POWER QUALITY IMPROVEMENT OF GRID CONNECTED SHP STATION

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

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ALTERNATE HYDRO ENERGY SYSTEMS

By

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CANDIDATES DECLARATION

I hereby certify that the work which is presented in this Dissertation entitled, "**Power Quality Improvement of Grid Connected SHP Station**", in partial fulfillment of the requirement for the award of the degree of **Master of Technology** in "**Alternate Hydro Energy Systems**", submitted in **Alternate Hydro Energy Centre, Indian Institute of Technology, Roorkee** is an authentic record of my own work carried out during the period from July, 2005 to June, 2006 under the guidance of **Shri S. N. Singh**, Senior Scientific Oficcer, **Alternate Hydro Energy Centre, Indian Institute of Technology, Roorkee** and **Dr. J. D. Sharma**, Professor, **Electrcal Engineering Department, Indian Institute of Technology, Roorkee.**

I have not submitted the matter embodied in the Project for award of any other degree.

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This is certified that the above statement made by the candidate is correct to best of my knowledge and belief.

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ABSTRACT

Since last three decades the power quality has become a subject of great importance. The increase in demand of power supply and change in the nature of load has contributed to the importance of power quality issues. Small hydropower stations are generally located in remote areas. In such areas the grid network is weak due to long distance and relatively high R/X ratio of the distribution cables. With increasing demand being placed on these networks, power quality issues such as poor voltage regulation, voltage sag and harmonic distortion are becoming significant problems. These problems hamper the normal operating condition of small hydro power stations. Upgrading the network to solve these problems and to improve the power quality of small hydro power stations is quite expensive. Recent developments in power electronic technologies have made it possible to create some converter based power compensation systems. The potential of these systems to improve the power quality is high. In this dissertation work the general power quality problems are discussed and development of power electronics based devices to mitigate the problems of voltage sag and harmonics are done.

In the introductory chapter (chapter 1) the general power quality issues like recent interest in power quality, power quality problems, its sources and effects are discussed. Different international standards related to power quality are discussed. Based on the limits provided these standards, some mitigation techniques, which are common in practice, are also discussed.

In chapter 2 the modeling of small hydropower plant is presented. It is important to develop a model small hydro power plant connected to grid, in order to test the behavior of the compensating devices. Standard IEEE models for different components of

small hydropower plant are adopted in the plant model. The detail discussions on the models of different components are given also. The model is simulated in MATLAB/SIMULINK software package to show its operation under normal conditions.

In chapter 3 model of dynamic voltage restorer is developed to mitigate the problems with voltage sag. The principle of control strategy of dynamic voltage restorer is based on pre-sag compensation technique, which is discussed in detail. Model of a voltage source pulse width modulated inverter is developed to inject voltage, with required magnitude and phase in series with the supply voltage, to mitigate the problem related to voltage sag. Gate turn off thyristor has been used as the power switches for the voltage source inverter. The total system is simulated in MATLAB/SIMULINK software package to show the behavior and compensation capability of the proposed model of dynamic voltage restorer.

The power quality problems related to current harmonics are dealt in chapter 4. The model of a shunt active filter has been developed to compensate for the current harmonics drawn by non-linear load. The shunt active filter is modeled as a current source, which injects the harmonic components of the load current in anti phase to compensate for the supply line harmonics. Thus, the source current can be freed from the effect of harmonic. Gate turn off thyristor based inverter with pulse width modulation technique is also used here. The control strategy is based on p-q theory, which is applied to find out the harmonic component present in the line current. The developed model is simulated in MATLAB/SIMULINK software package to show the performance of shunt active power filter in compensating harmonic currents.

In chapter 5, as a conclusion the results obtained from various models developed is this dissertation work are discussed. The limitations of the devices are also discussed with future scope of work for advancements in these types of compensating devices.

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INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Over the thirty years or so, the amount of equipment containing electronics has increased dramatically. Such equipment can both cause and be affected by electromagnetic disturbances. Therefore, transporters and users of electricity have become much more interested in the nature and frequency of disturbances in the power supply. The term power quality has become one of the most common expressions in the power industry during the last ten years [1]. The term includes numerous phenomena observed in electric power systems. Although such disturbances have always occurred in the systems, greater attention has recently been dedicated to minimizing their effects to the end users.

Here the difference between power quality and reliability needs to be clarified. Reliability of power is related to the availability of power with/without interruption. The less the interruption the more is the reliability. In the past, it can be said that the concepts of power quality and reliability were very similar because the loads were mostly linear and the amount of power electronics components were negligible. The loads were typically lighting, heating, and motors, which in general, are not very sensitive to momentary voltage variations. Moreover, the loads were more or less isolated from each other and process automation was almost non-existent. In resume, the loads did not properly work only in the case of an interruption of the supplied voltage.

