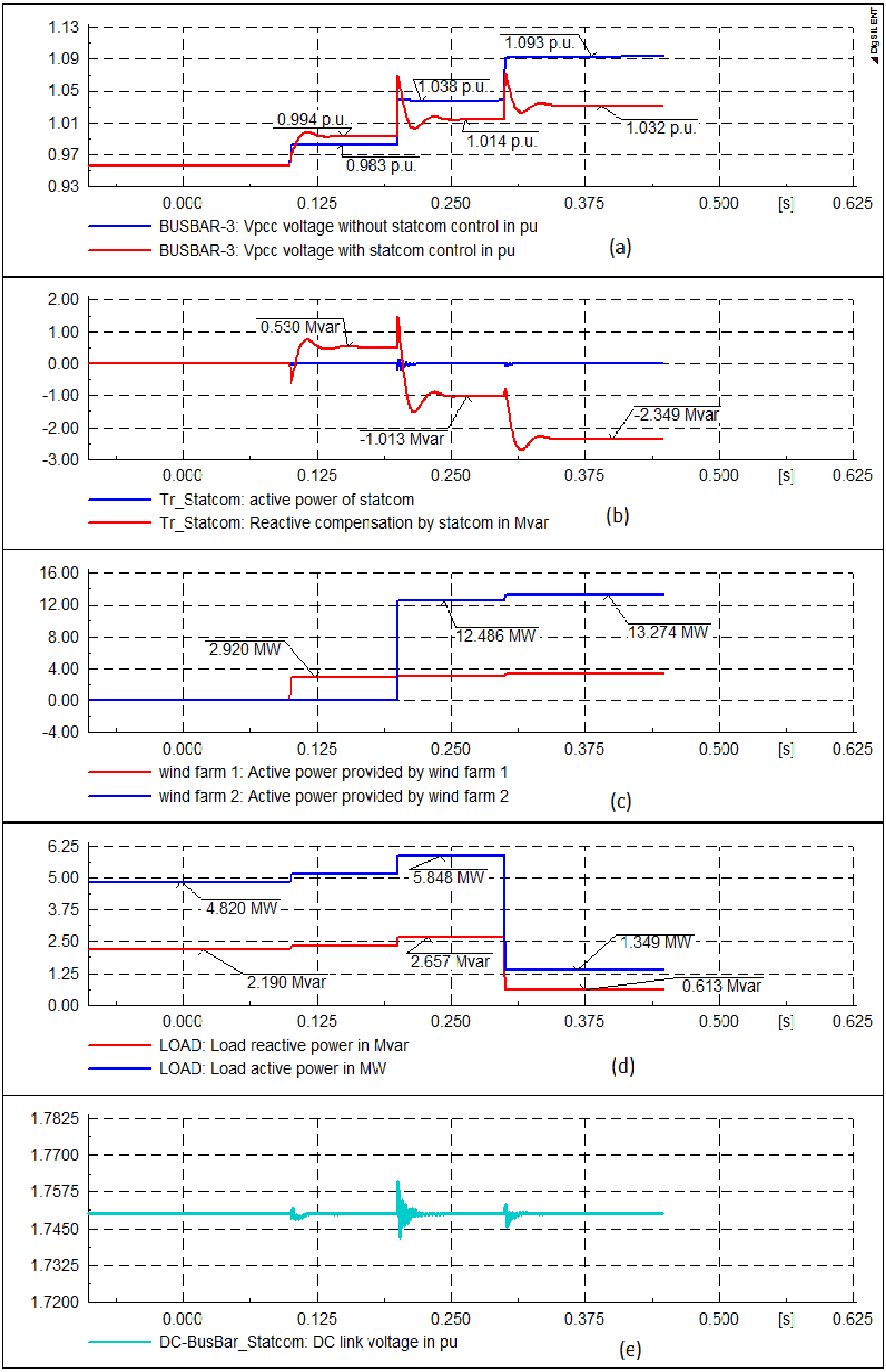

Figure 4.4 Regulation of PCC voltage by statcom control of solar farm

4.2.2 Performance of System When a Wind Farm Is Integrated at Different Bus

The effect of wind farm integration of 20 MW capacity at different bus is shown in Figure 4.5. Wind farm is integrated at time instant 0.1 sec while STATCOM control is provided at time instant 0.2 sec. In Figure 4.5(a) comparison of voltage at PCC done when PCC voltage is regulated by PV STATCOM. Figure shows comparison of reactive power support provided by STATCOM. Here in figure Red, Green and Blue line represents three cases respectively as following

(1) When wind farm is connected on load bus
(2) When wind farm is connected on bus bar - 4
(3) When wind farm is connected on bus bar - 3 (PCC)

When wind farm is connected, feeder voltages rise instantaneously. When statcom compensation is provided voltage regulated near 1 pu within 0.05 second.

From Figure 4.5 it can be observed that when wind farm is connected on bus bar – 3, distribution feeder required more reactive power compensation to regulate the voltage of PCC. It happened because the point at which DG is connected get more voltage rise compared to others. When wind farm is connected to Load bus then feeder requires minimum reactive power to regulate PCC voltage.

Here figure 4.5(a) shows voltage magnitude at PCC and Figure 4.5(b) shows reactive power compensation provided by PV STATCOM.

In figure 4.5(b) blue line shows Active power exchange between PV STATCOM and grid. It fluctuates slightly at the time of switching and comes to steady state value of zero.

