Chapter 8
Harmonic Reduction Techniques in Renewable Energy Systems

Learning Objectives
On completion of this chapter, the reader will have knowledge on:

- Basic concepts of harmonics and power quality issues.
- Reactive power compensation using custom power devices such as DSTATCOM, DVR and UPQC.
- Power quality problems and standards associated with power quality issues.
- Procedure for measurement of power quality in PV system.
- Harmonic reduction in Wind Energy Conversion Systems with power quality issues and a case study.

8.1 Introduction

During recent years, power system harmonics is a vital area which is seeking a great deal of attention. The reason behind this is mainly due to the non-linear (or maybe harmonic causing) loads. These loads consistently increase a portion on the total load for the typical industrial place. Such kind of an increase in load has provoked more strict recommendations in the IEEE Std. 519 and strict limits imposed by utilities. Incidence of harmonic related complications is low, merely awareness of harmonic issues cannot help to increase the reliability of power systems. The harmonics causes problems on occasions either due to the power system resonance or due to the magnitude of the harmonics produced.

Harmonics can be defined as a mathematical representation of distortion in a voltage or current waveform. More precisely, the term harmonic refers to a section of a waveform that occurs at an integer multiples of the fundamental frequency. Based on Fourier analysis, it is noted that any repetitive waveform can be represented as summing sinusoidal waves which in turn are integer multiples of

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the fundamental frequency. The Fourier series of a steady state waveform with equal positive and negative half-cycles can be represented according to Eq. 8.1,

$$f(t) = \sum_{n=1}^{\infty} A_n \sin\left(n \prod t/T\right) \quad (8.1)$$

where

f(t) is the time domain function.
n is the harmonic number (only odd values of n are required)
A_n is the amplitude of the nth harmonic component
T is the length of one cycle in seconds

In general harmonics should not be mistaken with spikes, dips, impulses, oscillations or other forms of transients. The important feature to be understood while dealing with harmonics is that harmonics are steady state event and they are repetitive in every cycle of 50 Hz. The terms Total Harmonic Distortion (THD) used in close relation with the harmonic theory is used to compute the voltage or current distortion according to Eq. 8.2,

$$THD(\%) = \sqrt{ID_1^2 + ID_2^2 + \ldots\ldots + ID_n^2} \quad (8.2)$$

where ID_n is the magnitude of the nth harmonic as a percentage of the fundamental.

Harmonics are mainly produced due to non-linear loads. The non-linear loads draw non-sinusoidal current from a sinusoidal voltage source. Loads such as electric arc furnaces, static VAR compensators, inverters, DC converters, switch-mode power supplies, and AC or DC motor drives are examples that cause harmonics. While using a motor drive, the AC current at the input to the rectifier looks more like a square wave than a sine wave as shown in Fig. 8.1.

Though power system problems based on harmonics are occasional, it is quite possible for a number of undesirable effects to occur. High degrees of harmonic distortion can cause effects as increased transformer heating, capacitor heating, motor or generator heating, malfunctioning of electronic equipment, error readings on meters, malfunctioning of protective relays, interference with telephone circuits, etc. The likelihood of such harmful effects occurring is greatly increased if the resonant condition occurs. Resonance occurs if a harmonic frequency produced by a non-linear load closely coincides using a grid natural frequency.

Power Quality (PQ) issues are of vital concern in most industries today because of the increased usage of sensitive and critical equipments such as communication networks, process industries, precise manufacturing processes and non-linear variable frequency drives. Power quality measurement and assessment was done as a case study on different solar PV generation systems such as 100, 80, and 60 kW located at PSG College of Technology. The analysis was carried out with the help of FLUKE 434 series II Energy analyzer reported as class-S meter according to IEC/IEEE standards. It was observed from the case study that power quality

Fig. 8.1 Rectifier output

problems such as reactive power, 10 % sag/swell for duration of ≤1,000 μs, and 4 % of VTHD, 10 % ITHD in which 3rd, 5th and 7th harmonics are dominating and existing in system when connected to the load. To compensate these power quality problems, technologies like custom power devices have emerged. These are series-connected compensators known as Dynamic Voltage Restorer (DVR), shunt connected compensators such as Distribution STATic COMpensator (DSTATCOM) and a combination of series and shunt connected compensators known as Unified Power Quality Conditioner (UPQC).

In this chapter, the techniques for correcting the supply voltage sag/swell, harmonics and reactive power compensation in a distribution system by custom power devices such as DSTATCOM, DVR and UPQC are discussed. The custom power devices meet the power quality standards such as IEEE 519-1992 and IEC 61000-3-2/IEC 61000-3-4. A phase shift controlled voltage source converter based DSTATCOM has been implemented in the MATLAB/SIMULINK R2011a environment. DVR modeling, analysis and simulation has been done in MATLAB/SIMULINK environment to regulate voltage sag/swell, harmonics in supply voltage. The UPQC system is modeled using the elements of SIMULINK and it is simulated using MATLAB.

8.2 Power Quality Issues

Power quality issues are of vital concern generally in most industries today, due to surge in the quantity of loads sensitive to power disturbances. The electricity quality is usually an index to quality of current and voltage offered to industrial, commercial and household consumers of electricity. The condition regards both utilities and customers. With the utilities, to offer adequate power quality is really a moving objective because of changes in user equipment as well as. For consumers, problems stemming on the sensitivity of electrical equipment to voltage quality have often very heavy consequences.

Power quality is usually a topic embracing a substantial field. On one side, several different events are going to complete power quality: spikes or surges, sags, swells, outages, under or higher voltages, harmonics, flicker, frequency deviations, and electrical noise. Accordingly, different measurements and analysis tools must investigate such phenomena, and various remedial actions could be adopted to pay them or reduce their effects. On the other side, many electronic devices (such as computers, process controls, adjustable speed drives, solid-state-relays, optical devices, to name a few) are sensitive to another touch power quality. Since a certain event may not be a serious issue for any given customer class, nevertheless it may represent a big problem for another class, it offers doubtful practical sense to rank the above mentioned events when it comes to importance without talking about an increasingly specific context. As far as industrial and commercial customers are involved, several recent studies acknowledge the statement that voltage sags has to be regarded as the most important concerns in power quality. This statement is especially true for producers, where even short duration voltage sags will often be accountable for a lot more long-lasting production downtimes and consequent large lost revenue. It is difficult to place a value about the impact of power quality problems, but it's reliable advice that unscheduled shutdowns could cost of countless rupees. Combined with tangible expense of lost production time (and therefore sales), wasted raw materials and damaged equipment, in addition there are indirect costs, for instance damaged to customer confidence brought on by missed delivery schedules.

Many times a custom power device offers probably the most economical solution by establishing the proper power quality level that is needed through the customer. Often this type of device would negate the necessity for the utility to set up additional feeders or substations or customer to run individual power conditioners on the load level. IEEE Standard 1100-1992 (IEEE Emerald Book) defines sag as "an rms cut in the AC voltage, with the power frequency, for durations from a half-cycle to some seconds". Note: The IEC terminology for sag is dip. They usually are followed by phase jumps. When the voltage is reduced to zero, the disturbance is said to be a momentary outage or micro interruption. Eat way to characterize a voltage sag was in the reduced voltage rms, duration and in all probability accompanied phase jump. The European Standard (EN50160-1994) defines adequately regarding the sags and it is indicative values; Voltage dips (sags) usually are due to faults occurring within the customers' installations on in the public distribution system. They're unpredictable, largely random events. The annular frequency varies depending on the sort of the provision systems additionally, on the point of observation. Moreover, the distribution over the year can be extremely irregular.

Voltage sags are sometimes generated by starting of large loads, like motors, transformer energizing, equipment faults, transmission and distribution system faults. Faults for the distribution and transmission systems can be due to numerous sources like lightning strikes, conductors blowing together within a storm, experience of objects (e.g. tree branches, animals) or vandalism. These faults (70–80 %) are temporary as the name indicated; they're self-clearing in a few milliseconds. The fault which does not clear will result in a protective device/s (e.g. fuse, breaker, or recloser) to use it to get rid of current area of the system within the affected region.

8.3 Sources and Effects of Power Quality Problems

Power distribution systems, ideally, must provide their clients by having an uninterrupted flow of smooth sinusoidal voltage in the contracted magnitude level and frequency However, in practice, power systems, specially the distribution systems, have numerous nonlinear loads, which significantly affect the standard of power supplies. Caused by the nonlinear loads, the purity in the waveform of supplies is lost. This ultimately ends up producing many power quality problems.

While power disturbances occur on all electrical systems, the sensitivity nowdays sophisticated gadgets brings about weaker on the quality of power supply. For most sensitive devices, a momentary disturbance can cause scrambled data, interrupted communications, a frozen mouse, system crashes and equipment failure etc. An electric voltage spike damages valuable components. Power quality problems encompass a variety of disturbances such as voltage sags/swells, flicker, harmonics distortion, impulse transient, and interruptions, plus the definitions are listed below:

- Voltage dip: The short-term decrease in voltage of less than half a second is known as voltage dip.
- Voltage sag: The amplitudes of voltage sags occurring at any instant of time ranges from 10 % to 90 % and lasts for half a cycle to one minute.
- Voltage swell: An increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min is known as voltage swell.
- Voltage 'spikes', 'impulses' or 'surges': These are terms used to describe abrupt, very brief increases in voltage value.
- Voltage transients: They are temporary, undesirable voltages that appear on the power supply line. Transients are high over-voltage disturbances (up to 20 KV) that last for a very short time.
- Harmonics: The fundamental frequency of the AC electric power distribution system is 50 Hz. A harmonic frequency is any sinusoidal frequency, which is a multiple of the fundamental frequency. Harmonic frequencies can be even or odd multiples of the sinusoidal fundamental frequency.
- Flicker: Visual irritation and introduction of many harmonic components in the supply power and their associated ill effects.

Causes of Dips, Swell, Harmonics, Flicker, and Surges

(i) Rural location remote from power source.
(ii) Unbalanced load on a three phase system.
(iii) Switching of heavy loads.
(iv) Long distance from a distribution transformer with interposed loads.
(v) Unreliable grid systems.
(vi) Equipments not suitable for local supply.

Causes of Transients and Spikes

(i) Lightening.
(ii) Arc Welding.
(iii) Switching on reactive equipments such as motors, transformers, Variable Frequency Drives (VFDs).

8.4 Standards Associated with Power Quality

Standards regarding voltage sags are intended to be utilized for reference documents describing single components and systems in a power grid. The manufacturers as well as the buyers are using these standards to fulfill better power quality requirements. Manufacturers develop products meeting the needs of any standard, and buyers demand from your manufactures which the product stick to the standard. The most prevalent standards managing power quality are the types issued by Institute of Electrical and Electronics Engineers (IEEE), International Electro Chemical (IEC), Computer Business Equipment Manufacturing Association (CBEMA) and Semiconductor Equipment and Materials International (SEMI).

8.4.1 IEEE Standards

The Technical Committees in the IEEE societies along with the standards coordinating committees of IEEE standards board develop IEEE standards. The IEEE standards related to voltage sags are given below.

IEEE 446-1995, "IEEE recommended practice for emergency and standby power systems for industrial and commercial applications selection of sensibility loads." The standard discusses the effects of voltage sags on sensitive equipment. The principles and examples regarding how systems should be built to avoid voltage sags as well as other power quality problems when backup system operates.

IEEE 493-1990, "Recommended practice to the design of reliable industrial and commercial power systems." The normal proposes different techniques to predict voltage sag characteristics, magnitude, duration and frequency. You can find mainly three areas of interest for voltage sags. The several areas can be summarized the following:

(i) Calculating voltage sag magnitude by calculating voltage drop at critical load with expertise in the network impedance, fault impedance as well as placement of fault.
(ii) By studying protection equipment and fault clearing time it is achievable to estimate the duration of the voltage sag.
(iii) Dependant on reliable data to the neighborhood and knowledge of the system parameters an estimation of frequency of occurrence can be achieved.

IEEE 1100-1999, "IEEE recommended practice for powering and grounding Electronic equipment." This standard presents different monitoring criteria for voltage sags possesses a chapter explaining the fundamentals of voltage sags. It also explains the setting and putting on the CBEMA and I . t . Industry Council (ITIC) curves. It can be in some parts nearly the same as Std. 1159 but not as specific in defining various kinds of disturbances.

IEEE 1159-1995, "IEEE recommended practice for monitoring electrical energy quality." The aim of this standard is always to describe how you can interpret and monitor electromagnetic phenomena properly. It offers unique definitions for each kind of disturbance.

IEEE 1250-1995, "IEEE guide for service to equipment understanding of momentary voltage disturbances." This standard describes the effect of voltage sags on computers and sensitive equipment using solid-state power conversion. The key purpose would be to help identify potential problems. What's more, it aims to suggest techniques for voltage sag sensitive devices to operate safely during disturbances. It tries to categorize the voltage-related conditions that could be fixed from the utility and the ones that have for being addressed by the user or equipment designer. Second goal is usually to help designers of equipment to higher understand the planet by which their devices will operate. The typical explains different reasons behind sags, lists of examples of sensitive loads, and offers solutions to the problems.

8.4.2 SEMI International Standards

The SEMI international standards program is usually a service made available from Semiconductor Equipment and Materials Overseas (SEMI). Its purpose is always to supply the semiconductor and flat panel display industries with standards and advice to boost productivity and business. SEMI criteria are written documents as specifications, guides, test methods, lingo, and practices. The standards are usually voluntary technical agreements between apparatus manufacturer and end-user.

The actual standards ensure compatibility and interoperability of products and services. Considering voltage sags, two standards address the challenge to the equipment. SEMI F47-0200, "Specs for semiconductor processing equipment current sag immunity." The typical addresses specifications for semiconductor producing equipment voltage sag immunity. That only specifies voltage sags together with duration from 50 ms approximately 1 s. It is usually limited by phase-to-phase and cycle-to-neutral voltage incidents, in addition to presents a voltage-duration graph, "Test method for semiconductor processing equipment voltage drop immunity."

This standard defines the test methodology employed to determine the susceptibility of semiconductor processing equipment and ways to qualify it from the specifications. It further describes test apparatus, test set-up, analyze procedure to look for the susceptibility of semiconductor processing equipment, and ultimately tips on how to report the results.