In order to improve the efficiency and to minimize costs, modern industrial equipment typically uses a large amount of electronic components, such as programmable logic controllers (PLC), adjustable speed drives (ASD), power supplies in computers, and optical devices. Nevertheless, such pieces of equipment are more susceptible to malfunction in the case of a power system disturbance than traditional techniques based on electromechanical parts. Minor power disruptions, which once would have been noticed only as a momentary flickering of the lights, may now completely interrupt whole automated factories because of sensitive electronic controllers or make all the computer screens at an office go blank at once. In order to restart the whole production, computers, etc, a considerable time might be necessary (in the range of some hours), implying on significant financial losses to an industry.

It is thus natural that electric utilities and end-users of electrical power are becoming increasingly concerned about the quality of electric power in transmission & distribution systems.

1.2 DEFINITION OF POWER QUALITY

A power quality problem can be defined as - Any power problem manifested in voltage/current or leading to frequency deviations that results in failure or misoperation of customer equipment. The power quality can also be described as - the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment.

1.3 INTEREST IN POWER QUALITY

The fact that power quality has become an issue recently, does not mean that it was not important in the past. Utilities all over the world have for decades worked on the improvement of what is now known as power quality. And actually, even the term has been in use for a rather long time already. The recent increased interest in power quality can be explained in the following ways [2].

1.3.1 Equipment Has Become More Sensitive to Voltage Disturbances

Electronic and power electronic equipment has especially become much more sensitive than past devices. Not only has equipment become more sensitive, companies have also become more sensitive to loss of production time due to their reduced profit margins. On the domestic market, electricity is more and more considered a basic right, which should simply always be present. The consequence is that an interruption of supply will much more than before lead to complaints, even if there are no dangers or costs related to it.

1.3.2 Equipment Causes Voltage Disturbances

Tripping of equipment due to disturbances in the supply voltage is often described by customers as "bad power quality". Utilities on the other side, often view disturbances due to end user equipment as the main power quality problem. Modern power electronic equipment is not only sensitive to voltage disturbances, it also causes disturbances for other customers. The increased use of converter driven equipment has led to a large growth of voltage disturbances, although fortunately not yet to a level where equipment becomes sensitive. The main issue here is non-sinusoidal current of rectifiers and inverters. The harmonic distortion of the current leads to harmonic components to the supply voltage. Equipments have already produced harmonic distortion for a number of decades. But only recently has the amount of load fed via power electronic converters increased enormously, not only large adjustable speed drives but also small consumer electronics equipment. The later cause a large part of the harmonic voltage distortion, each individual devices does not generate much harmonic currents but all of them together causes a serious distortion of the supply voltage.

1.3.3 A Growing Need for Standardization and Performance Criteria

The consumer of electrical energy used to be viewed by most utilities simply as a 'load'. Interruption and other voltage disturbances were part of the deal, and the utility decided what was reasonable. Any customer who was not satisfied with the offered reliability and quality had to pay the utility for improving the supply. Today the utilities have to treat the consumers as 'customers'. Even if the utility does not need to reduce the number of voltage disturbances, it does have to quantify them one way or the other. Electricity is viewed as a product with certain characteristics, which have to be measured, predicted, guaranteed, improved etc. this is further triggered by the drive towards privatization and deregulation of the electricity industry.

1.3.4 Utilities Want To Deliver A Good Product

Most utilities simply want to deliver a good product, and have been committed to do that for many decades. Designing a system with a high reliability of supply, for a limited cost, is a technical challenge, which appealed to many in the power industry, and hopefully still does in the future.

1.3.5 The Power Quality Can Be Measured

The availability of electronic devices to measure and show waveforms has certainly contributed to the interest in power quality. Harmonic currents and voltage sags were simply hard to measure on a large scale in the past. Measurement were restricted to rms voltage, frequency, and long interruptions; phenomena which are now considered part of power quality, but were simply part of power system operation in the past.

1.4 POWER QUALITY PROBLEMS

Power quality phenomena include all possible situations in which the waveform of the supply voltage (voltage quality) or load current (current quality) deviate from the sinusoidal waveform at rated frequency with amplitude corresponding to the rated rms value for all three phases of a three-phase system. The wide range of power quality disturbances covers sudden, short-duration deviations, e.g. impulsive and oscillatory transients, voltage dips (or sags), short interruptions, as well as steady-state deviations, such as harmonics and flicker. One can also distinguish, based on the cause, between disturbances related to the quality of the supply voltage and those related to the quality of the current taken by the load.

The power quality problem can be discussed, considering the deviation of a few parameters from its ideal conditions, as presented below.