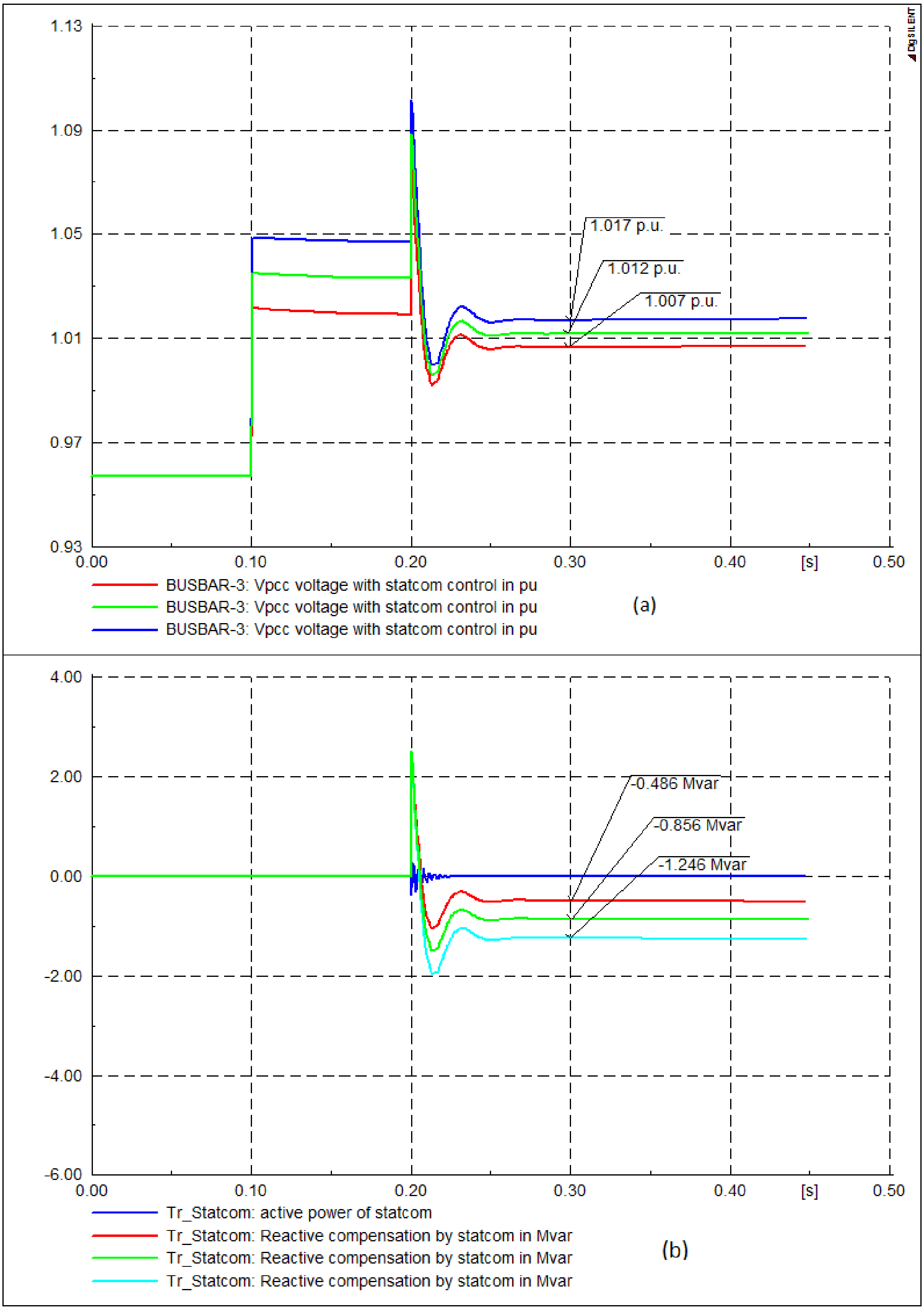

Figure 4.5 Comparison of wind farm integration at different location

4.2.3 Effect of Solar Farm Integration at Different Location

When solar farm is connected at different location, the compensation provided by PV STATCOM also changes. A three phase fault with 5 ohm reactance is simulated at time instant 0.1 sec at Load bus. The fault is cleared at time instant 0.2 sec. When fault occurred bus voltages decreases rapidly. By using FACTS controller we can improve these voltage profiles. The load bus voltage is shown in Figure 4.6 (a). The reactive power compensation provided by the statcom is shown in Figure 4.6 (b).

The three cases which are simulated are as following

(1) When solar farm is located on fault bus
(2) When solar farm is located 10 km away from the fault bus
(3) When solar farm is located 20 km away from the fault bus

When solar farm is located 20 km away from the fault bus it has less impact on system voltage during fault duration. As we decrease the distance between solar farm and fault bus the voltage improves. So at fault bus we get maximum voltage as compared to any other case during fault.

So From Figure 4.6 it is clear that when PV STATCOM is connected at load bus it gives the better fault recovery compare to other two cases so we can say that PV STATCOM gives better fault recovery and good reactive power compensation when it is connected on faulty bus.