8.5 Measurement of Power Quality in Solar PV Systems

This section provides a discussion about the system under study, various measurement procedure involved in power quality monitoring, and PQ assessment techniques used in this work. The results of the case study performed on the system are given in Appendix IV. The power quality studies on different solar Photovoltaic (PV) systems have been done using FLUKE power analyzer referred in Appendix IV. Case Study-I: The case study done in 100 kW Solar PV system at PSG College of Technology K-block referred in Appendix IV. Case Study-II: The case study done in 100 kW Solar PV system at PSG College of Technology K-block load side referred in Appendix IV. Case Study-III: The power quality measurements done in 200 kW at Sarvajana Higher Secondary School, Peelamedu referred in Appendix IV.

8.5.1 System Description

In 100 kW Photovoltaic (PV) system each 20 kW is interfaced to a distribution system through parallel connection of 10 kHz PWM three phase inverter, a 750 μH three phase ac choke, a Δ-Δ (374–480) V, 250 kVA three phase isolation transformer, approximately 300 ft underground cable, and a grounded 11 kV-470 V, 500 kVA step-up transformer. The PWM inverter is an SMA Sunny Tripower of STP 20000TLEE-10 series specially designed for PV power conversion applications.

In Fig. 8.2 the single line diagram for Solar PV power system has been described. The 100 kW solar PV system is Connected to load through 10 kHz inverter. The grid power is synchronized with the Solar PV power generated with the help of synchronizing bus and fed to the load through an isolator switch. The Block diagram of solar PV generation system in PSG Tech, Coimbatore is shown in Fig. 8.3.

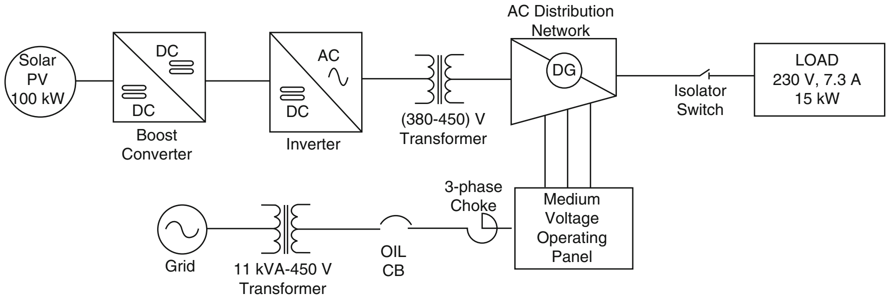

Fig. 8.2 Single line diagram of PSG Tech. power system

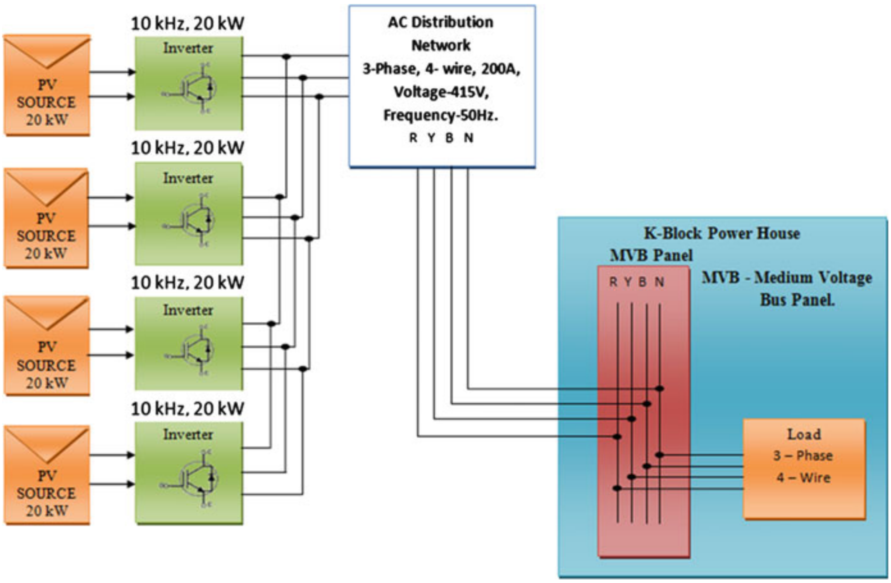

Fig. 8.3 Block diagram of solar PV generation system in PSG Tech, Coimbatore

8.5.2 Measurement Procedure for Power Quality in PV System

The actual measurement procedure includes test conditions, characteristics of the measurement equipment, and Power Quality (PQ) measurements. Test source conditions for small PV systems should agree with IEC 61000-3-2/12 and IEC 61000-3-3/11. Network conditions for large PV systems should be in accordance with IEC 61400-21.

Thus, the main requirements at Point of Common Coupling (PCC) when the PV unit is not generating are the following:

(i) THD of the voltage should be less than 4 %.
(ii) Voltage unbalance should be less than 2 %.
(iii) Measurement equipment should have class-A accuracy as defined by European standard IEC 61000-4-7.

The required PQ measurements for large PV systems are the following:

(i) 3-s/10-min harmonic currents up to the 50th order harmonic.
(ii) short-term/ long-term flicker.
(iii) A 3-s/10-min negative-sequence ratio of current unbalance, which should be raised to the 50th-order harmonic;
(iv) 1-min fundamental voltage.

Above all, measurements should be continuously recorded throughout the week so that PQ indices can be monitored for a period of time to know how changes are occurring. Measurements during hours without irradiance should be deleted to avoid distorting percentiles with measurements not determined by the PV unit.

The thermal effects of disturbances on the power system are presumably related to the disturbance level during 10-min periods. They are not related to the short time disturbance level, which affects the malfunction of relaying or electronic devices. Consequently, short time measurements should only be required when the PV unit has a significant impact on the power system.

8.5.3 Assessment Procedure for Power Quality in PV Systems

This section describes the procedure for assessing compliance with PQ requirements for PV systems based on PQ measurements. For small PV systems, the harmonic current emission should fulfill the objectives in IEC 61000-3-2/12. In contrast, the flicker emission should meet the objectives in IEC 61000-3-3/11. Focusing hence forth on large PV systems, the harmonic current emission from a PV unit (I_h, with $h = 1–50$) must be limited to comply with the harmonic current emission objective for the PV unit i at its PCC $(E_{I_h i})$ as in Eq. 8.3.

$$I_h \leq E_{I_h i} \tag{8.3}$$

According to, this assessment should be carried out for the ten intervals of nominal power of the PV unit. The flicker emission from a PV unit (P_{st}, P_{lt}) should be limited to comply with the flicker emission objective for the PV unit i at its PCC $\left(E_{p_{st} i}, E_{p_{lt} i}\right)$ expressed in Eqs. 8.4 and 8.5.

$$P_{st} \leq E_{p_{st}i} \tag{8.4}$$

$$P_{lt} \leq E_{p_{lt}i} \tag{8.5}$$

The emission of current unbalance from a PV unit must be limited so as to attain the voltage unbalance emission objective for the PV unit at its PCC. The steady-state voltage change resulting from a PV unit switching (ε) must be limited to comply with the voltage change objective resulting from the switching of the PV unit at its PCC ($E_{\varepsilon i}$) is given by Eq. 8.6.

$$\varepsilon \leq E_{\varepsilon i} = \frac{100}{U_n^2}(R_{sc,i} \cdot P_n + X_{sc,i} \cdot Q_n) \tag{8.6}$$

8.5.4 Description of Case Studies

The description of case studies used in this section is described below:

8.5.4.1 Case Study-I

The case study (Fig. 8.4) done in 100 kW Solar PV system at PSG College of Technology K-block referred in Appendix IV. In which a 100 kW PV source is divided into (5*20) kW. Each 20 kW is integrated to a distribution network through parallel connection of 10 kHz, 20 kW three-phase PWM inverter.

8.5.4.2 Case Study-II

The case study done in 100 kW Solar PV system at PSG College of Technology K-block load side referred in Appendix IV. In which the grid power and Solar PV power is synchronized and supplied to the load.

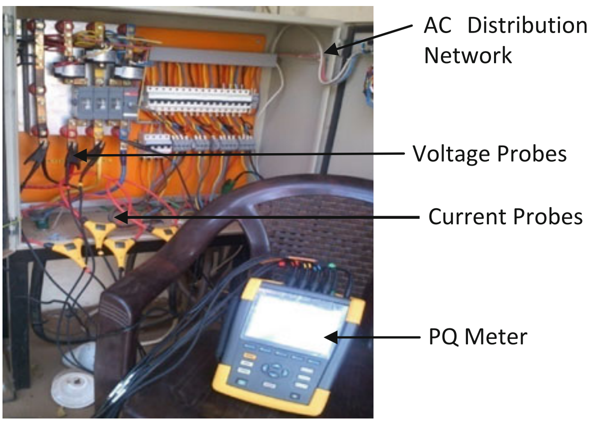

Fig. 8.4 PQ meter connections at load connected solar PV system

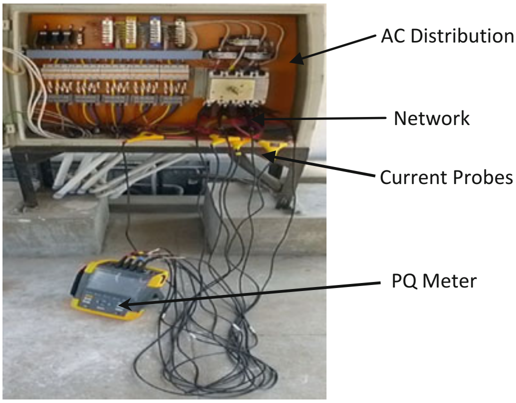

Fig. 8.5 PQ analyzer connected at AC choke in solar PV system

8.5.4.3 Case Study-III

The power quality measurements done in 200 kW at Sarvajana Higher Secondary School, Peelamedu (Fig. 8.5) referred in Appendix IV. In which the Solar PV power generated is directly connected to the lightning load.

8.5.5 Problem Evaluation and Solution Description

A complete analysis of the recorded data yielded the following results:

- The results taken from the case study-I done at "PSG College of Technology 100 kW system," as per Appendix IV shows that the current injected by the solar PV had a Total Harmonic Distortion (THD) of 5.2 % which is above 5 % limit set by the IEEE 519-1992. The average voltage THD at input and load side is 2.7 % which is below 3 % the limit set by the IEEE 519-1992. It is found that voltage injection profile of system is very satisfactory compared to current injection profile.
- When connected at the load side of 100 kW PV system at "PSG College of Technology K-Block," the results referred from Appendix IV, shows that voltage and current THD were 2.7 % and 5.1 % respectively. Also no voltage related problems noted, this confirms that PQ problems do not exist in the system. The wave shape of current is also purely sinusoidal no phase shift between voltage and current that shows reactive power flowing in system is zero.
- The results taken from the case study done at "SARVAJANA HIGHER SECONDARY SCHOOL, Peelamedu" as per Appendix IV, shows that PQ meter has recorded one voltage sag, four transients, and two interruptions. However, an analysis of the individual harmonic components revealed that 3rd, 5th, and 7th order harmonics are dominating because of the inductive load connected to the distributive system which may cause severe damage to sensitive equipments. In

that case, mitigation needs to be done by choosing custom power devices like Dynamic Voltage Restorer (DVR) to compensate voltage related problems as well as harmonics. For reactive power compensation, Distribution STATic COMpensator (DSTATCOM) was used.

8.6 Distribution Static Compensator

The problem of reactive power and harmonics in system are studied in the case study referred in Appendix IV. The phase shift controlled voltage source converter Distribution STATic COMpensator (DSTATCOM) is modelled in MATLAB for reducing harmonics in source side current and reactive power compensation. In this control algorithm the voltage regulation is achieved in a STATCOM by the measurement of the rms voltage at the load point and no reactive power measurements are required. Figure 8.6 shows the block diagram of the implemented scheme.

Sinusoidal PWM strategy is used since it is simple and offers a good response. The error signal obtained by comparing the measured system rms voltage along with the reference voltage. It really is fed into a PI controller which generates the angle which decides the mandatory phase shift between your output voltage on the VSC and also the AC terminal voltage. This angle is summed up with the phase on the balanced supply voltages that happen to be assumed to become equally spaced at 1,200 to create the required synchronizing signal forced to operate the PWM generator. The schematic diagram of phase shift control is shown in Fig. 8.7. In this method, the compensation is achieved by the measuring of the RMS voltage at the load point, whereas no reactive power measurements are required. Sinusoidal PWM technique is used with constant switching frequency. The error signal obtained by comparing the measured system rms voltage and the reference voltage is fed to a PI controller, which generates the angle for deciding the necessary phase shift between the output voltage of the VSC and the AC terminal voltage. This angle is summed with the phase angle of the balanced supply voltages, assumed to be equally spaced at 120° to produce the desired synchronizing signal required to operate the PWM generator. In this scheme, the DC voltage is maintained constant, using a separate battery source.