1.4.1 Voltage Magnitude Variation

(a) Voltage sags - A sag is sometimes defined as a decrease between 0.1 and 0.9 p.u. in rms voltage at the network fundamental frequency with duration from 0.5 cycle to one minute [1]. According to this definition, voltage drops lasting less than half cycle cannot effectively be characterized by a change in the rms value. In such a case, these events are considered transients. Voltage sags are usually associated with system fault currents but can also be caused by energisation of heavy loads or starting of large motors. The duration of the sag represents the greatest difference between sags caused by a fault from those caused by a motor start-up. Typical fault clearing times vary from 3 to 30 cycles, depending on fault current magnitude and the type of over current protection. Meanwhile, an induction motor can draw 6 to 10 times its full load current during start-up, which can take some seconds. If the current magnitude is relatively large compared to the available fault current at that point, the resulting voltage sag can be significant both in amplitude and duration.

(b) Voltage swell - A swell is defined as an increase to between 1.1 and 1.8 p.u. in rms voltage at the network fundamental frequency with duration from 0.5 cycle to one minute. The term momentary over voltage is also used as a synonym for swell. Switching off a large inductive load or energizing a large capacitor bank are typical system maneuvers that cause swells. Although not as common as voltage sags, swells are also usually associated to system faults. The severity of a voltage swell during a fault condition is a function of the fault location, system impedance, and grounding. During a single phase-to-ground fault on an impedance grounded system, i.e. with some zero sequence impedance, the non-faulted phase-to-ground voltages can increase up to 3 times the per-unit value (in the case of a non-grounded or high impedance grounded system). The difference in the zero- and positive-sequence impedance causes a change in the non-faulted phases, not only in magnitude but also in phase.

1.4.2 Voltage Frequency Variation

Like the magnitude, also the frequency of the supply voltage is not constant [2]. Voltage frequency variation is due to unbalance between load and generation. The term "frequency deviation" is also used. Short-duration frequency transients due to short circuit and failure of generating stations are often also included in voltage frequency variation.

1.4.3 Current Magnitude Variation

On the load side the current is normally also not constant in magnitude. The variation in voltage magnitude is mainly due to variation in current magnitude. The variation in current magnitude plays an important role in the design of power distribution system. The system has to be designed for the maximum current, where the revenue of the utility is mainly based on average current. The more constant the current, the cheaper the system per delivered energy unit.

1.4.4 Current Phase Variation

Ideally, voltage and current waveforms are in phase. In that case the power factor of the load equals unity, and the reactive power consumption is zero. That situation enables the most efficient transport of (active) power and thus the cheapest distribution system.

1.4.5 Voltage And Current Unbalance

Unbalance, or three-phase unbalance, is the phenomenon in a three-phase system, in which the rms values of the voltages or the phase angles between consecutive phases are not equal. The severity of the voltage unbalance in a three-phase system can be expressed in a number of ways, as listed below.

(a) The ratio of the negative sequence and the positive sequence voltage components

(b) The ratio of the difference between the highest and the lowest voltage magnitude, and the average of the three voltage magnitudes

(c) The difference between the largest and the smallest phase difference between consecutive phases.

These three severity indicators can be referred to as "negative sequence unbalance", "magnitude unbalance" and "phase unbalance" respectively.

The primary source of voltage unbalance is unbalance load (thus current unbalance). This can be due to an uneven spread of (single phase) low voltage customers over the three phases, but more commonly unbalance is due to a large single phase load. Examples of the later can be found among railway traction supplies and arc furnaces.

Three-phase voltage unbalance can also be the result of capacitor bank anomalies, such as a blown fuse in one phase of a three-phase bank.

Voltage unbalance is mainly of concern for three phase loads. Unbalance leads to additional heat production in the winding of induction and synchronous machines; this reduces the efficiency of the machine.

1.4.6 Voltage Fluctuation

If the voltage magnitude varies, the power flow to equipment will normally also vary. If the variations are large enough or in critical frequency range, the performance of equipment can be affected. Cases in which voltage variation affects load behavior are rare, with the exception of lighting load. If the illumination of a lamp varies with frequencies between about 1 Hz to 10 Hz, our eyes are sensitive to it and above a certain magnitude the resulting light flicker can become rather disturbing. It is the sensitivity of the human eye which explains the interest in this phenomenon. The fast variation in voltage magnitude is called "voltage fluctuation", the visual phenomenon as perceived by our brain is called "light flicker". The term "voltage flicker" is confusing but sometimes used as a shortening for "voltage fluctuation leading to light flicker".

To quantify voltage fluctuation and light flicker, a quantity called "flicker intensity" has been introduced. Its value is an objective measure of the severity of the light flicker due to a certain voltage fluctuation. The flicker intensity can be treated as a variation, just like voltage magnitude variation. It can be plotted as a function of time, and probability density and distribution functions can be obtained.