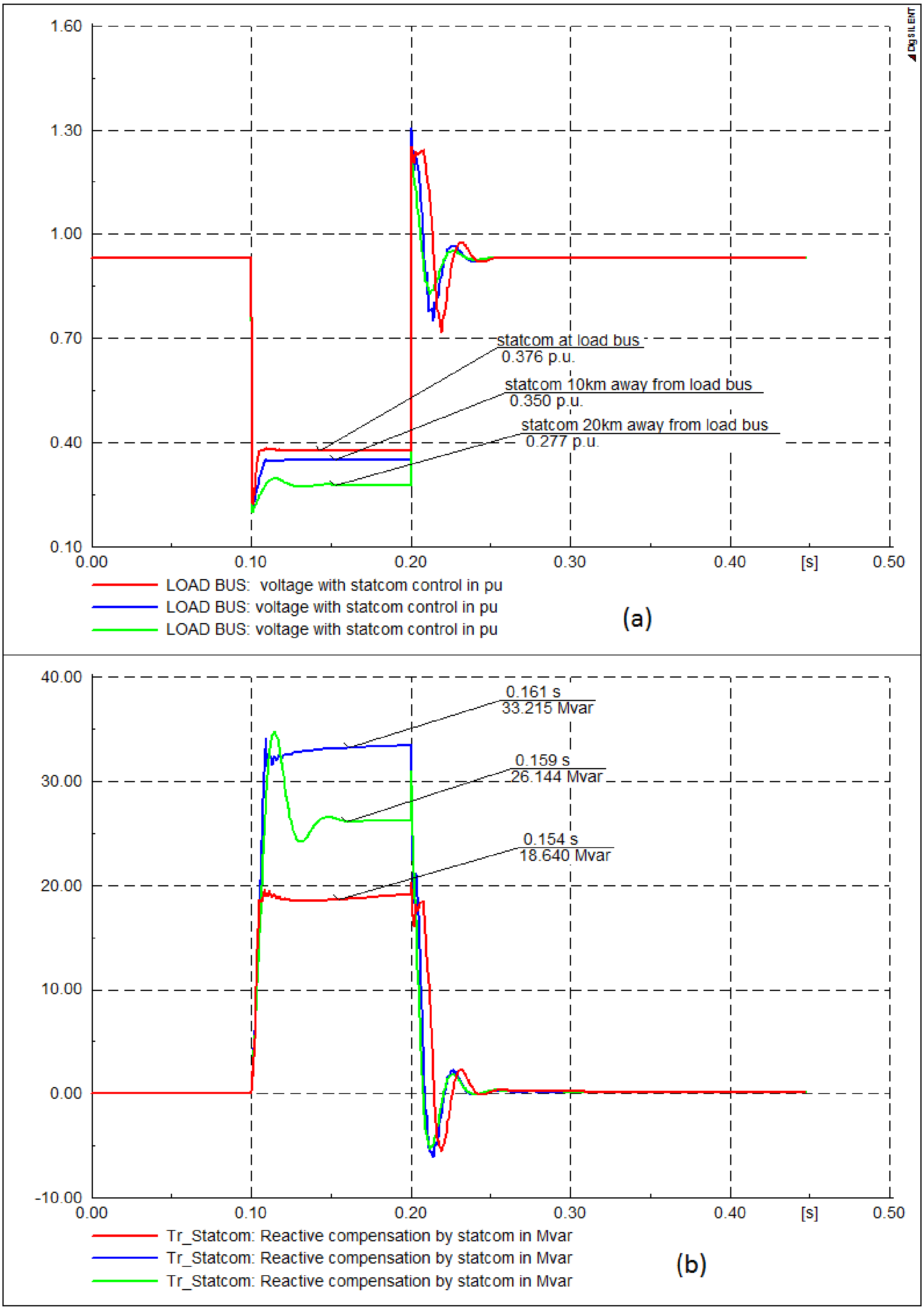

Figure 4.6 Comparison of statcom performance when connected to different location

4.2.4 Performance of System under 3LG Fault Condition at Different Inverter Rating

In this section the regulation provided by the PV STATCOM for different MVA rating of inverter is discussed. The simulation is performed for a 3LG fault occurred at load bus for 0.1 sec. the fault occurred at time instant 0.0 sec and cleared at 0.1 sec. simulation are performed using Electromechanical transient stability simulation (RMS values).

When fault occurs, voltages of feeder decreases. The dynamic compensation provided by the PV STATCOM improves the voltage profile. When fault is cleared a voltage peak is generated for an instant due to high reactive power compensation at that instant.

Figure 4.7 gives the transient performance of PV STATCOM during 3LG fault. Figure 4.7(a) gives the load bus voltage profile during fault recovery. Figure 4.7 (b) gives voltage profile of PCC. Figure 4.7 (c) shows the dynamic reactive power compensation provided by the statcom. Figure 4.7 (d) shows the dc link voltage regulation during fault recovery. We can see that the dc link voltage is constant throughout the simulation except some fluctuation at the instant of fault occurring and clearing

Similarly Figure 4.8 and 4.9 gives the same study for the 10 MVA and 16 MVA inverter respectively. The above observations can also be noted for these scenarios when inverter ratings are double and triple to the above discussed 5 MVA rating inverter.