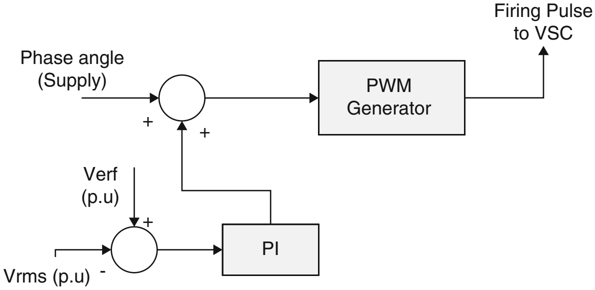

Fig. 8.6 Block diagram of phase shift control method

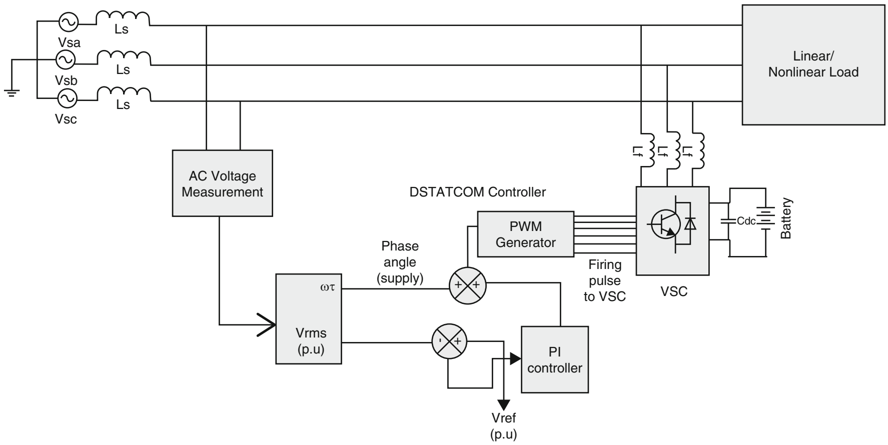

Fig. 8.7 Schematic of phase shift controlled DSTATCOM

8.6.1 SIMULINK Model of DSTATCOM

Figure 8.8 shows the SIMULINK model of the phase shift controlled DSTATCOM, in which a three-phase 230 V, 50 Hz system with line impedance of 0.1 + j3.5 mH is connected to the non-linear load of rectifier at 0.15 s and the DSTATCOM is connected via a circuit breaker with external control at 0.18 s to control the reactive power and current harmonics present in the system. Sinusoidal PWM technique is used with constant switching frequency. The error signal obtained by comparing the measured system rms voltage and the reference voltage is fed to a PI controller, which generates the angle for deciding the necessary phase shift between the output voltage of the VSC and the AC terminal voltage. This angle is summed with the phase angle of the balanced supply voltages, assumed to be equally spaced at 120̊ to produce the desired synchronizing signal required to operate the PWM generator.

8.6.2 Simulation Results

Figure 8.9 show the simulation results obtained using phase shift control for reactive power compensation and harmonic mitigation for a balanced varying linear load and for a non-linear load respectively. It is observed that the source current and the source voltage are in phase, correcting the power factor of the system in case of a linearly varying load; whereas, complete compensation is not achieved in case of non-linear load (source current THD 4.8 %) as can be seen in Fig. 8.10. The major disadvantages in this system of DSTATCOM are as follows:

- DC-link voltage is varying one but, it should be constant to make it constant some control techniques can be used like PI controller.
- The controller does not use a self supporting DC bus and thus requires a very large DC source to pre charge the capacitor.

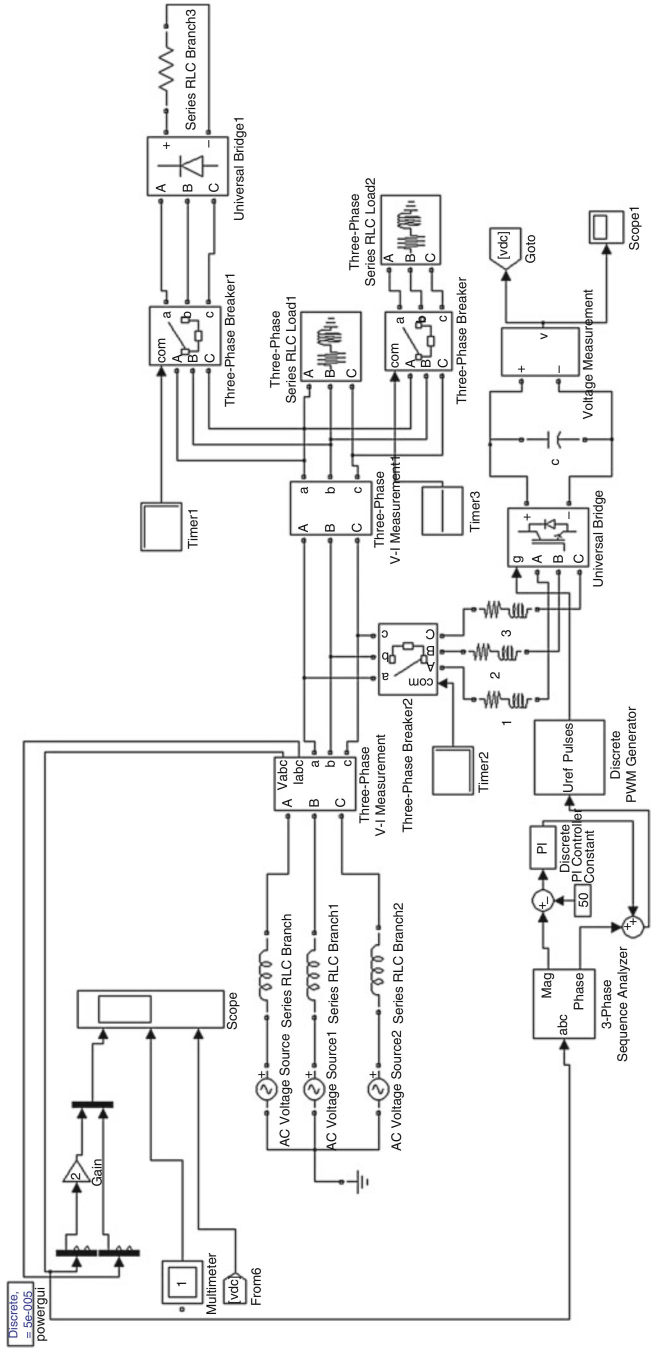

Fig. 8.8 SIMULINK model of DSTATCOM connected to a system with non-linear load

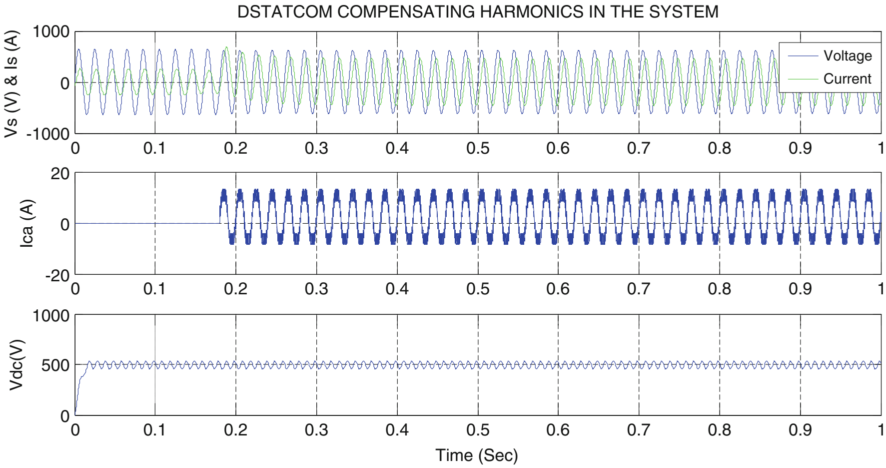

Fig. 8.9 Harmonics and reactive power compensation using DSTATCOM

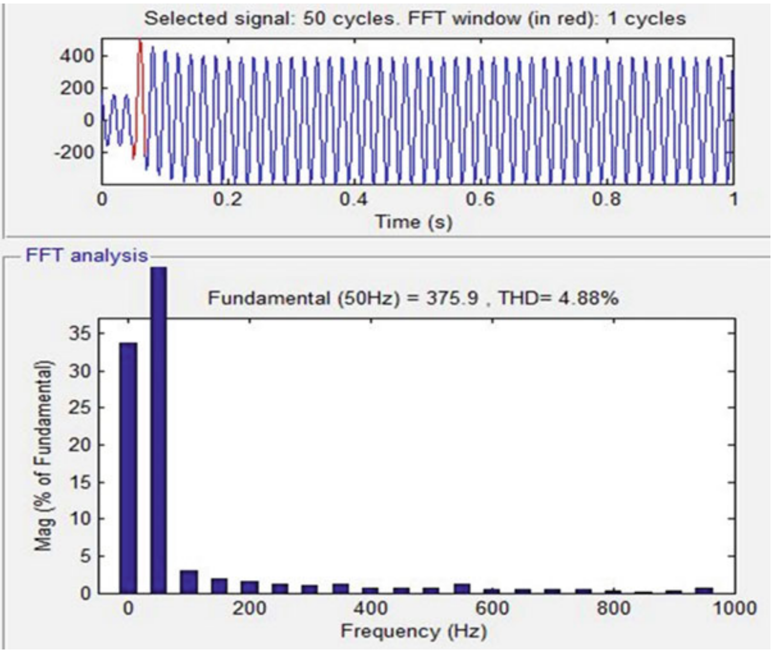

Fig. 8.10 THD% of source current waveform with DSTATCOM

- Balanced source supply as rms voltage is assumed and the supply phase angle are calculated over the fundamental only.
- No harmonic suppression and partial compensation is achieved in case of non-linear loads.

The phase shift controller for the DSTATCOM connected to a system with non-linear load compensating source side current harmonic %THD to 4.8 % which is less than 5 % limit specified by IEEE 519-1992.

8.7 Dynamic Voltage Restorer

This section discusses the modeling, simulation and analysis of Dynamic Voltage Restorer (DVR). Which is emerging custom power device to mitigate the power quality problems in distribution system. The DVR is similar to Static Synchronous Series Compensator (SSSC) a major difference involves the injection of harmonic currents and voltages to separate the source from load. A DVR can work as a harmonic isolator to prevent the harmonics in the source voltage reaching the load in addition to balancing the voltages and providing voltage regulation.

The results of case study referred from Appendix IV, yields that voltage sag/swell, interruptions, and transients are existed in the system. To compensate those problems DVR is modelled in MATLAB for providing constant voltage apart from disturbances in the supply voltage. The general configuration of the DVR shown in Fig. 8.11 consists of:

(i) An Injection/Booster transformer.
(ii) A Harmonic filter.
(iii) Storage Devices.
(iv) A Voltage Source Converter.
(v) DC charging circuit.
(vi) A Control and Protection system.

8.7.1 Equations Related to DVR

The system impedance Z_{TH} depends on the fault level of the load bus. When the system voltage (V_{TH}) drops, the DVR injects a series voltage V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be

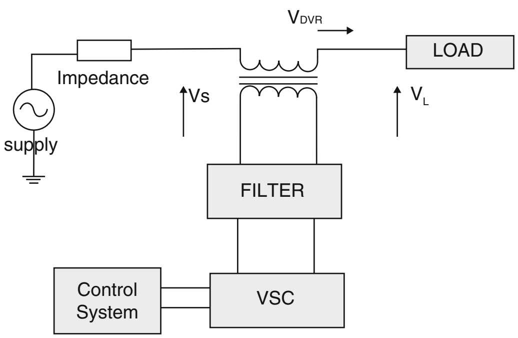

Fig. 8.11 Schematic diagram of DVR system

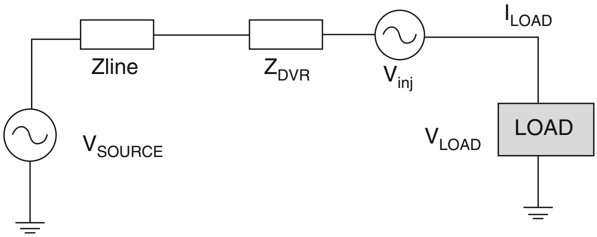

Fig. 8.12 Equivalent circuit diagram of DVR

maintained. The equivalent circuit diagram of DVR is shown in Fig. 8.12. The series injected voltage of the DVR can be written as Eq. 8.7.

$$V_{DVR} = V_L + Z_{TH} I_L - V_{TH} \quad (8.7)$$

where

V_L = The desired load voltage magnitude
Z_{TH} = The load impedance
I_L = The load current
V_{TH} = The system voltage during fault condition

The load current I_L is given by Eq. 8.8.

$$I_L = \frac{[P_L + jQ_L]}{V} \quad (8.8)$$

When V_L is considered as a reference equation can be rewritten as Eq. 8.9.

$$V_{DVR}^{*} = V_L^{\angle 0} + Z_{TH}^{\angle(\beta-\theta)} - V_{TH}^{\angle\delta} \quad (8.9)$$

α, β, δ are angles of V_{DVR}, Z_{TH}, V_{TH} respectively and is load power angle is given by Eq. 8.10.

$$\theta = \tan^{-1}\left(\frac{\theta_L}{P_L}\right) \quad (8.10)$$

The complex power injection of the DVR can be written as Eq. 8.11.

$$S_{DVR} = V_{DVR} I_L^{*} \quad (8.11)$$

It requires the injection of only reactive power and the DVR itself is capable of generating the reactive power.

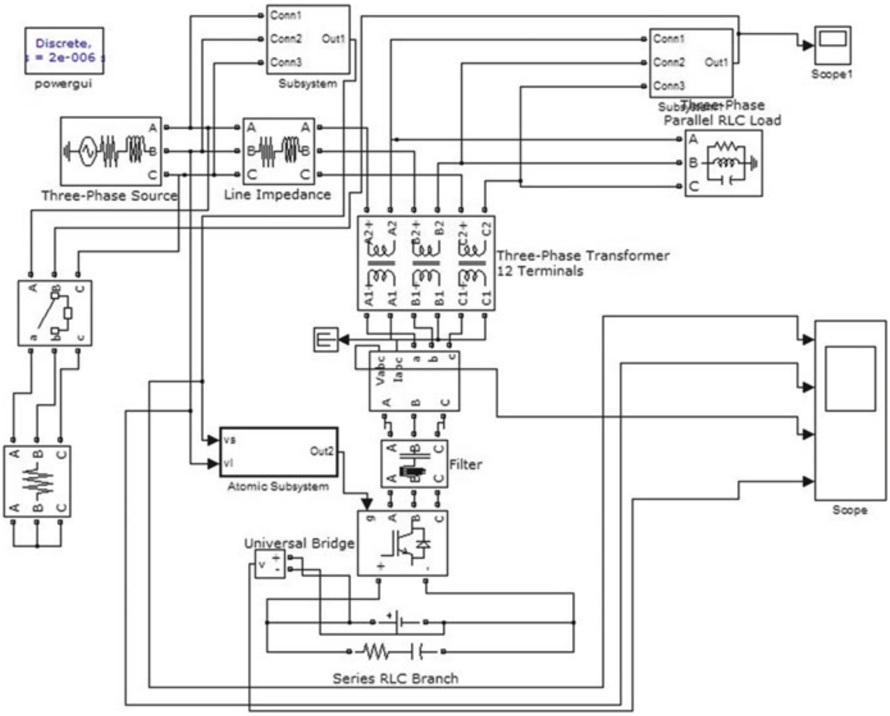

Fig. 8.13 SIMULINK model of dynamic voltage restorer

8.7.2 SIMULINK Model of DVR

Figure 8.13 shows the MATLAB model of the DVR connected system. The supply voltage is realized by using a three-phase voltage source and source impedance is connected in its series. In order to simulate the disturbances at the Point of Common Coupling (PCC) voltage, an additional load is switched on with a circuit breaker. The load considered is a lagging power factor load. The DVR is connected in series with the supply using an injection transformer. The VSC is connected to the transformer along with a ripple filter. The DC bus capacitor is selected based on the transient energy requirement and the DC bus voltage is selected based on the injection voltage level. The DC capacitor decides the ripple content in the DC voltage. The reference load terminal voltages are derived from the sensed supply voltages, supply currents, load terminal voltages and the DC bus voltage of DVR. The parameters used in SIMULINK are shown in Table 8.1.