1.4.7 Harmonic Distortion

Harmonics in power systems have received increased attention in recent years with the widespread application of advanced solid-state power switching devices in a multitude of power electronic applications. The ac power system has a substantial number of large harmonic generating devices, i.e. adjustable speed drives for motor control and switch-mode power supplies used in a variety of office equipment such as PCs, fax machines etc. These devices draw nonsinusoidal load currents consisting primarily of lower order 5th, 7th, 11th, and 13th harmonics that distort the system power quality. With the widespread use of harmonic-generating devices, the control of harmonic currents to maintain a high level of power quality is becoming increasingly important. A few detrimental impact of harmonic distortion over other devices can be listed as below.

(a) In transformers harmonic currents can cause over-heating forcing the devices to be derated to prevent damage [3]

(b) Many modern power electronics based devices require a clean supply current to determine proper firing angles. Harmonics may cause the device to function incorrectly or not at all.

(c) The presence of any harmonic currents cause lowering of the power factor with equal power, which means higher currents must be generated by the utility leading to an increase in line losses.

(d) Inductive interference with telecommunication lines.

(e) Errors in watt-hour induction meters.

(f) Some devices are directly affected by the presence of voltage harmonics. For example capacitors are affected by the voltage harmonics because they induce harmonics currents to flow which may cause the device to exceed it's kVA rating.

The harmonic distortion problem can be realized in three ways, namely harmonic voltage distortion, harmonic current distortion and interharmonic distortion. These are described as follows.

1.4.7.1 Harmonic voltage distortion

The voltage waveform is never exactly a single frequency sine wave. This phenomenon is called "harmonic voltage distortion" or simply "voltage distortion". When we assume a waveform to be periodic, it can be describe as a sum of sine waves with frequencies being multiple of the fundamental frequency. The nonfundamental components are called "harmonic distortion".

There are three contributions to the harmonic voltage distortion [2]

(a) The voltage generated by a synchronous machine in a hydro power plant is not exactly sinusoidal due to small deviation from the ideal shape of the machine.

(b) The power system transporting electrical energy from the power plants to the loads is not completely linear, although the deviation is small. Some components in the system draw nonsinusoidal current, even for a sinusoidal voltage. The classical example is the power transformer, where the nonlinearity is due to the saturation of the magnetic flux in the iron core of the power transformer. The amount of harmonic distortion originating in the power system is normally small. The increasing use of power electronics for control of power flow and voltage carries the risk of increasing the amount of harmonic distortion originating in the power system. The same technology also offers the possibility of removing a large part of the harmonic distortion originating elsewhere in the system or in the load.

(c) The main contribution to harmonic voltage distortion is due to nonlinear load. A growing part of the load is fed through power electronics converters drawing a nonsinusoidal current. The harmonic current components cause harmonic voltage components, and thus a nonsinusoidal voltage in the system.

1.4.7.2 Harmonic current distortion

The complementary phenomenon of harmonic voltage distortion is harmonic current distortion. The first is a voltage quality phenomenon, the later a current quality phenomenon. As harmonic voltage distortion mainly due to nonsinusoidal load currents, harmonic voltage and current are strongly linked. Harmonic current distortion requires over-rating of series components like transformer and cables. As the series resistance increase with frequency, a distorted current will cause more losses than a sinusoidal current of the same rms value.

1.4.7.3 The sources for harmonics [4]

(a) From domestic loads

- (i) TV receivers
- (ii) Fluorescent lamps
- (iii) Electronic devices

(b) From industrial loads

   (i) Diode/Thyristor converters

   (ii) Electric furnaces

   (iii) Discharge lamps

(c) Control devices

   (i) Static VAR compensators

   (ii) Transformers

1.4.8 Interharmonic Voltage and Current Distortion

Some equipment produces current components with a frequency which is not an integer multiple of the fundamental frequency. Examples are cycloconverters and some type of heating controllers. These components of current are referred to as "interharmonic components". Their magnitude is normally small enough not to cause any problem, but sometimes they can excite unexpected resonances between transformer inductances and capacitor banks. More dangerous are current and voltage components with a frequency below the fundamental frequency, referred to as sub-harmonic distortion. Sub harmonic distortion can lead to saturation of transformer and damage to synchronous generators and turbines.

Another source of interharmonic distortion are arc furnaces. Strictly speaking arc furnaces don't produce any interharmonic voltage or current components, but a number of integer harmonics plus a continuous spectrum. Due to resonances in the power system some of the frequencies in this spectrum are amplified. The amplified frequency components are normally referred to as interharmonics due to arc furnaces. These voltage interharmonics have recently become of special interest, as they are responsible for serious light flicker problems.