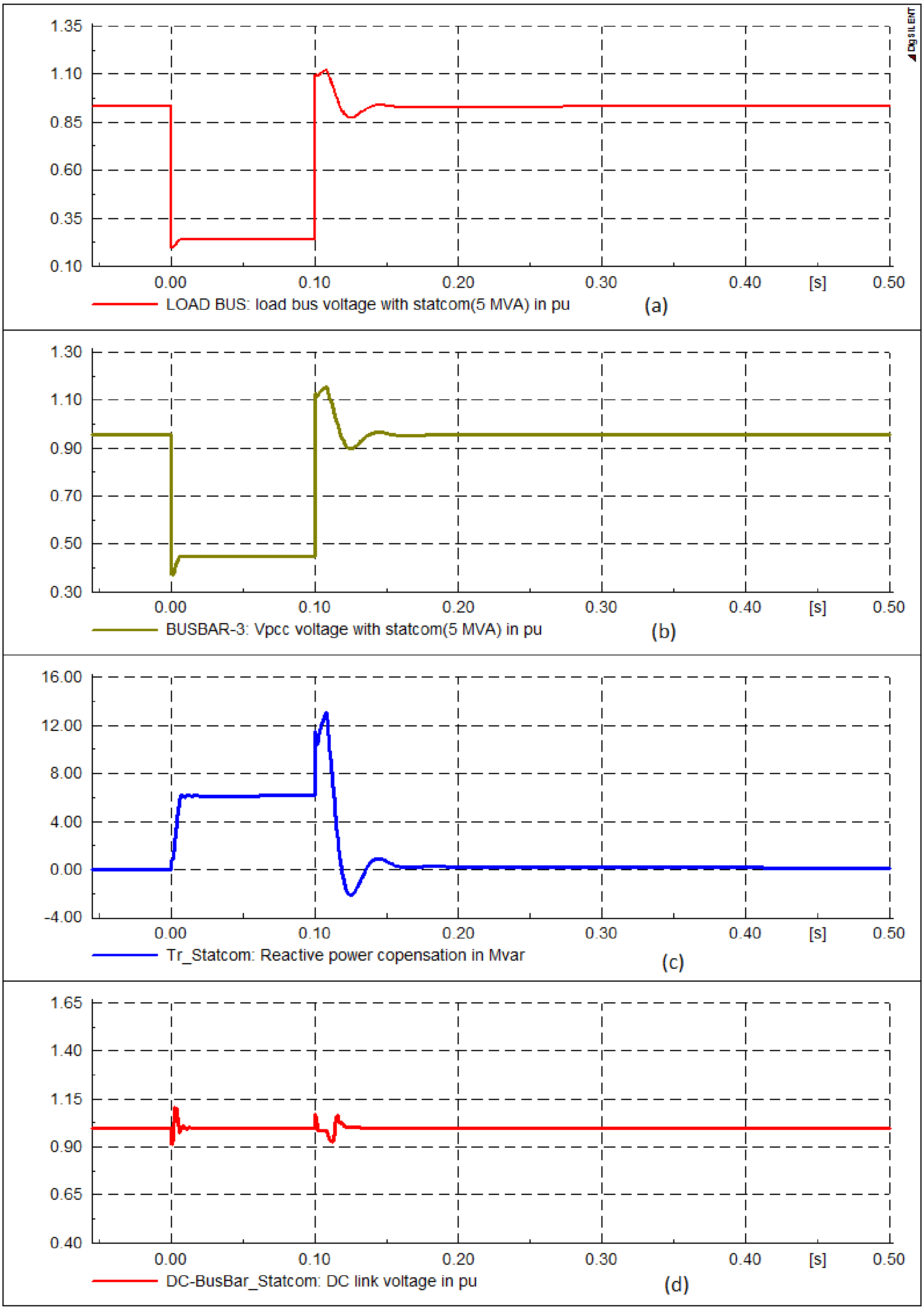

Figure 4.7 Transient performance during 3LG fault for 5 MVA inverter

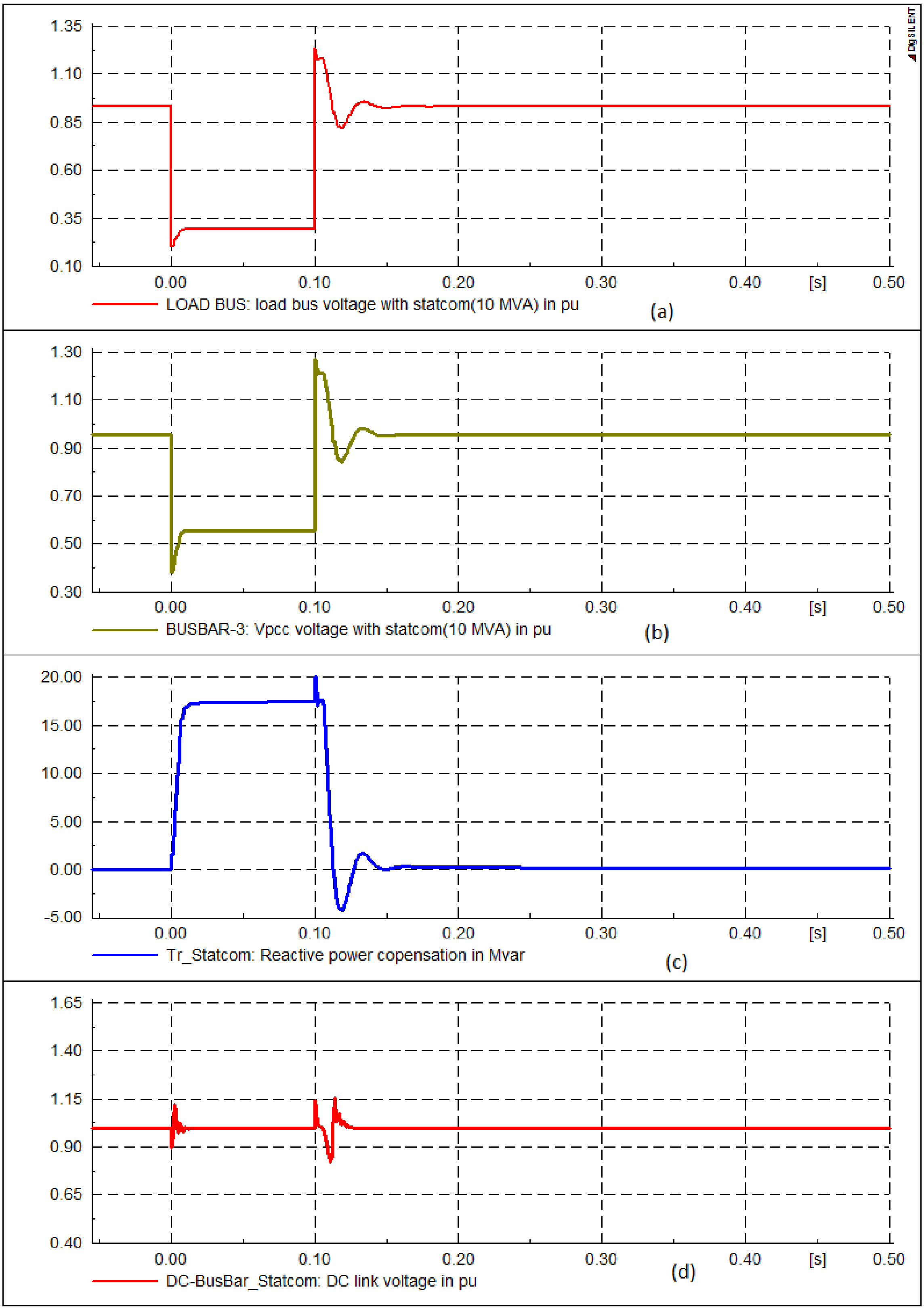

Figure 4.8 Transient performance during 3LG fault for 10 MVA inverter

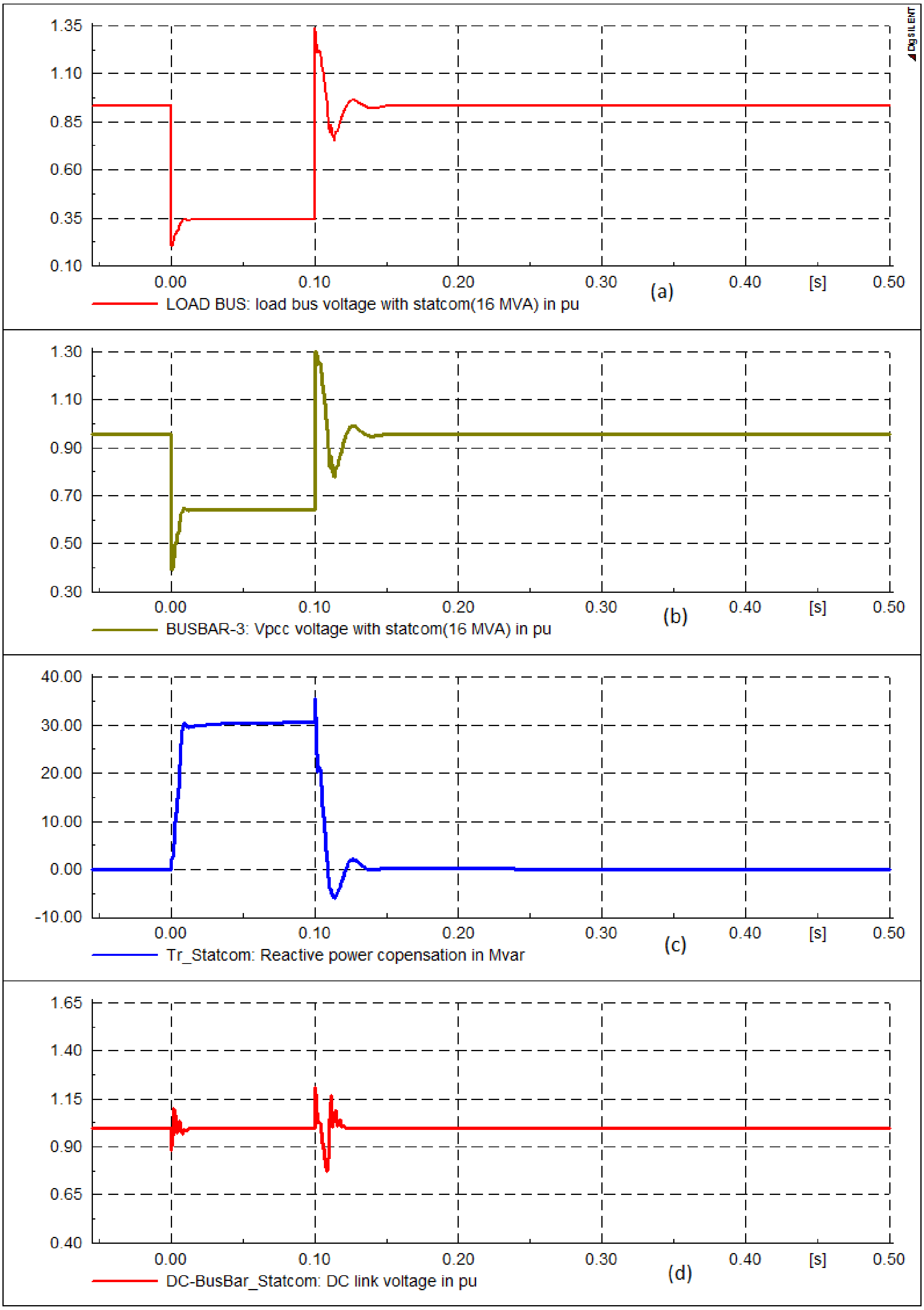

Figure 4.9 Transient performance during 3LG fault for 16 MVA inverter

The transient performance during 3LG fault are compared for three different cases as following

(1) When inverter rating is 5 MVA
(2) When inverter rating is 10 MVA
(3) When inverter rating is 16 MVA

These three cases are compared with the case when there is no STATCOM control of solar farm.

Figure 4.10(a) shows PCC voltage

Figure 4.10(b) shows Load bus voltage

Green line shows the case when there is no STATCOM control of solar farm. Brown line shows the statcom control with 5 MVA rating. Blue line gives the recovery curve for 10 MVA inverter rating and red line gives the statcom control with 16 MVA rating.