Figure 8.13 shows a 415 V, 50 Hz three-phase source is connected to a linear load of 415 V, 10 kVA, 0.8 pf lag which will inject harmonics into the system to compensate this harmonics and voltage sag or swell created by connecting or

Table 8.1 List of parameters used in SIMULINK model of DVR

Symbol	Parameter	Value
V_s	**AC line voltage**	415 V
f	**System frequency**	50 Hz
R_S, L_S	**Source impedance**	0.01 + j 0.942
R_f, C_f	**Filter impedance**	4.8 + j 318.3
DVR with DC bus capacitor supported:		
V_{dcref}	**Reference DC-link voltage of DVR**	300 V
C_{dc}	**DC-link capacitance**	2,000 μF
K_{P1}, K_{i1}	**DC bus voltage PI controller**	0.5, 0.35
K_{p2}, K_{i2}	**AC load voltage PI controller**	0.1, 0.5
f_{sw}	**Switching frequency**	10 kHz
Three phase transformer 12 terminals	10 kVA, 200 V/300 V	

disconnecting a load in parallel to the existing load. The three-phase series injection transformer is used to inject voltage in series with the system to compensate voltage of sag/swell and supply constant voltage load. A ripple filter is used to filter out the voltage to inject into system. The three-phase circuit breaker is used to connect or disconnect load to create voltage sag/swell in system that the control feedback is given to the control circuit for controlling DVR system to compensate the voltage related problems. Voltage source converter based DVR system is simulated in the MATLAB which supported by the capacitor and battery storage system.

Figure 8.14 shows the control circuit for the Dynamic Voltage Restorer in which the synchronous reference frame theory is used for reference signal estimation of DVR voltages. The voltages at PCC and load voltages are converted to abc-dqo by using park's transformation. The unit vectors method is used to convert abc-dqo transformation unit vectors is provided by Phase Locked Loop (PLL) then, the reference voltages is obtained in rotating frame as Eqs. 8.12 and 8.13.

$$V_{Dd}^{*} = V_{Sd}^{*} - V_{Ld} \tag{8.12}$$

$$V_{Dq}^{*} = V_{Sq}^{*} - V_{Lq} \tag{8.13}$$

The error between the reference and actual DVR voltages in the rotating reference frame is regulated using two PI controllers. Reference DVR voltages ($V_{dvra}^{*}, V_{dvrb}^{*}, V_{dvrc}^{*}$) and actual DVR voltages ($V_{dvra}, V_{dvrb}, V_{dvrc}$) are used in a Pulse Width Modulated (PWM) controller to generate gating pulses to a VSC of the DVR.

8.7.2.1 Control Strategy

In the control algorithm the shunt compensator is controlled for harmonic current compensation, load current balancing and power factor correction. Here, the sag and swell in supply voltage are compensated by controlling the DVR. The control

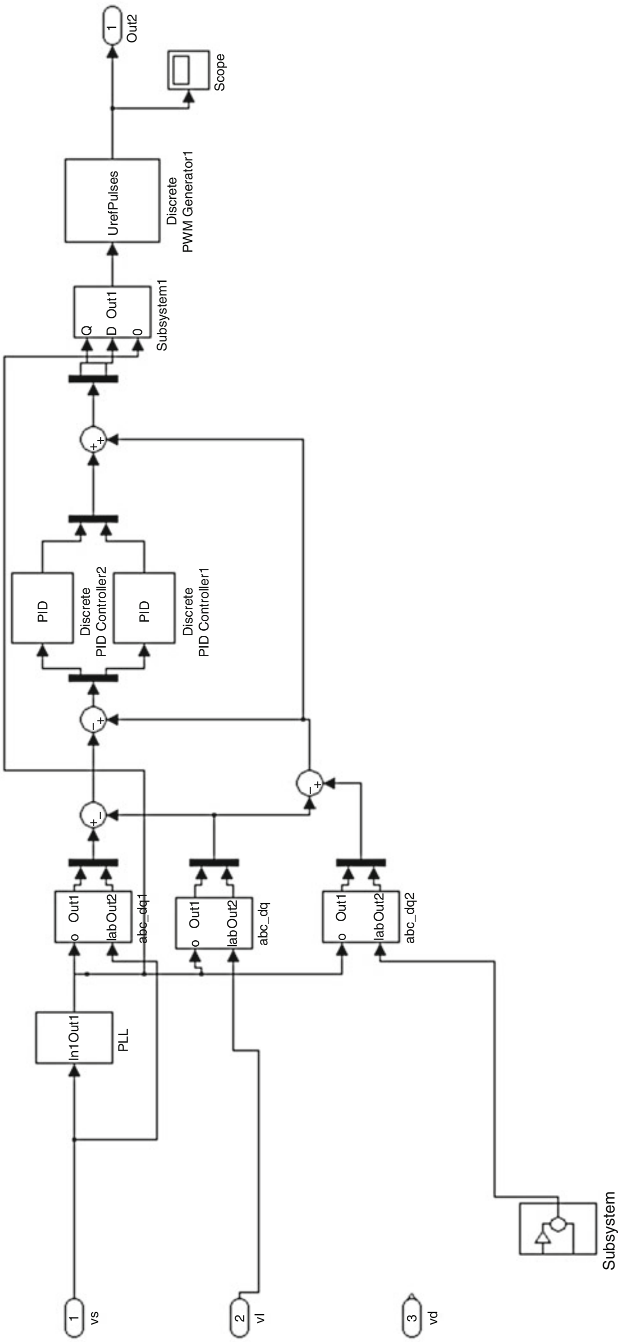

Fig. 8.14 SIMULINK model of control circuit for DVR

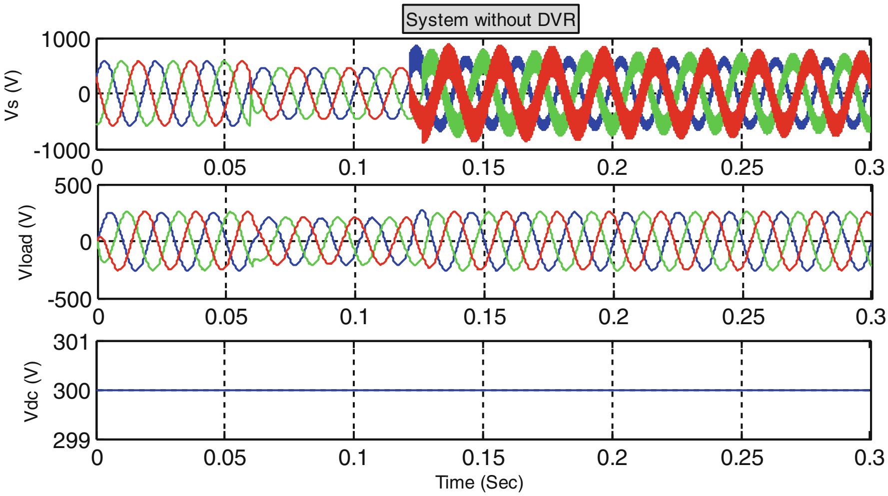

Fig. 8.15 3-Φ load and source voltages without DVR

technique used is developed with Synchronous Reference Frame theory (SRF) method. The actual voltage of DVR and estimated voltages of DVR are given to a specific voltage controlled PWM controller developed for generating pulses for triggering the IGBT's in VSC of DVR system.

8.7.3 Results and Discussion

Figure 8.15 shows the Supply voltage (V_S), load voltage (V_L), DVR voltages (V_{dvr}) and DC bus voltage without the operation of Dynamic Voltage Restorer in the system. From that we can observe that whenever a certain amount of load increases in parallel with the existing load, a sudden fall in supply voltage exists; i.e., followed in load voltage which may disturb and damage the sensitive equipments.

The dynamic performances of the DVR for a Voltage sag in supply voltage is given in Fig. 8.16 shows balanced sag of 30 % in supply voltage at 0.15 s and occur for 5 cycles of ac mains. The load voltage (V_L) is regulated at rated value, which shows the satisfactory performance of the DVR. The supply voltage (V_S), DVR voltage (V_{dvr}) and the DC bus voltage (V_{dc}) are also shown in the Fig. 8.16. The DC bus voltage is regulated at the reference value, though small fluctuation occurs during transients. The load voltage is maintained by DVR as constant value apart from disturbances caused in the supply voltages.

The dynamic performance of the DVR for a voltage swell in supply voltage is given in Fig. 8.17. The load voltage (V_L) is regulated at rated value, which shows the satisfactory performance of the DVR. The DVR voltage (V_C) supply current (i_s), the amplitude of load terminal voltage (V_{Lp}), the amplitude of supply voltage

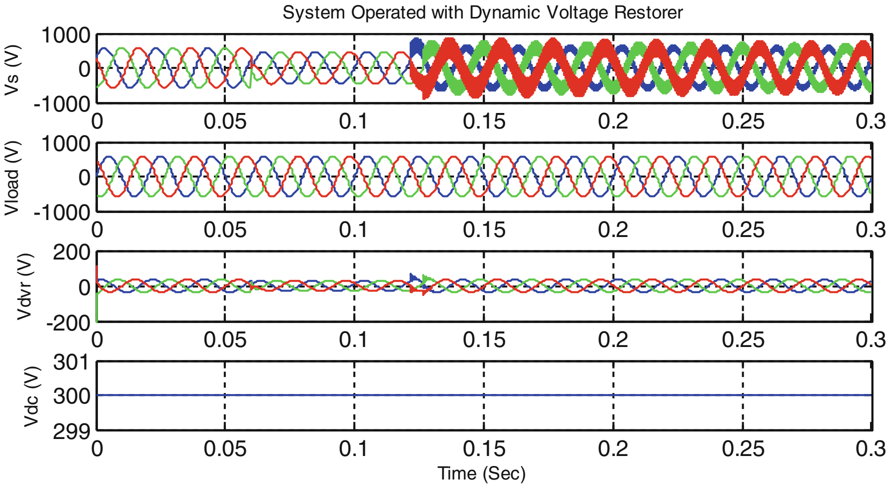

Fig. 8.16 DVR compensating voltage sag

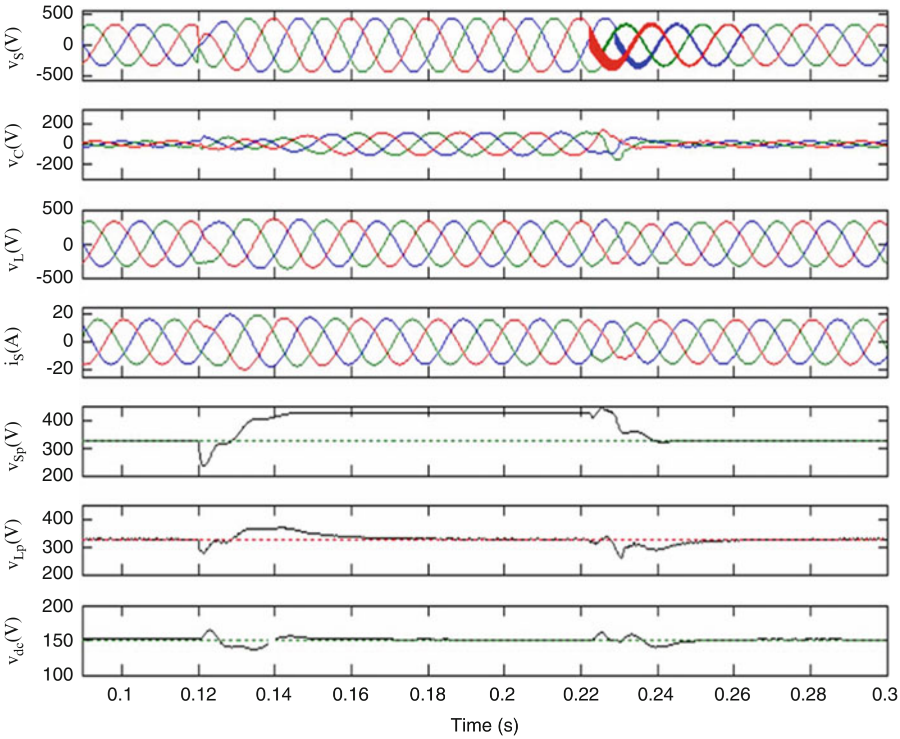

Fig. 8.17 DVR compensating voltage swell

(V_{Sp}) and the DC bus voltage (V_{dc}) are also shown in the Fig. 8.17. The DC bus voltage is regulated at the reference value, though small fluctuations occur during transients.

Power Quality (PQ) measurement and assessment was done as a case study on different solar PV generation systems such as 100, 80, and 60 kW located at PSG College of Technology. The Analysis was carried out with the help of FLUKE 434 series II Energy analyzer reported as Class-S meter according to IEC/IEEE standards. It was observed from the case study that power quality problems such as reactive power, 10 % sag/swell for duration of $\leq$1,000 μs, and 4 % of VTHD, 10 % ITHD in which 3rd, 5th, and 7th harmonics are dominating and existing in system when connected to the load. To mitigate these problems custom power devices Distribution STATic Compensator (DSTATCOM) and Dynamic Voltage Restorer (DVR) are simulated in MATLAB/SIMULINK.

The phase shift control scheme is described with the help of simulation results. The DSTATCOM shows better performance when connected to system by compensating the reactive power flow and harmonic mitigation in source side current waveform. The %THD of source current is 4.8 % after connecting DSTATCOM which is below the IEEE 519-1992 set limit.