A special case of sub-harmonic currents are those due to oscillations in the earth magnetic field following a solar flare. These so called geomagnetically induced currents have periods around five minutes and the resulting transformer saturation has led to large-scale blackouts [5].

Different types of power quality problems along with their causes and impacts can be summarized as listed in Table 1.1 [6].

Table 1.1 :- Power Quality Problems, Causes and Impacts

Sl. No.	Category	Causes	Impacts
1	Voltage dips	Local and remote faults Inductive loading Switch on of larg loads	Tripping of sensitive equipment Resetting of control systems Motor stalling/tripping
2	Voltage surges	Capacitor switching Switch off of large loads Phase faults	Tripping of sensitive equipment Damage to insulation and windings Damage to power supplies for electronic equipment
3	Over Voltage	Load switching Capacitor switching System voltage regulation	Problems with equipment that requires constant steady-state voltage

4	Harmonics	Industrial furnaces Non-linear loads Transformers/generators Rectifier equipment	Mal-operation of sensitive equipment and relays Capacitor fuse or capacitor failures Telephone interference
5	Power frequency variation	Loss of generation Extreme loading conditions	Negligible most of time Motors run slower De-tuning of harmonic filters
6	Voltage fluctuation	AC motor drives Inter-harmonic current components Welding and arc furnaces	Flicker in: Fluorescent lamps Incandescent lamps
7	Rapid voltage change	Motor starting Transformer tap changing	Light flicker Tripping of equipment
8	Voltage imbalance	Unbalanced loads Unbalanced impedances	Overheating in motors/generators Interruption of 3-phase operation
9	Short and long voltage interruption	Power system faults Equipment failures Control malfunctions CB tripping	Loss of supply to customer equipment Computer shutdowns Motor tripping
10	Under voltage	Heavy network loading Loss of generation Poor power factor Lack of var support	All equipment without backup supply facilities
11	Transients	Lightning Capacitive switching Non –linear switching loads System voltage regulation	Control system resetting Damage to sensitive electronic components Damage to insulation

1.5 POWER QUALITY STANDARDS

1.5.1 Purpose of Standardization

Standards that define the quality of the supply have been present for decades already. Almost any country has standards defining the margin in which frequency and voltage are allowed to vary. Other standards limit harmonic current and voltage distortion, voltage fluctuations, and duration of an interruption. There are three reasons for developing power quality standards [2].

(a) Defining the nominal environment

The nominal values of the parameters of voltage and current are needed to be mentioned in such standards. Like the nominal frequency of the voltage should be 50 Hz and nominal rms value of the voltage (line to neutral/ground) should be 230 V. Defining nominal voltage and frequency dose not say anything about the actual environment. To do this the deviations from the nominal values have to be known. Most countries have a standard giving the allowed variation in the rms voltage, a typical range between 90% to 110%.

(b) Defining the terminology

The standards are required to give exact definitions of various phenomenons, how their characteristic should be measured, and how equipment should be tested for its immunity. The aim of this is to enable communication between the various partners in the power quality field. It ensures that the results of two power quality monitors can be easily compared and that equipment immunity can be compared with the description of the environment. A typical example can be like this "The duration of a voltage dip is the time during which the rms voltage is less than 90% of the nominal rms voltage. The duration of a voltage dip shall be expressed in seconds. The rms voltage shall be determined every half cycle."

(c) Limit the number of power quality problems

Limiting the number of power quality problems is the final aim of all the work on power quality. Power quality problems can be mitigated by limiting the amount of voltage disturbances caused by equipment, by improving the performance of the supply, and by making equipment less sensitive to voltage disturbances. All mitigation methods require technical solutions which can be implemented independently of any standardization. But proper standardization will provide important incentives for the implementation of the technical solutions. Proper standardization will also solve the problem of responsibility for power quality disturbances.

1.5.2 Different International Standards on Power Quality

1.5.2.1 The IEC Electromagnetic Compatibility Standards

Within the International Electrotechnical Committee (IEC) a comprehensive framework of standards on electromagnetic compatibility is under development. Electromagnetic Compatibility (EMC) is defined as: the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment. There are two aspects to EMC: (1) a piece of equipment should be able to operate normally in its environment, and (2) it should not pollute the environment too much. In EMC terms: immunity and emission. The third term of importance is: electromagnetic environment", which gives the level disturbance against which the equipment should be immune. Within the EMC standards, a distinction is made between radiated disturbances and conducted disturbances. Radiated disturbances are delivered by one device and received by another without any conductor in between, but conducted disturbances require a conductor to travel from one device to another. These conducted disturbances are within the scope of power quality.

1.5.2.2 The European Voltage Characteristics standard

European standard 50160 describes electricity as a product, including its shortcomings. It gives the main characteristics of the voltage at the customer's supply terminal in public low-voltage and medium-voltage networks under normal operating conditions. Some disturbances are just mentioned, for others a wide range of typical values are given, and for some disturbances actual voltage characteristics are given.