From Figure 4.10 it can be observed that as we increases the inverter rating the performance of statcom increases. The voltage level at PCC increases significantly. But there is a limitation of increment of statcom rating as we can see that during fault recovery instant the voltage rises as we increases the inverter rating.

When we increases MVA rating of inverter the reactive power compensation provided by the statcom also increases it is shown in Figure 4.11

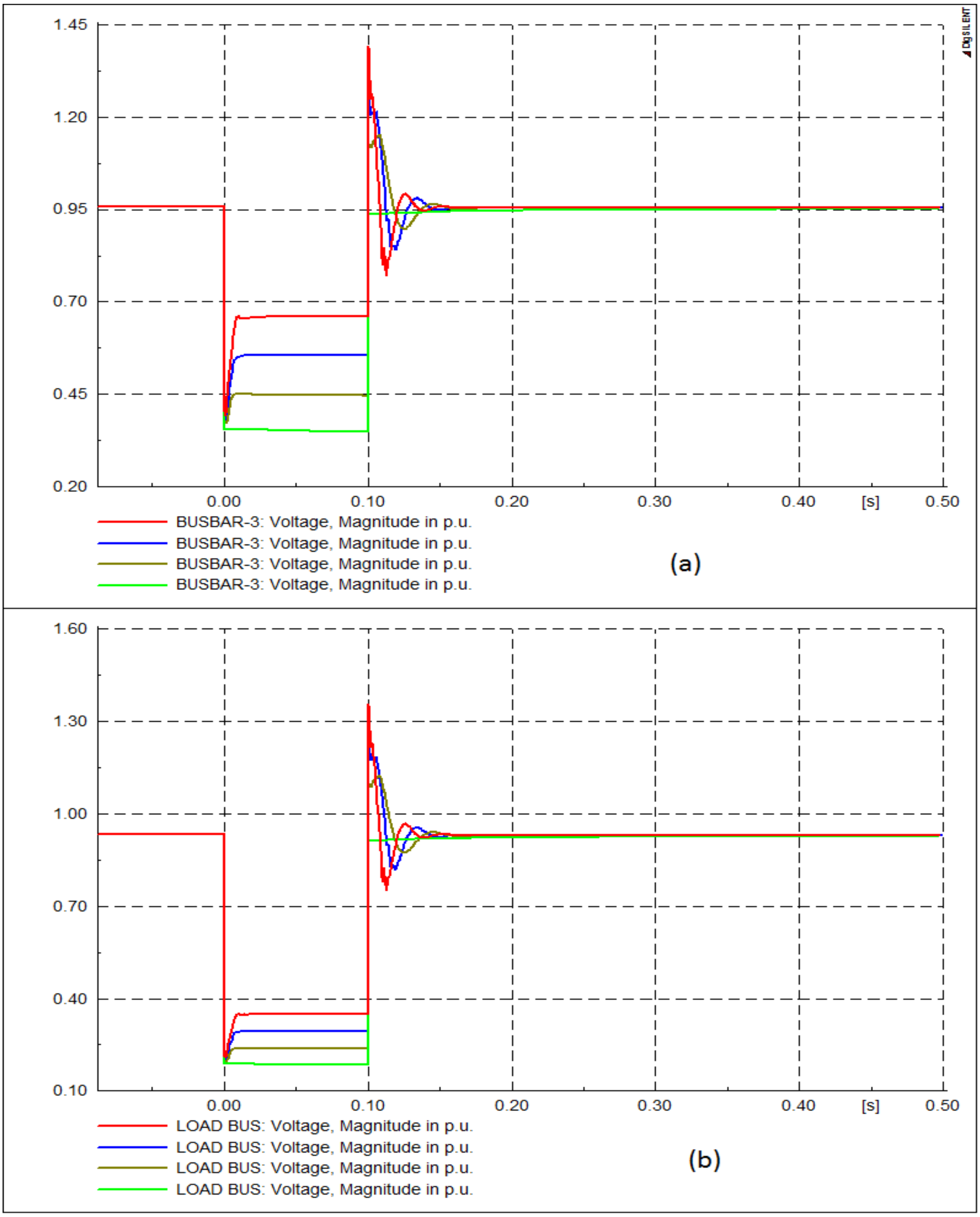

Figure 4.10 Comparison of transient performance during 3LG fault for different inverter rating