The control scheme of DVR has been validated through computer simulation using MATLAB software along with SIMULINK and power system block set toolboxes. The simulation results of DVR show that compensation of voltage sag/swell is reduced to 3 % of nominal voltage. The IEC/IEEE standards are met by the system control technique developed by Synchronous Reference Frame (SRF) theory is efficient in compensating the voltage related problems and supplying constant load apart from disturbances created in supply side.

8.8 Unified Power Quality Conditioner

The Unified Power Quality Conditioner (UPQC) is used in a power transmission system to compensate supply voltage, flicker/imbalance, reactive power, negative sequence current and harmonics. The UPQC has the ease of improving power quality on the point of setting up power distribution systems. The UPQC is predicted to get probably the most powerful answers to large capacity loads that are sensitive to supply voltage sparkle/imbalance. The UPQC (Fig. 8.18) comprises of series active power filter (APF) and also a shunt APF which aid in compensating the interruption in voltage when energy storage or battery is present in the DC-link. The shunt APF is normally connected through the loads to meet all current-associated problems such as the reactive power compensation, power factor improvement, current harmonic compensation, and load unbalance compensation whereas the series APF can be connected in a series with the line through series transformers. It operates as controlled voltage source and can compensate all voltage related problems, for example voltage harmonics, potential difference sag, voltage swell, flicker, etc.

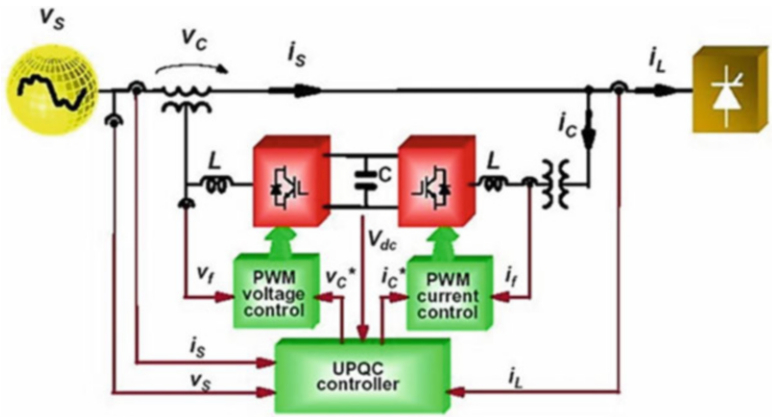

Fig. 8.18 General configuration of UPQC

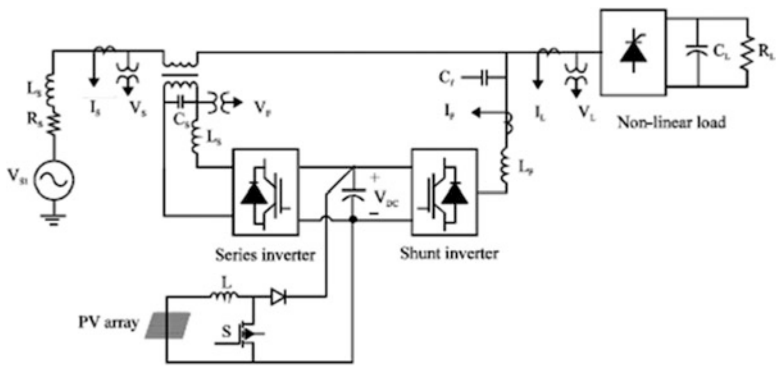

Fig. 8.19 UPQC system with PV array

8.8.1 UPQC with PV Array

The configuration of UPQC with PV array is shown in Fig. 8.19. The 3-phase 3-wire shunt inverters and series inverters are linked to a point of common coupling (PCC) by means of a shunt transformer. The series inverter lies between the source and coupling as a current source and it operates as a voltage source. By neglecting the resistance in the line, the real and reactive powers are given by Eqs. 8.14) and 8.15:

$$P = \frac{V_S V_R}{X} \sin(\delta_1 - \delta_2) \tag{8.14}$$

$$Q = \frac{V_R}{X}(V_S - V_R) \tag{8.15}$$

The boost converter is designed using Eq. 8.16,

$$V_o = \frac{V_i}{(1 - \delta)} \tag{8.16}$$

The values of inductance and capacitance are calculated according to Eqs. 8.17 and 8.18,

$$L = \frac{V_i \delta}{f \Delta I} \tag{8.17}$$

$$C = \frac{\delta}{2fR} \tag{8.18}$$

8.8.2 SIMULINK Model of UPQC

The values of L and C are designed based on Eqs. 8.17 and 8.18, assuming $\Delta I = 0.4$ A, f = 3 kHz & R = 1 K Ω. For boost converter, the values of L and C are 8.8 mH and 0.147 μF with $T_{ON} = 0.29$ ms and $T_{OFF} = 0.04$ ms. The SIMULINK model of the UPQC system with PV array is shown in Fig. 8.20.

8.8.3 Simulation Results

The receiving end voltage, receiving end current, real power and reactive power are measured with scopes connected appropriately. The load on the receiving end is series combination of resistance 200 Ω and inductance of 100 mH. The parameters in the additional load are 50 Ω and 50 mH. DC required by UPQC is applied from the photo cell. The output of UPQC is injected utilizing a series transformer. The inverter of DVR employed in the UPQC is triggered at 50 Hz. Each of the switches are operated with pulses of width 10 ms. The pulses provided to additional two switches are displaced by 10 ms. The output of inverter is filtered by making use of LC filter. It will reduce heating since harmonics are reduced. The inverter switches of active filter are triggered at 250 Hz. The DC required by the DC-link is supplied using solar cell and boost converter. The output of solar cell is not sufficient to drive the capacitor at the input of the inverter. Therefore the output of solar cell is boosted by using a boost converter. The boost converter uses boost inductor, capacitor and blocking diode. The output voltage is controlled by using a MOSFET. An additional load is applied at t = 0.2 s. The total load current increases and the drop in the line impedance increases. The receiving end voltage is reduced. At t = 0.3 s, the voltage is injected by the UPQC to bring the receiving end voltage to the normal value. From the waveform of VL1, it can be seen that the sag is compensated by using the DVR part of UPQC. The voltage VL2 is zero up to 0.2 s, since the breaker is open. The real and reactive powers increase at t = 0.2 s due to the increase in the load. This increases further at t = 0.3 s, due to the injection of the voltage by UPQC.

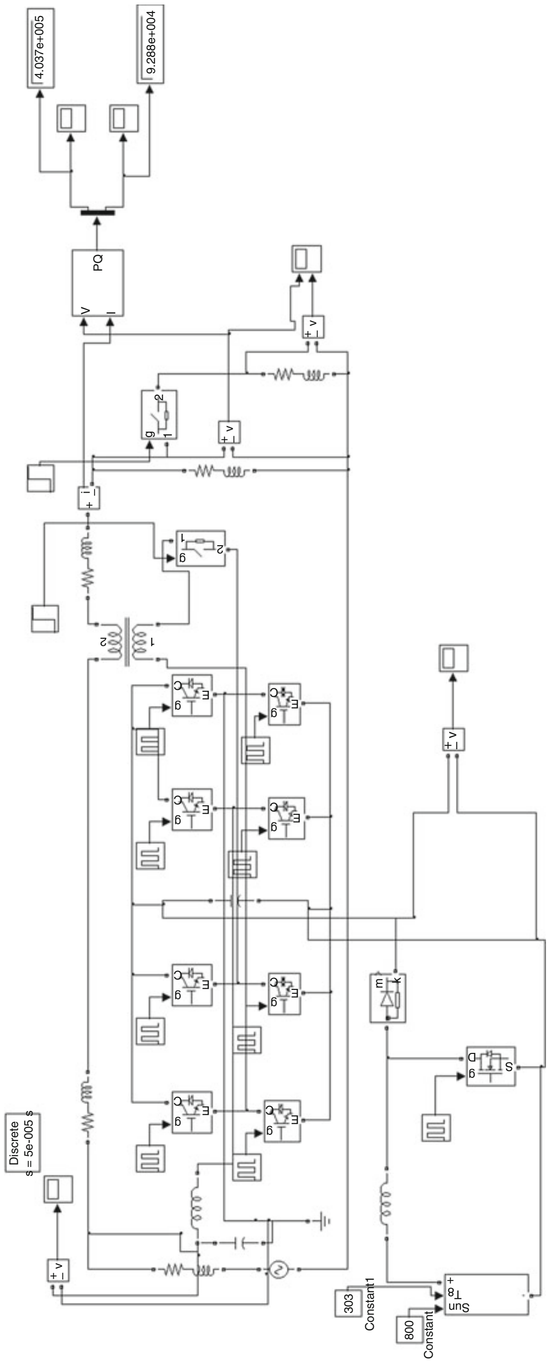

Fig. 8.20 SIMULINK model of UPQC

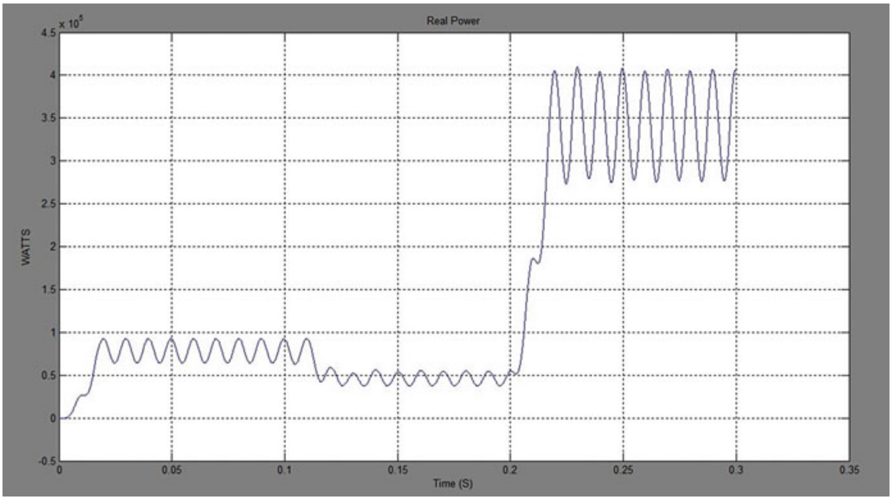

Fig. 8.21 Real power

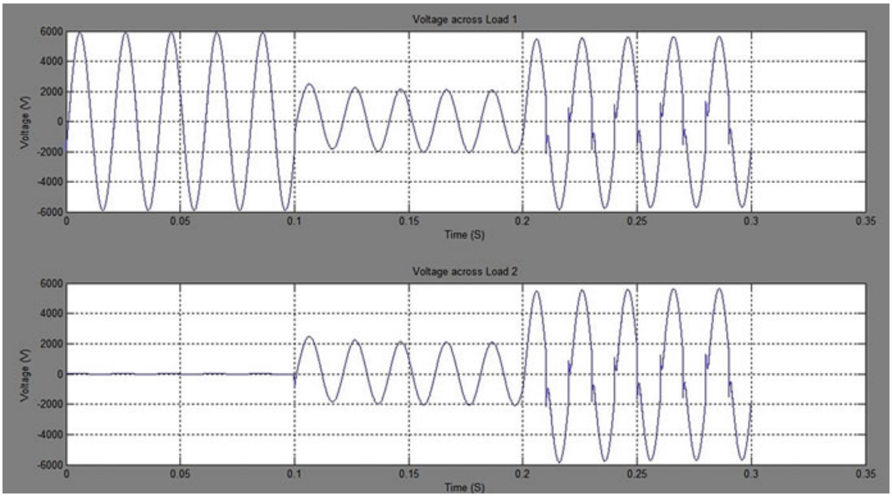

Fig. 8.22 Output voltage

The real power, output voltage and reactive power are shown in Figs. 8.21, 8.22, and 8.23 respectively. A nonlinear rectifier system with inductive load is connected in parallel with the linear load. This nonlinear load draws alternating square current which contains 5th harmonic. The THD is 8.6 %. The output of active filter is connected to the load. The inverter in the active filter is triggered at 250 Hz. FFT analysis is done for the receiving end current and the frequency spectrum is obtained. The THD is 1.6 %. Thus the THD is reduced to a minimum value by using active filter. Thus the quality of sending end current is improved by using UPQC.

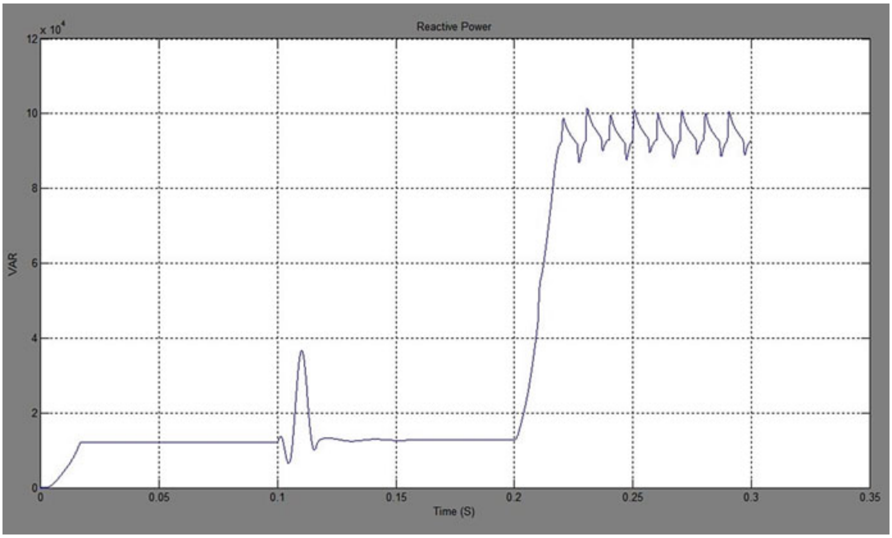

Fig. 8.23 Reactive power

Although the likelihood of harmonic problems is very low, the cases in which they do occur can result in decreasing power system reliability. An understanding of the causes, potential effects and mitigation means for harmonics can help to prevent harmonic related problems at the design stage and reduce the probability of undesired effects occurring on start-up. The UPQC system is successfully designed and modeled using the circuit elements of SIMULINK. The sag in the voltage is created by applying an additional heavy load at the receiving end. This sag is compensated by using DVR part of UPQC. The simulation results are in line with the predictions. The THD in the output is reduced by operating the inverter at 250 Hz.