1.5.2.3 IEEE Standards on Power Quality

The American standards setting organization, ANSI and IEEE, do not have such a comprehensive and structured set of power quality standards as the IEC. On the other hand, the IEEE standards give much more practical and some theoretical background of the phenomenon. This makes many of the IEEE standard documents very useful reference documents. Some of the useful standards are, "IEEE 493-1997 Recommended practice for the design of reliable industrial and commercial power system" also known as Gold Book, "IEEE 519-1992 Recommended practice and requirements for Harmonic control in electric power system", "IEEE 1100-1992 Recommended practice for powering and grounding sensitive electronic equipment" also known as Emerald Book, "IEEE 1159-1995 Recommended practice for monitoring electric power quality" etc.

1.6 MITIGATION TECHNIQUES TO POWER QUALITY PROBLEMS

The recent interest in power quality and different mitigation techniques to eliminate the power quality problems have already been discussed above. With the advent of new power electronic equipment and technology the whole matter has become very challenging. Here different mitigation techniques based on power electronic devices will be discussed shortly.

1.6.1 Mitigation of Voltage Variation

1.6.1.1 Static Series Compensator

The static series compensator (SSC) provides an effective solution for compensation of voltage sags, which constitute a major concern for industrial plant engineers [7]. The SSC is constituted by a Voltage Source Converter (VSC) connected in series with the load via a series-injection transformer, as shown in Fig.1.1. The device injects three AC voltages of controllable amplitude and phase angle, which add up independently to the corresponding source voltages, thus performing both supply unbalance compensation and load voltage regulation. The use of pulse-width modulation (PWM) with rather high switching frequency (some kHz) ensures a smooth voltage waveform, with distortion components shifted to high frequencies. Harmonics can thus be canceled by using a small passive filter placed between the converter and the transformer.

1.6.1.2 Dynamic Voltage Restorer

The function of a Dynamic Voltage Restorer (DVR) is illustrated in Fig 1.2. In the event of a voltage dip, the power electronic converter injects the appropriate voltage required into the supply bus to compensate for the sag. Rapid control cycles and millisecond switching speed of the converter enable accurate control of the voltage experienced by the load. This can be critical in sensitive manufacturing processes, where a single voltage sag may cause the loss of production, and with it, very high costs. A DVR will typically have sufficient energy storage capacity to compensate a 50 per cent three-phase voltage dip for up to 10 cycles, the period normally required for fault clearance. Although a DVR may be rated to compensate up to a 90 per cent voltage dip, it does not support complete outages. Capacitors serve as energy storage device.

The main function of a DVR is the protection of sensitive loads from voltage sags coming from network [8]. Therefore, as shown in Fig 1.2, the DVR is located on approach of sensitive loads. If a fault occurs on other lines, DVR inserts series voltage, V_{dvr} and compensates load voltage to pre fault value.