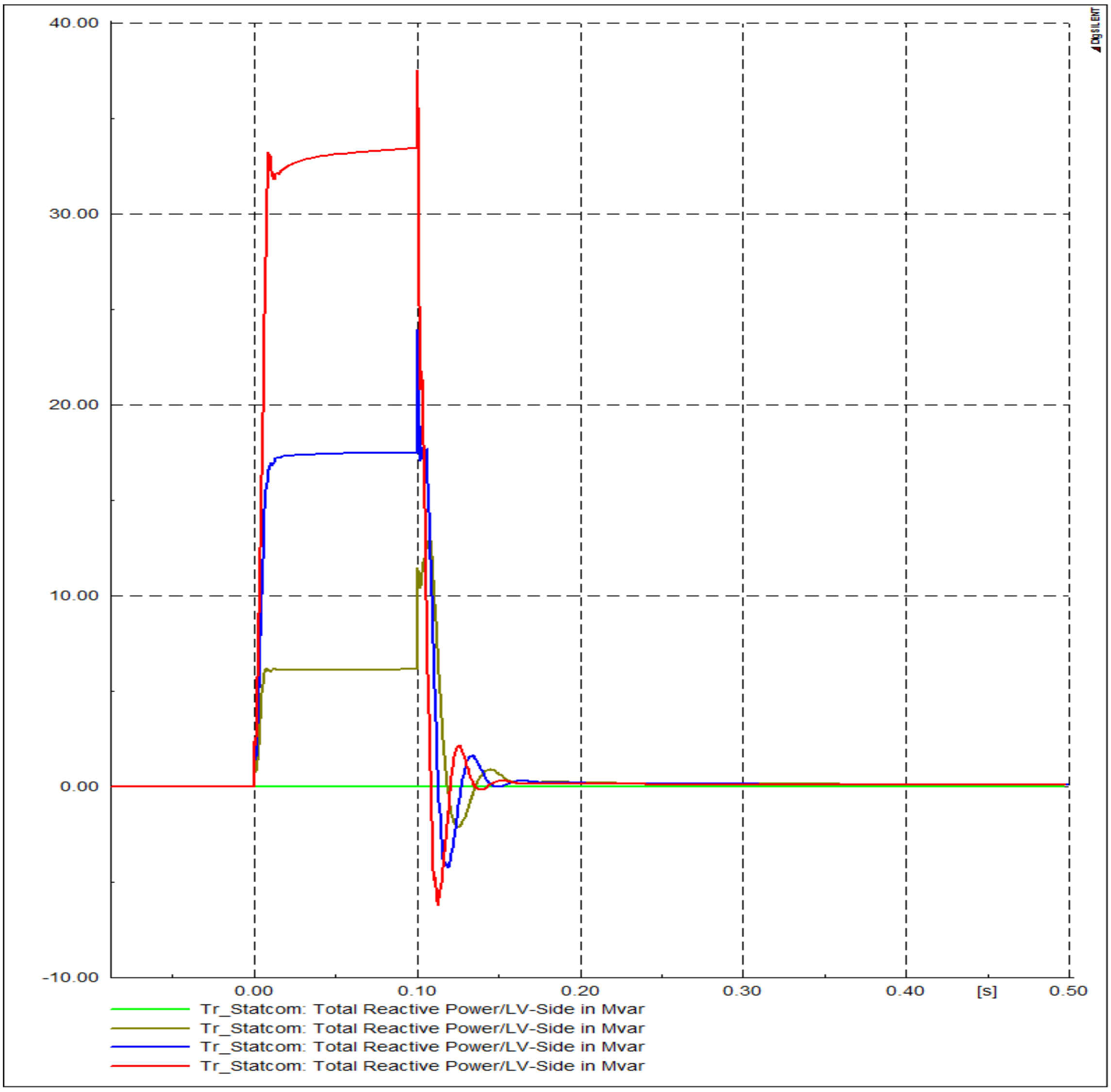

Figure 4.11 Reactive power compensation provided by statcom for different MVA ratings

CHAPTER 5

CONCLUSION & FUTURE WORK

CONCLUSION

In this thesis the Solar Farm inverter is used to regulate the distribution feeder voltage at PCC and Load bus. In previous chapter we observed that using this control strategy we can regulate voltages within pre-specified limits during wide variations in Wind Farm output and loads. Therefore this control strategy of PV Solar Farm control will provide integration of more solar and wind farm like DGs in the system without the need of additional voltage regulating devices. According to this control strategy PV solar plant is used as DG during the day [providing Active power (MW)] and as STATCOM during night [providing Reactive power (Mvars)]. It can also be concluded that this control strategy provides better fault recovery during 3LG fault and it will give best performance during fault when it is situated near the faulty bus.

FUTURE WORK

Some of the studies that can be done in future research are given as follows

(1) Wind farm inverter can also be used as STATCOM for voltage regulation.
(2) The application of PV STATCOM for harmonic reduction and system stability may also be studied.
(3) The study of this type of control can also be done for ring main feeder.
(4) The application of PV STATCOM to increase power transfer limit of transmission line can also be studied.

APPENDIX

(1) Three Phase Distribution Feeder Parameters (π-section)
336AL427 Overhead Line

$R1$= 0.1691 Ω/*km*
$X1$= 0.4182 Ω /*km*
$R0$ =0.4441 Ω /*km*
$X0$ =1.1899 Ω /*km*
$B1$ =3.954x10^{-6} mho/*km*
$B0$= 0.0
Ampacity (Thermal Capacity) =665.0 *Amp*(32 *MVA* @ 27.6 *kV*)

(2) Supply Station Transformer (Y-Y Connected)
3-Phase, 2-Winding Transformer

S= 32.0 *MVA*
V_1 / V_2= 115.0 / 27.6 *kV*
R= 0.0
X= 0.05 *pu*

(3)PV Solar Farm

Transformer (delta-star connected)
S= 25.0 *MVA*
$V1 / V2$= 0.4 / 27.6 *kV*
R= 0.0
X= 0.05 *pu*

PWM Converter
AC side V_{LL}= *0.4 kV*
DC side V_{DC} = *0.7 kV*

DC bus Capacitor

C=10 mF

REFRENCES

[1] *Global Wind Report 2015*, Global Wind Energy Council (GWEC), available at http://www.gwec.net.

[2] *Renewable Energy Statistics 2016*, International Renewable Energy Agency (IRENA), available at http://www.irena.org

[3] E. J. Coster, J. M. Myrzik, B. Kruimer, and W. L. Kling, "Integration Issues of Distributed Generation in Distribution Grids," *Proceedings of the IEEE*, vol. 99,no. 1, pp. 28 – 39, Jan. 2011.