8.9 Harmonic Reduction in WECS

To have sustainable growth and social progress, it is necessary to meet the energy need by utilizing the renewable energy resources like wind, biomass, hydro, co-generation, etc In sustainable energy system, energy conservation and the use of renewable source are the key paradigm. The need to integrate the renewable energy like wind energy into power system is to make it possible to minimize the environmental impact on conventional plant. The integration of wind energy into existing power system presents a technical challenges and that requires consideration of voltage regulation, stability, power quality problems. The power quality is an essential customer- focused measure and is greatly affected by the operation of a distribution and transmission network. The problem of power quality is of great importance towards the turbine. There is a substantial growth and quick rise in the exploitation of wind energy recently. From the fixed-speed turbine operation, all the fluctuation within the wind speed are transmitted as fluctuations within the mechanical torque, energy around the grid and brings about large voltage fluctuations.

During the normal operation, wind mill creates a continuous variable output power. These power variations are generally attributable to the issue of turbulence, wind shear, and tower-shadow and of control system in the power system. Thus, the network needs to manage for such fluctuations. The power quality issues can be looked at based on the wind power, transmission and distribution network, for example voltage sag, swells, flickers, harmonics etc. However the wind generator introduces disturbances into the distribution network. One of many simple types of running a wind generating technique is to make use of the induction generator connected on to the grid system. The induction generator has inherent attributes of cost effectiveness and robustness. However; induction generators require reactive power for magnetization. When the generated active power of an induction generator is varied as a result of wind, absorbed reactive power and terminal voltage associated with an induction generator may be significantly affected. A correct control scheme in wind energy generation product is required under normal operating condition to permit the proper control in the active power production. In the case of increasing grid disturbance, an assortment energy storage system for wind energy generating strategy is generally necessary to compensate the fluctuation generated by wind generator.

8.9.1 Power Quality Standards and Issues

8.9.1.1 International Electro Technical Commission Guidelines

The policies are provided for measurement of power quality of wind mill. The International standards are produced by the working group of Technical Committee-88 from the International Electro-technical Commission (IEC), IEC standard 61400-21, describes the procedure for determining the electricity quality characteristics from the wind generator.

The standard norms are specified.

(a) IEC 61400-21: Wind turbine generating system, part-21. Measurement and Assessment of power quality characteristic of grid connected wind turbine.
(b) IEC 61400-13: Wind Turbine – measuring procedure in determining the power behavior.
(c) IEC 61400-3-7: Assessment of emission limits for fluctuating load IEC 61400-12: Wind Turbine performance.

8.9.1.2 Voltage Variation

The voltage variation issue results on the wind velocity and generator torque. The voltage variation is directly related to real and reactive power variations. The voltage variation is usually classified as Voltage Sag/Voltage Dips, Voltage Swells, Short

Interruptions, Long duration voltage variation. The voltage flicker issue describes dynamic variations within the network attributable to windmill or by varying loads. Thus the energy fluctuation from wind turbine occurs during continuous operation. The amplitude of voltage fluctuation is determined by grid strength, network impedance, and phase-angle and power factor on the wind turbines.

8.9.1.3 Harmonics

The harmonic results due to the operation of power electronic converters. The harmonic voltage and current ought to be restricted to the acceptable level for the point of wind generator link to the network. To ensure the harmonic voltage within limit, each method of obtaining harmonic current can allow only a limited contribution, as per the IEC-61400-36 guideline. The rapid switching gives a large cut in lower order harmonic current when compared to line commutated converter, even so the output current will have high frequency current which enables it to easily be filter-out.

8.9.1.4 Self Excitation of Wind Turbine Generating System

The self excitation of windmill generating system (WTGS) with an asynchronous generator takes place after disconnection of turbine generating system (WTGS) with local load. Potential risk of self excitation arises particularly when WTGS gives you compensating capacitor.

8.9.1.5 Consequences in the Issues

The voltage variation, flicker, harmonics causes the malfunction of equipments namely microprocessor based control system, programmable logic controller; adjustable speed drives, flickering of light and screen. It might brings about tripping of contractors, tripping of protection devices, stoppage of sensitive equipments like personal computer, programmable logic control system and will stop the process and in many cases can damage of sensitive equipments. Thus it degrades the electricity quality in the grid.

8.9.2 Power Curtailment or Wind Turbine Disconnection

In case of:

- grid capacity constraint resulting from a thermal constraint in a grid component,
- or an operating constraint,

- or security constraints, a possible solution would consist in limiting the active power delivered by the wind farm to the network. This could be:
  1. A permanent limitation defined prior to the connection and eventually modified during the life duration of the wind farm,
  2. A periodic limitation for a given duration if the constraint appears only during a forecasted time in the year (due to seasonal maximal external temperature, due to load and/or generation profile in the year).

8.9.3 Coordination with Other Generating Plants

The coordination of wind farms with one or several other generating plants (using other primary sources than wind) may allow:

- To compensate for the short term, midterm or long term power variations of the wind farm. This enables to limit the solicitation on the network, to facilitate the power system operation, and to improve the security.
- To share the frequency control participation between different generation units. In case of grid capacity constraints corresponding to a thermal constraint in a grid component, the true coordination of the wind farm with other generation plants (for instance hydro power plants) may provide a solution. The other generating units may adapt their production in order to allow the wind farm to deliver all the power it can provide while the grid thermal limits are respected. However this possibility is highly dependent of the location of the other production units regarding the grid equipment pieces under constraint. In the same way, if a wind farm and another production unit have their connection point close to each other; it could be envisaged to share the reactive power production or the voltage control. Different applications have been developed for the compensation of short term, midterm and long term power variations, for instance in:
  - isolated grids with diesel – wind coordination,
  - The Nordic Power Pool with Hydro electric – wind coordination.

8.9.4 Load Control

Local loads can be switched on or off to:

- Compensate slow active power variations of wind farms,
- Perform a frequency regulation with a load control,
- In order to facilitate the integration of wind farms to the grid,
- Solve a thermal constraint.

This can be achieved for instance by:

- the use of a remote control signal to shut on or off loads on the network,
- a automatic frequency control integrated directly at the load level,
- The use of an additional communication system.

Note that this requires that the loads can withstand an intermittent functioning and that the service associated to them is still acceptable. For instance, different applications are presently developed and tested with water heating (used for heating purposes or for domestic consumption), with water pumping or with different kinds of domestic loads which present "inertia" characteristics or a low priority for the consumers. In case of network congestions or when the power injected on the grid is limited, the wind power which cannot be supplied to the grid can be used for other applications. For instance, applications are presently considered with:

- Desalination plants,
- Hydrogen production,
- Water pumping.

8.9.5 Reactive Compensation and Voltage Control

Solutions to power quality issues are delineated in Table 8.2. A few of them are discussed below:

8.9.5.1 Wind Turbine Technology

Depending on the technology, the wind turbines can directly (without need of additional device) participate to the reactive compensation and voltage control. More precisely, doubly-fed and WTG connected to the grid through power electronics interfaces can be used to control the reactive power and the voltage. The reactive power provided or consumed by these WTGs is limited by the current limitation of the converters and so their rating. Depending on the technology, it generally enables to produce or consume a reactive power up to 30 % of the nominal active power. To perform the grid voltage control at the connection point of the wind farm, a coordinated voltage control strategy between the different wind turbines in the wind farm has to be defined. Classical squirrel cage induction WTGs and induction WTGs with dynamic slip control can only consume reactive power. They need additional devices to perform the reactive compensation and possibly contribute to the grid voltage control.

Table 8.2 Solutions for power quality issues

		Wind turbine technology	Wind farms and power system operation	Reactive compensation and voltage control	FRT systems	Energy storage system	Icc limitation devices	Other devices
Grid capacity	Steady state current	✓	✓			✓		
	Short circuit current	✓			✓		✓	
	Steady state voltage	✓		✓		✓		
Power quality	Voltage fluctuations	✓	✓	✓		✓		
	Flicker	✓		✓		✓		
	Harmonic	✓						
	Remote control disturbances							✓
Protection issues								✓
Dynamic behavior and ancillary services	Voltage dips	✓			✓	✓		
	Stability	✓	✓			✓		
	Voltage control	✓		✓		✓		
	Frequency control	✓ partially	✓			✓		

8.9.5.2 Thyristor-Switched Capacitor (TSC)

TSC are designed to insert the appropriate number of multi-stage power capacitors into the network, without transient effects. For that purpose, capacitors are switched into the circuit when the grid voltage and the capacitor voltage are both equal to the positive or negative peak voltage. Tow types of TSC systems may be found:

- the first one is based on 2 thyristors connected in back to back and
- the second one consists of a thyristor and diode connected in anti parallel for each valve.

A microprocessor-based system manages the measurements, calculates the amount of reactive power to compensate and the gating signals to the thyristors. TSC are often used to regulate voltage especially when it fluctuates slowly. The dynamic of a TSC is limited, as in any device including line commutated thyristors, at the double of the 50 Hz network frequency, i.e. 10 ms. Practically one should add to this time interval, the computation delay of the regulator (typically some milliseconds). Therefore the typical response time of a TSC is about 20 ms.

8.9.5.3 Static VAR Compensator (SVC)

Over the last three decades, utilization of large pulsed type loads such as arc furnaces, welding equipment, rolling mills has increased with the growing need of steel. The increasing number and size of those fluctuating loads caused power quality problems such as flicker, harmonics and unbalance. Static Var Compensators have been used in the factories to reduce flicker and unbalance. Some 900 SVC applications are running to date around the world. The technology, based on thyristor-controlled reactors (TCR) is mature. Its exploitation to improve reactive compensation and grid voltage control in wind farms can be envisaged. The device utilizes a Thyristor Controlled Reactor (TCR) and a Fixed Capacitor (C). Thanks to the semi-conductors, three branches of TCR are delta-connected to form a 3-phase variable inductance capable of absorbing continuously a amount of reactive power from -QL to QC.

8.9.5.4 STATCOM

The STATCOM (static compensator) and variant, the D-STATCOM, provide voltage sourced converters (VSC), and so are voltage sources where amplitude, period and frequency are entirely governable. The dc bus capacitor can be applied a dc voltage for the input in the inverter. Its output is connected to the AC grid via an inductance. While adjusting the converter potential drop (U2) depending on network Voltage (U1), the ripping tools can right away supply or absorb reactive power due to the gating signals set on the switches of the converter. The response time is influenced with the switching frequency (Typically 1–2 kHz) by how big the inductance.

8.9.5.5 Synchronous Condenser

Synchronous condensers are synchronous generators without prime mover, that can be controlled to soak up or provide reactive power and will perform a voltage control. They have been partly supplanted by static compensators. However developments by way of example on superconductor synchronous condensers (AMSC) may make them interesting for reactive settlement and voltage power over wind farms.

8.9.5.6 Rotary Phase Shifter (RPS)

By the end of the nineties, the study of a doubly-fed adjustable-speed flywheel generating system was initiated in Japan, with prospective applications in the stabilization of power in decentralized systems. Basically the system is an induction machine with a wound rotor. In the series type RPS with stator connected to the grid and rotor connected to a wind farm and no additional impedance element, thanks to the torque controller, the device works as a phase shifter, capable (in the same way as a phase shifting transformer) of controlling the power flowing between the stator and the rotor. Thanks to the slip of the induction machine, it can also acts as a frequency changer.

8.9.5.7 FRT Systems

The aim of a Fault Ride Through technique is to allow the wind energy facility (WF) to face up to a severe voltage dip with the connection point. Through the voltage dip, the active power provided to the grid by the WF is instantaneously reduced. This power becomes at least temporarily below the mechanical power available; hence the rotor speed of the generator increases. If the FRT capability is needed, the WTGs mustn't disconnect, for example caused by over speed or under voltage protections. Following the clearing with the fault that led to the voltage dip, the voltage at the wind turbine bus increases. The WTGs must resume their power supply towards network (but not lose stability). Risking potential a lack of stability after the fault clearing can be quite limited for induction or synchronous generators with full power electronics converters, and limited for doubly-fed WTG, with the control capabilities of the power electronic converters.

The WTGs never disconnect in case there is a voltage dip, due to the following:

- to limit the increase in the rotor speed so that it doesn't exceed the maximal permitted value,
- to hold the voltage with the generator bus inside permissible range,
- never to lose stability to be able to be capable of resume the energy supply following the fault clearing.

8.9.5.8 Energy Storage Systems

There are numerous forms of energy storage systems depending on different technologies and then for various time scales. Each one of these storage systems don't inevitably fit the specificities of blowing wind energy and don't essentially help with the grid integration of wind generation.

However, according to the technology and so on the rating with the energy storage systems, they will enable to:

- improve power high quality,
- smooth the voltage and energy variations on account of wind turbulences,
- smooth power versions these days scale of minutes, hours or even days,
- solve steady state current constraints,
- take part in voltage and frequency control,
- both help wind farms to resist voltage dips.

8.10 Power Quality in WECS- A Case Study

A PQ study was undertaken at the substation at incoming 110 kV and 11 kV feeder levels. Fluke Power Quality Analysers were positioned in 'A' substation specifically in 110 kV Group control in-comer breaker along with the 11 kV feeder.

Frequency dips as well as other electrical data were collected simultaneously in 110 kV level and 11 kV level and derived from one of wind mills also. The collected Information is analysed and lots of interesting inference could possibly be concluded.

From the above data (Figs. 8.24, 8.25, 8.26, 8.27, and 8.28), maybe it's inferred that severe dip in voltage is responsible for tripping in the wind mills. The dips inside the feeder originate from Tripping of adjacent feeder within the same substation. The fault within the feeders caused tripping from the feeders. In the study, it might be figured that the tripping of windmills result from severe voltage dips brought on by tripping of adjacent feeders due to feeder fault, mostly on the planet fault condition. Throughout the voltage dip, feeder current roseate abnormally creating severe stain for the aero generator, and related Transformers. Frequent pressure may ultimately damage the creator and Transformers also. There are numerous other occasions where dips saved minus the windmill Tripping. During the sort of condition on 5-6-'08 at 18.38 h there were dip in voltage in the feeder. On this condition there was clearly intense raise of feeder current in addition to feeder current increased by 400 %.