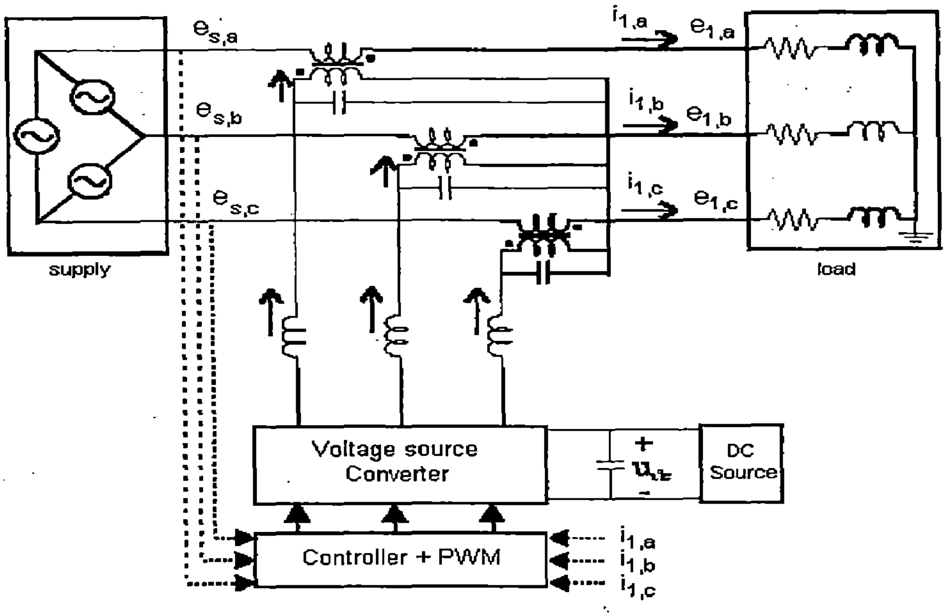


Figure 1.1: - Schematic of Static Series Compensator

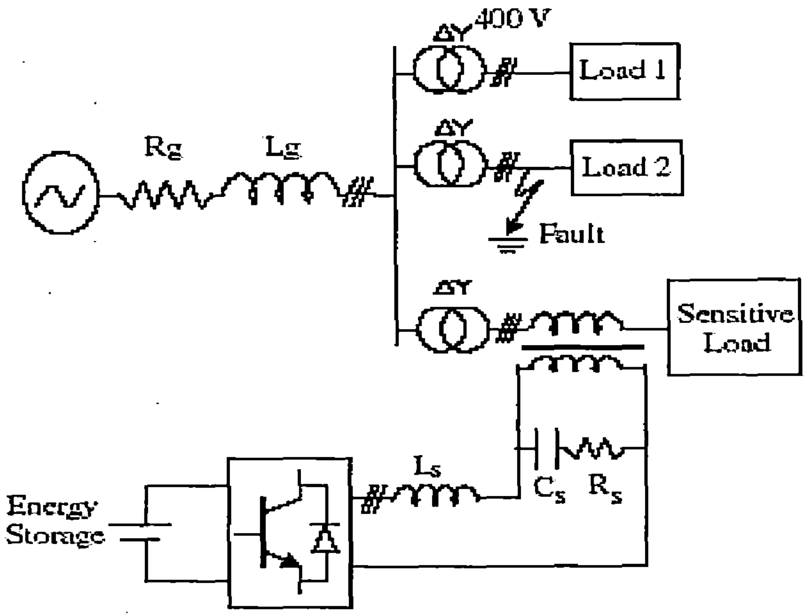


Figure 1.2: - Power circuit of a DVR

1.6.1.3 Unified Power Flow Controller

The Unified Power Flow Controller (UPFC) is composed of shunt and series forced commutated voltage-source converters connected to a common DC link, as seen in Fig 1.3. The main purpose of the device is the independent control of active and reactive power on a certain node of the transmission line [1]. It offers the potential for not only improved system performance, but also reduced maintenance, less overall property for facilities, and simplified operations for dispatchers. It also holds considerable potential in the restructured utility industry, where the voltage support and active power flow control capabilities can be used to guarantee high-quality transmission service.

The power flow control is performed by the series converter, by introducing a three-phase series voltage along the transmission line, with controllable magnitude and phase. Since the phase angle between the series voltage and the line current is not restricted, active power may flow in the series transformer and consequently from/into the DC link. The primary task of the shunt converter is then to compensate for this active power in order that the DC voltage is, in principle, kept constant by either injecting to or extracting from the AC side. The minimum rating of the shunt inverter is thus determined by the maximum active power that flows through the series transformer. In principle, if it could be guaranteed that the active power would always flow from the series converter to the line at any operating point of the series voltage and line current, the shunt converter could be replaced by a rectifier.

1.6.2 Flicker Mitigation

1.6.2.1 Static Var Compensator (SVC)

An SVC can be used for ac voltage control by generation and absorption of reactive power by means of passive elements. It can also be used for balancing unsymmetrical loads. As shown in Fig 1.4, it is normally constituted by one thyristor controllable reactor (TCR) and a number of thyristor switched capacitor (TSC) branches. The value of the reactance of the inductor is changed continuously by controlling the firing angle of the thyristors, while each capacitor can only be switched on and off at the instants corresponding to the current zero crossings, in order to avoid inrush currents in the capacitors. With this arrangement, the SVC can generate continuously variable reactive power in a specified range, and the size of the TCR is limited to the rating of one TSC branch. Obviously, the size of the reactor limits the power that can be absorbed in the inductive range.

The ability to absorb changes in reactive power makes to some extent the SVC suitable for flicker reduction. In this case, the SVC normally consists of a TCR branch with a filter (no TSC). An SVC installed together with an arc furnace not only reduces the flicker, but also, thanks to the stabilized ac voltage, increases the steel production and its quality. However, the ability of the SVC to mitigate flicker is limited by its low speed of response.

1.6.2.2 ***D-STATCOM***

Among the advantages of using forced-commutated converters are the ability of both produce and consume active and reactive power. The active power can also be controlled independently of the reactive power and vice versa. Moreover, using a voltage source converter (VSC) with pulse-width modulation (PWM) gives a faster converter control, which is needed for flicker mitigation purposes.

A forced-commutated VSC with PWM technique is the most suitable apparatus for flicker mitigation purposes now a day. Recent progresses in voltage and current ratings of the power switches allow using integrated gate bipolar transistors (IGBTs) with high switching frequencies improving the speed of response. A shunt-connected VSC mounting IGBTs and operated with PWM is normally referred to as "Statcom" or "D-Statcom," as it is normally installed at distribution levels, as shown in Fig 1.5. This device is available in market with different names. Manufacturers are successfully producing these devices.