[4] C. L. Masters, "Voltage rise: the big issue when connecting embedded generation to long 11 kV overhead lines," *Power Engineering Journal*, vol. 16, no. 1, pp. 5 –12, Feb. 2002

[5] *Distributed generation technical interconnection requirements: interconnections at voltages 50 kV and below,* Hydro One Networks Ltd., DT-10-015 R2, June 2011

[6] B. Fox, D. Flynn, L. Bryans, N. Jenkins, D. Milborrow, M. O'Malley, R. Watson, and O. Anaya-Lara, Wind Power integration, Connection and System Operational Aspects, vol. 50, 1st ed. London, U.K.: IET, 2007, ser. Power & Energy.

[7] N. Jenkins, R. Allen, P. Crossley, D. Kirchen, and G. Strbac, Embedded Generation,vol. 31, 1st ed. London, U.K.: IET, 2000.

[8] T. Ackermann and V. Knyazkin, BInteraction of distributed generation and the distribution network: Operation aspects,[in Proc. PES T&D Conf., Asia Pacific, 2002, vol. 2, pp. 1357–1362.

[9] J. H. R. Enslin and P. J. M. Heskes, BHarmonic interaction between large numbers of Photovoltaic inverters and the distribution network,[IEEE Trans. Power Electron., vol. 19, no. 6, pp. 1586–1593, Nov. 2004 ser. Power & Energy.

[10] F. M. Gatta, A. Geri, S. Lauria, and M. Maccioni, "Analytical prediction of abnormal temporary overvoltages due to ground faults in MV networks," *Electric Power Systems Research*, vol. 77, no. 10, pp. 1305 – 1313, Sep. 2006.

[11] A. Cerretti, F. M. Gatta, A. Geri, S. Lauria, M. Maccioni, and G. Valtorta, "Ground fault temporary overvoltages in MV networks: Evaluation and experimental tests,"*IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1592-1600, Jul. 2012.

[12] *IEEEStd1313.1-1996, IEEE Standard for Insulation Coordination Definitions, Principles and Rules*, Technical Council of the IEEE Power Engineering Society,IEEE Standards Board, July 1996.

[13] K. Kauhaniemi and L. Kumpulainen, BImpact of distributed generation on the protection of distribution networks,[in Proc. 8th IEE Conf. Develop. Power Syst. Protection, 2004, pp. 315–318.

[14] L. K. Kumpulainen and K. T. Kauhaniemi, Analysis of the impact of distributed generation on automatic reclosing,[in Proc. IEEE Power Eng. Soc. Power Syst. Conf. Exhib., 2004, pp. 603–608.

[15] Farid Katiraei, Chad Abbey, and Richard Bahry, "Analysis of Voltage Regulation Problem for a 25-kV Distribution Network with Distributed Generation", *IEEE Power Engineering Society Summer Meeting*, pp. 1 – 8, 16 October 2006.

[16] Joon-Ho Choi, and Jae-Chul Kim, "Advanced voltage regulation method at the power distribution systems interconnected with dispersed storage and generation systems," *IEEE Transactions on Power Delivery*, vol. 15, no. 2, pp. 691 – 696,April 2000.

[17] R. M. Mathur and R. K. Varma, *Thyristor-based FACTS Controllers for Electrical Transmission Systems*, IEEE Power Engineering Society, IEEE Press, Piscataway,NJ, 2002.

[18] N. G. Hingorani and Laszlo Gyugyi, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*, IEEE Power Engineering Society, IEEE Press, Piscataway, NJ, 1999.

[19] S. A. Rahman, Rajiv K. Varma, and Wayne H. Litzenberger. "Bibliography of FACTS applications for grid integration of wind and PV solar power systems: 1995–2010 IEEE working group report." *Power and Energy Society General Meeting, 2011 IEEE*. IEEE, 2011.

[20] N.A. Lahaçani, D. Aouzellag, and B. Mendil, "Contribution to the improvement of voltage profile in electrical network with wind generator using SVC device,"*Renewable Energy*, vol. 35, no. 1, pp. 243-248, January 2010.

[21] I. Papic, "Power quality improvement using distribution static compensator withenergy storage system," *Harmonics and Quality of Power, 2000. Proceedings.Ninth International Conference on*, vol. 3, pp. 916 – 920, 2000.

[22] C. Han, Alex Q. Huang, Mesut E. Baran, S. Bhattacharya, W. Litzenberger, L.Anderson, A. L. Johnson, and Abdel-Aty Edris, "STATCOM impact study on the integration of a large wind farm into a weak loop power system," *IEEE Trans. On Energy Conversion*, vol. 23, no. 1, pp. 226 – 233, Mar. 2008.

[23] Kalyan K. Sen,"STATCOM - static synchronous compensator: theory, modeling, and applications," *IEEE Engineering Society, Winter Meeting*, vol. 2, pp. 1177 – 1183, 1999.

[24] P. Rao, M. L. Crow, and Z. Yang, “STATCOM control for power system voltage control applications,” *IEEE Transactions on Power Delivery*, vol. *15,* no. 4, pp. 1311 – 1317, Oct. 2000.

[25] P. Garica-Gonzalez, and A. Garcia-Cerrada, “Control system for a PWM-based STATCOM,” *IEEE Transactions on Power Delivery*, vol. 15, no. 4, pp. 1252 –1257, Nov. 2000.

[26] R.K. Varma, S.A. Rahman, Mahendra A. C. , R. Seethapathy, and T. Vanderheide, "Novel nighttime application of PV solar farms as STATCOM (PV-STATCOM),"*IEEE Power and Energy Society General Meeting*, pp. 1 – 8, 22-26 July 2012.

[27] R. K. Varma, V. Khadkikar, and R. Seethapathy, “Nighttime application of PV solar farm as STATCOM to regulate grid voltage,” *IEEE Trans. on Energy Conversion*, vol. 24, no. 4, pp. 983 – 985, Dec. 2009.