The windmill generator sustained your fault condition and the generator current increased by 209 %. This disorder will also be injurious to the generator if frequent dip throughout voltage and swell in insert current affects the generator. During one condition it absolutely was observed that there were an over voltage caused due to

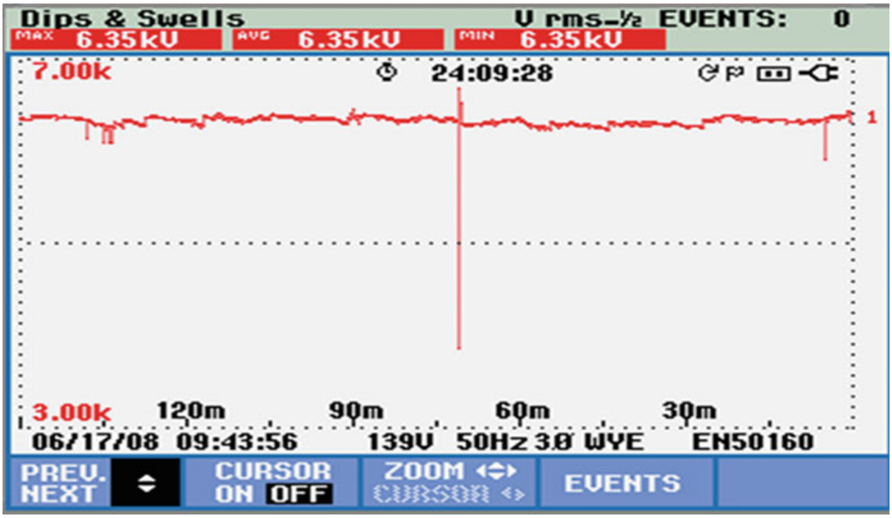

Fig. 8.24 Voltage dip in WM feeder

Fig. 8.25 Current rise in WM feeder

tripping in the feeders and before the voltage declined to zero economic value. Rrt had been observed the feeder voltage rose by 16.3 % before falling to absolutely no value. These phenomena may be due to discharge of stored energy with the Power factor correcting capacitors. This can be avoided by installing quick separate switches in case of voltage falling to zero importance. PQ analysis and recommendations Studies show that nearly 60 % of PQ issues are contributed by means of voltage sags and 29 % simply by voltage swells. Industrial customers are impacted 7–8 times by power electronic voltage sags than by means of outages.

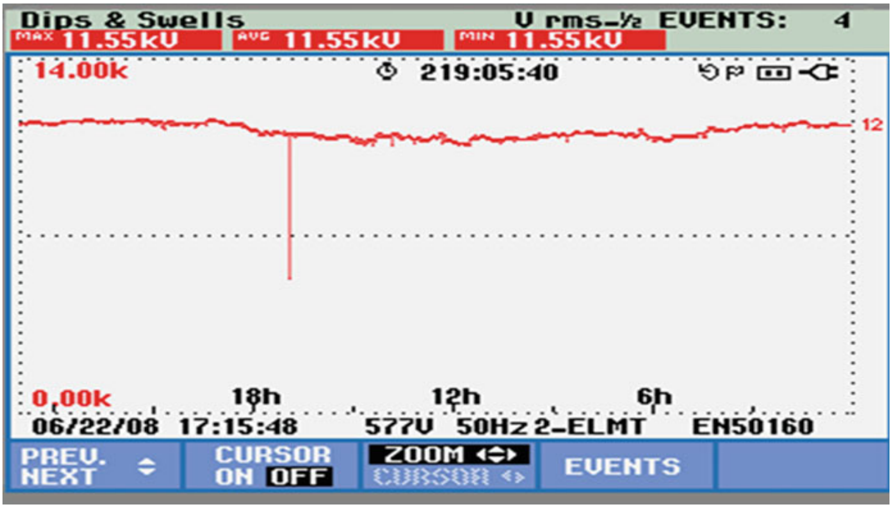

Fig. 8.26 Voltage dip

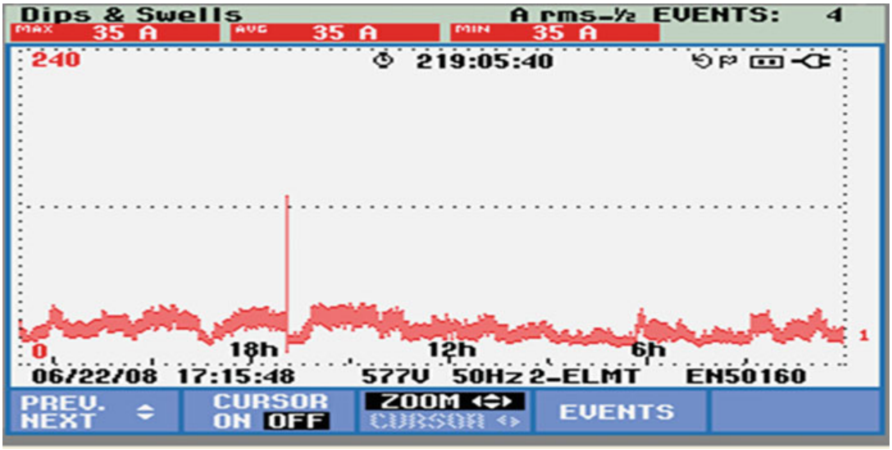

Fig. 8.27 Tripping of WM due to sag

To conquer these issues following recommendations were suggested:

1. To minimize the fault tripping from the feeders, it was recommended:
   (a) To pay off fouling trees.
   (b) To re also-sag the conductor within the feeders avoiding swinging of conductors during windy seasons.
   (c) Insulated conductors can be viewed in a few vulnerable areas.
   (d) Replace alleged insulators.

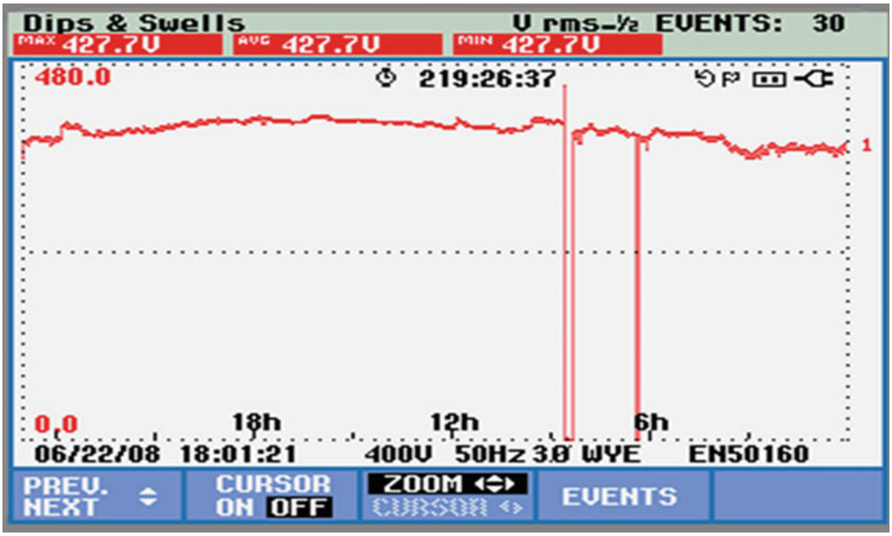

Fig. 8.28 Voltage rise in WM during supply failure

2. To setup improved version of relays inside feeder breaker to minimize the fault clearing time or otherwise prolonged fault condition could be injurious on the generator.
3. Certain kind of earth fault is not cleared or gets delayed reply through the relay caused by low fault current (due higher fault impedance). This type of situation might be overcome by installing improved variation of earth fault relay which may sense negative sequence/positive routine unbalance current and beneficial to detect weak earth faults. This would avoid persisting earth fault which often prolongs dip duration.
4. Around riding facility from the control circuit without injuring the generator/ turbine.

8.10.1 Topology for Power Quality Improvement

The STATCOM based current manage voltage source inverter injects the actual in the grid so that this source current are harmonic free of charge and their phase-angle with respect to source voltage carries a desired value. The injected recent will block out the reactive part and harmonized the main load and induction generator latest, thus it improves the ability factor along with the power quality. To perform these goals, the grid voltages are sensed and are also synchronized in generating the existing command for the inverter. The grid linked strategy is implemented for power quality improvement at point of common coupling (PCC). The grid connected organization contains wind energy generation system as well as battery energy storage system having STATCOM.

Table 8.3 System parameters

S. No.	Parameters	Ratings
1	Grid voltage	3-phase, 415 V, 50 Hz
2	Induction motor/ generator	3.35 kVA, 415 V, 50 Hz, P = 4, Speed = 1,440 rpm, Rs = 0.01 Ω, Rr = 0.015 Ω, Ls = 0.06 H, Lr = 0.06 H
3	Line series inductance	0.05 mH
4	Inverter parameters	DC-link voltage = 800 V, DC-link capacitance = 100 μF, switching frequency = 2 kHz
5	IGBT rating	Collector voltage = 1,200 V, forward current = 50 A, Gate voltage = 20 V, Power dissipation = 310 W
6	Load parameter	Non-linear load 25 kW

8.10.1.1 Wind Energy Generating System

Within this configuration, wind generations provide constant speed topologies with pitch control turbine. The induction generator is needed within the scheme due to its simplicity, it doesn't require a separate field circuit, it could accept constant and variable loads, and contains natural protection against short. The system parameters are shown in Table 8.3.

8.10.1.2 BESS-STATCOM

The battery energy storage program (BESS) is used as a power storage element for the reason for voltage regulation. The BESS will naturally maintain dc capacitor voltage regular and is best suited with STATCOM since it rapidly inserts or absorbed reactive power for you to stabilize the grid system. It also control the distribution and transmission system in a very fast charge. When power fluctuation occurs inside the system, the BESS can be familiar with level the power fluctuation through charging and discharging operation. Battery is connected in parallel towards the dc capacitor of STATCOM.

The STATCOM is a three-period voltage source inverter having the particular capacitance on its DC and connected at the place of common coupling. The STATCOM injects a compensating existing of variable magnitude and regularity component at the bus involving common coupling.

8.10.1.3 System Operation

The shunt connected STATCOM with battery energy storage is connected with the port of the induction generator (Fig. 8.29) and also non-linear load at your PCC in the grid process. The STATCOM compensator output is actually varied according to the controlled strategy, so as to conserve the power quality norms in this grid system. The current command strategy is included in the actual control scheme that

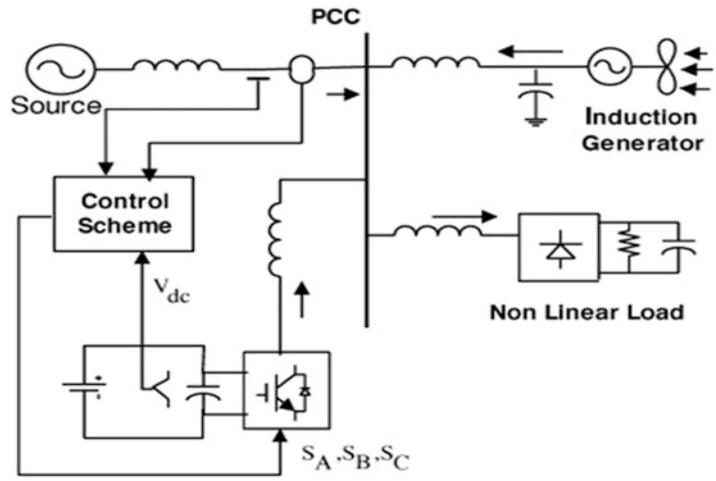

Fig. 8.29 System block diagram

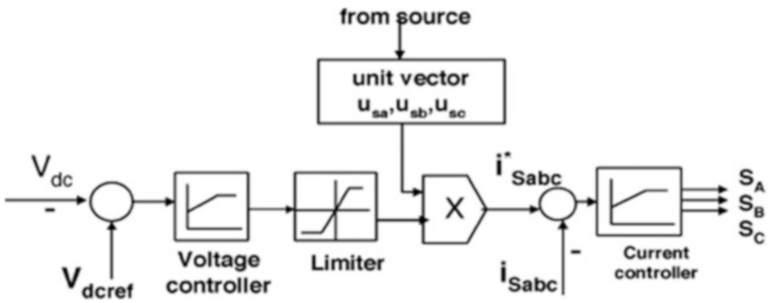

Fig. 8.30 Control system scheme

defines the actual functional operation of the STATCOM compensator in the grid. A single STATCOM using covered gate bipolar transistor is suggested to have a reactive strength support, to the induction generator and to the nonlinear weight in the grid system.

In three-phase balance system (Fig. 8.30), this RMS voltage resource amplitude is determined at the sampling frequency from the source phase electric potential and is also expressed, as test template Vsm, tried peak voltage is given in Eq. 8.19,

$$V_{sm} = \left\{ \frac{2}{3} \left(V_{sa}^2 + V_{sb}^2 + V_{sc}^2 \right) \right\}^{1/2} \tag{8.19}$$

The in-phase unit vectors are obtained from AC source – phase voltage and the RMS value of unit vector as shown in Eq. 8.20,

$$u_{sa} = \frac{V_{sa}}{V_{sm}}, u_{sb} = \frac{V_{sb}}{V_{sm}}, u_{sc} = \frac{V_{sc}}{V_{sm}} \tag{8.20}$$

The in-phase generated reference currents are derived using in-phase unit voltage vector is given by Eq. 8.21,

$$i^*_{Sa} = I.u_{Sa}, i^*_{Sb} = I.u_{Sb}, i^*_{Sc} = I.u_{Sc} \tag{8.21}$$

where I is proportional to magnitude of filtered source voltage for respective phases. This ensures that the source current is controlled to be sinusoidal. The unit vectors implement the important function in the grid connection for the synchronization for STATCOM. This method is simple, robust and favorable as compared with other methods.

8.10.2 SIMULINK Model of Grid Connected WECS

The wind energy generating system is connected with grid having the nonlinear load. The SIMULINK model is shown in Fig. 8.31. The source current and voltage waveforms without compensation is shown in Figs. 8.32 and 8.33.

8.10.3 SIMULINK Model of Grid Connected WECS with STATCOM

The control scheme is simulated using SIMULINK in power system block set as shown in Fig. 8.34.

The DC-link voltage regulates the source current in the grid system, so the DC-link voltage is maintained constant across the capacitor as shown in Fig. 8.35. The current through the dc link capacitor indicating the charging and discharging operation is as shown.

8.10.4 FFT Analysis

The FFT analysis of the Grid connected WECS is performed and the outputs are shown in Fig. 8.36 (without STATCOM controller) and Fig. 8.37 (with STATCOM controller).

In this simulation, various power quality issues related to grid connected WECS are studied. The major power quality issues, its causes and consequences are analyzed. The possible solutions for mitigating those issues were suggested. A grid connected WECS with SCIG is simulated using MATLAB/SIMULINK. The

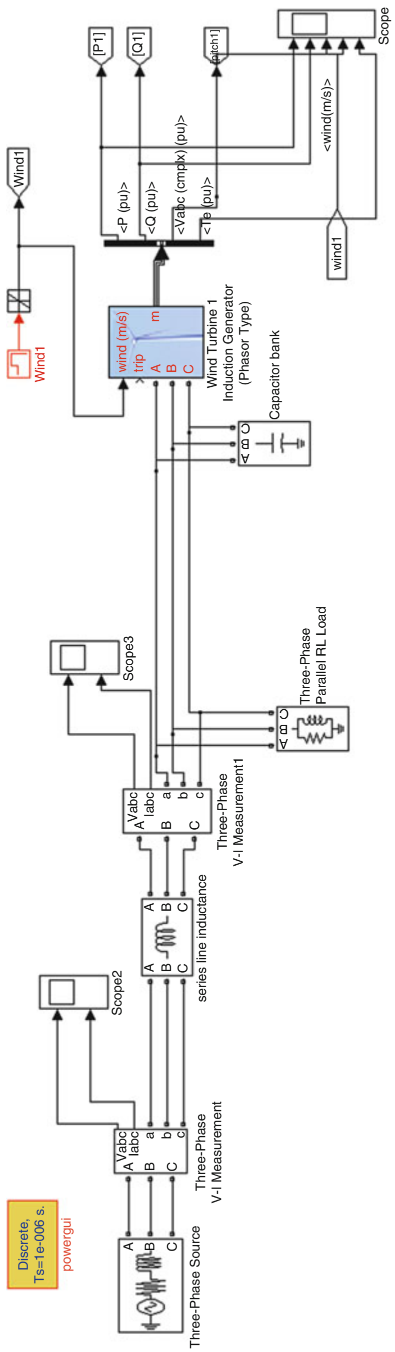

Fig. 8.31 Grid connected WECS

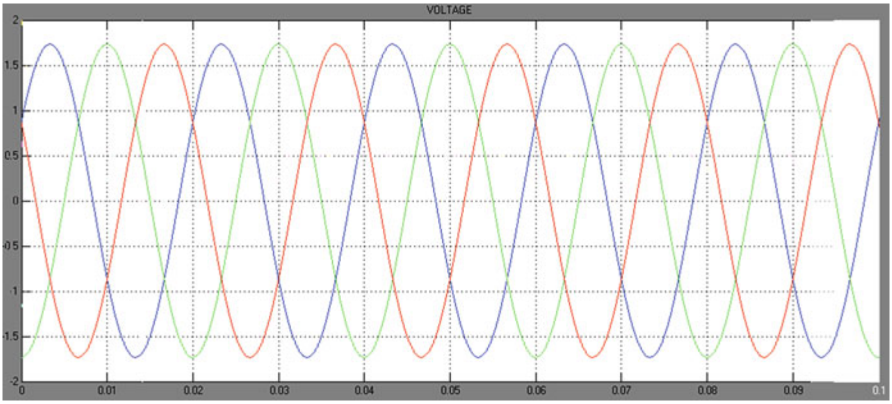

Fig. 8.32 Voltage at PCC (time v/s voltage (in pu))

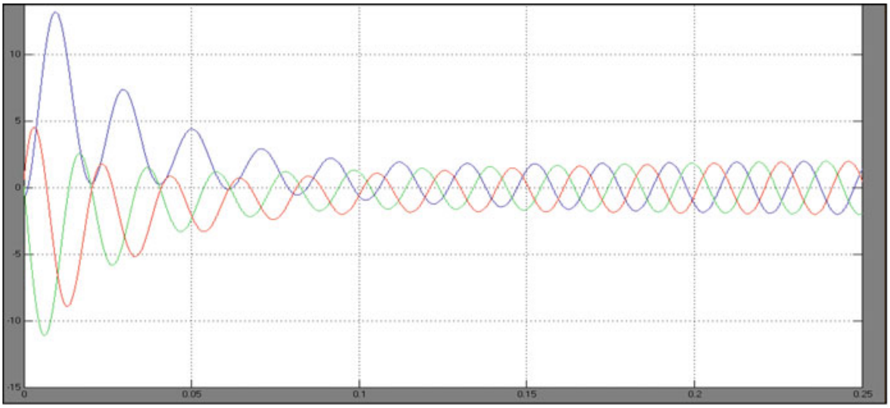

Fig. 8.33 Source current (time v/s current (in pu))

performance of the system is analyzed with a non linear load and during fault conditions. Any avoidance of downtime due to PQ related issue is direct contributor to revenue of the wind mill owner by avoiding the failure to supply to the grid. Reactive power draw during starting and voltage sag related events for grid connected wind mill are critical power quality areas that require attention. Also a STATCOM-based control scheme for power quality improvement in grid connected wind generating system is used for the comparative study on the system. The operation of the control system developed for the STATCOM in MATLAB/ SIMULINK for maintaining the power quality is simulated. It maintains the source

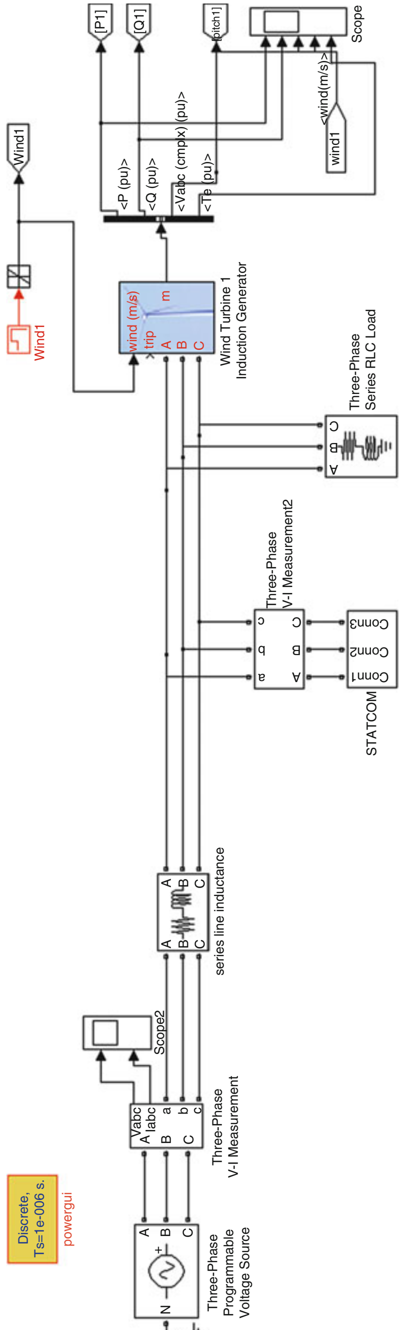

Fig. 8.34 Grid connected WECS with STATCOM

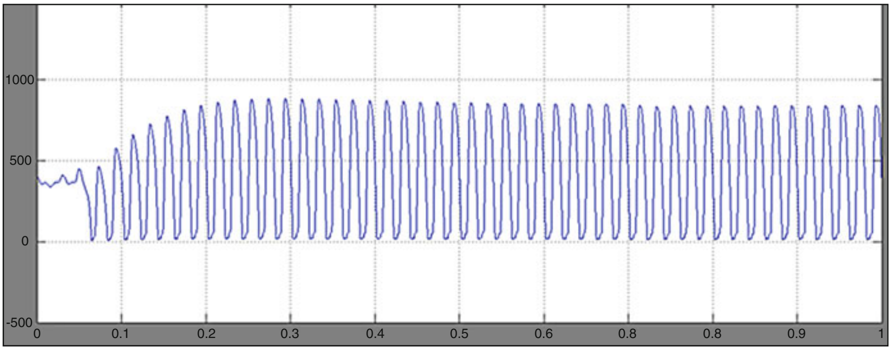

Fig. 8.35 Current through capacitor

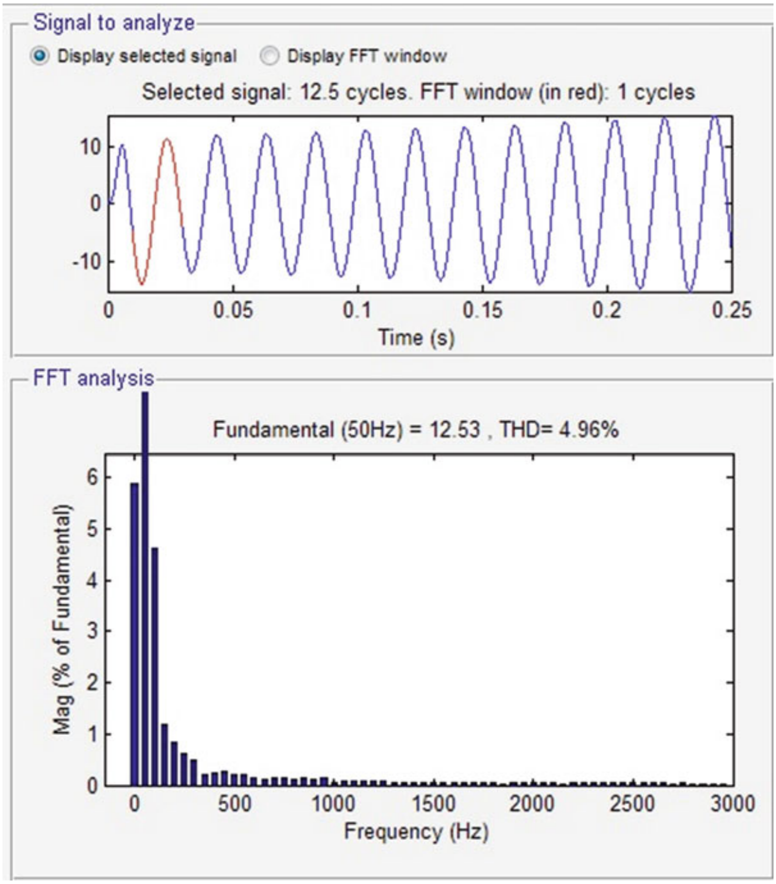

Fig. 8.36 FFT analysis without controller (THD = 4.96 %)

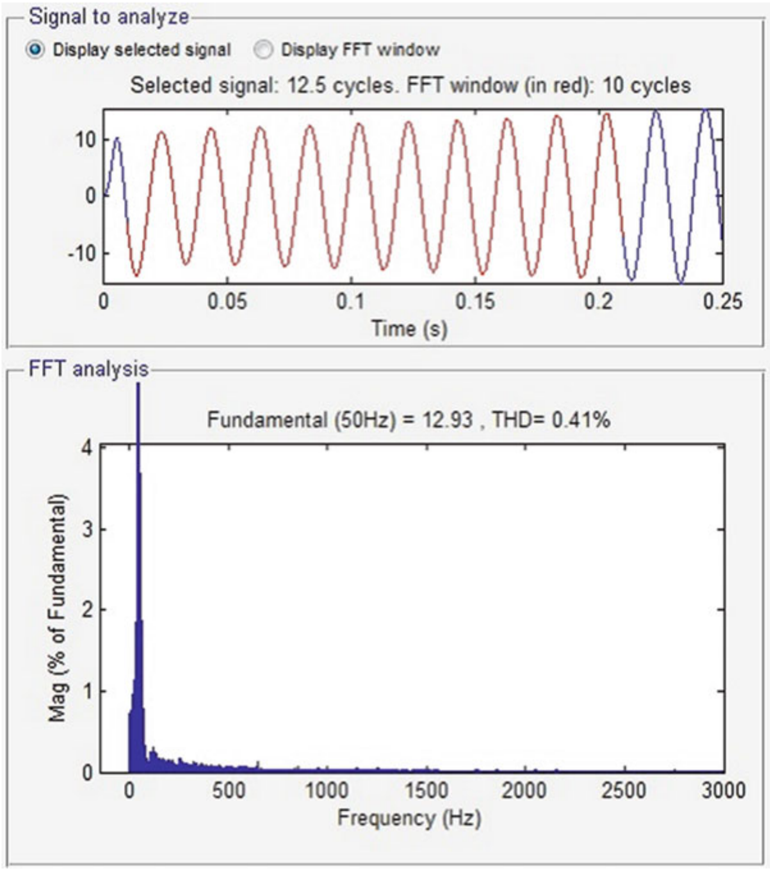

Fig. 8.37 FFT analysis with controller (THD = 0.41 %)

voltage and current in-phase and support the reactive power demand for the wind generator and load at PCC in the grid system, thus it gives an opportunity to enhance the utilization factor of transmission line.

8.11 Summary

In this chapter, the basic concepts of harmonics and power quality issues are discussed. The IEEE and SEMI standards associated with power quality are explained in detail. The measurement procedure for power quality in real time case studies is elaborated with suitable MATLAB/SIMULINK models. Reactive power compensation using custom power devices such as DSTATCOM, DVR and UPQC are given with relevant SIMULINK models. In addition, the power quality problems and standards associated with power quality issues, and harmonic reduction in Wind Energy Conversion Systems with power quality issues and a case study are also described in detail.

Review Questions

1. Mention issues related to power quality.
2. What are the sources and effects of power quality problems?
3. State the suitable methods for reducing harmonics in renewable energy systems.
4. How is power quality measured in solar PV systems? Explain with a SIMULINK model.
5. Discuss the role of converters in reducing harmonics in renewable energy systems.
6. Address reactive power compensation using DSTATCOM, DVR and UPQC.
7. What is the role of Rotary Phase Shifter in reactive power compensation?
8. What do you mean by Fault Ride Through technique?
9. Discuss power curtailment with respect to wind energy conversion systems.

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