1.6.3 Harmonics Mitigation

1.6.3.1 Passive filtering

Passive filters for harmonic reduction provide low impedance paths for current harmonics [9]. Thus, the current harmonics flow into the shunt filters instead of back to the supply. The passive filter consists of series LC filters tuned for specific harmonics, normally combined with a high pass filter used to eliminate the rest of the higher-order current harmonics. The shunt filter is the most common type of filtering scheme used in industry because of economic consideration and benefits such as power factor correction

[3]. Depending on the frequency response characteristics, there are different types of shunt filters. Some examples are the single-tuned filter, the 2^{nd} order filter and the high pass filter. The series filter has the capability of blocking harmonic currents. It is a parallel-tuned circuit that offers high impedance to the harmonic current. It is not used often because it is difficult to insulate and load voltage is very often distorted. The drawbacks with passive filters are that they are strongly dependent on the system impedance, which depends on the distribution network configuration and the loads. Therefore, the system impedance, which changes continuously, strongly influences the filtering characteristics.

1.6.3.2 ***Active filtering***

A shunt active filter consists of a controllable voltage source behind a reactance acting as a current source. The VSC based shunt active filter is by far the most common type used today, due to its well-known topology and straightforward installation procedure. It consists of a dc-link capacitor, power electronic switches and filter inductors between the VSC and the grid as shown in Fig 1.6. The operation of shunt active filters is based on injection of current harmonics in phase with the load current harmonics, thus eliminating the harmonic content of the line current. A typical active filter includes a power electronic converter with either a capacitor or inductor acting as an energy storage element and a controller for determining the desired reference signal and generating the converter gating pulse patterns.

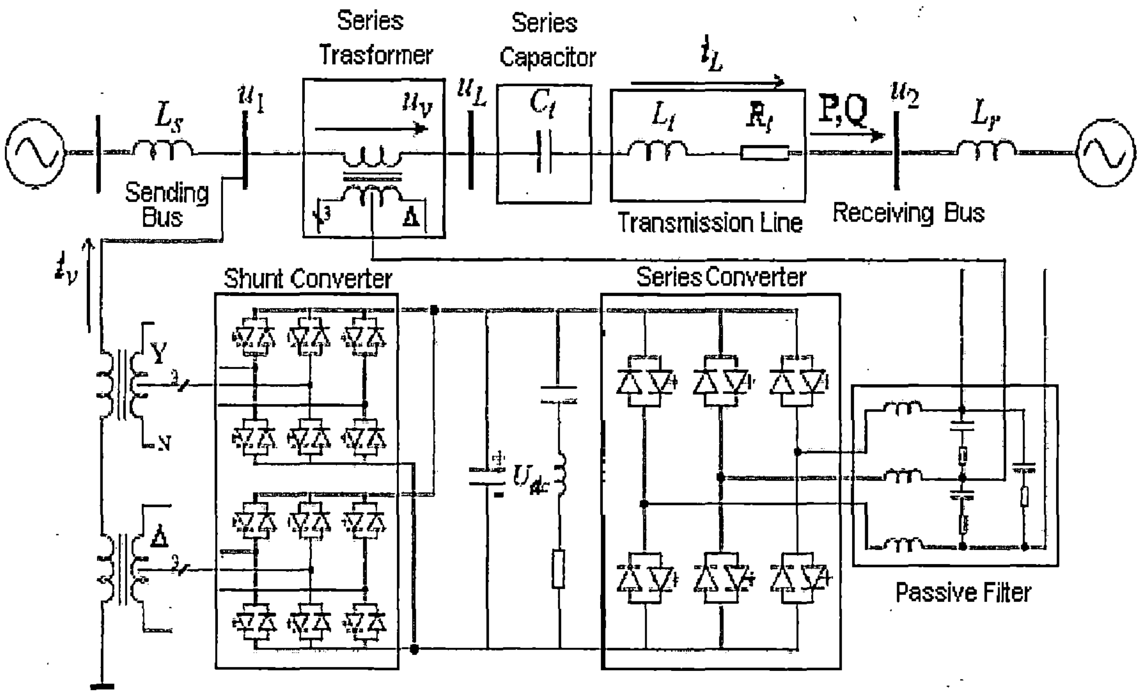


Figure 1.3: - Schematic of UPFC

1.6.3.3 *Alternative methods (current injection)*

Current injection technique is mainly based on injecting a 3rd current harmonic in the interphase transformer of converters [4]. Two groups of converters have to be available. As well, the source of the 3^{rd} current harmonic is connected between the star points of the two groups as shown in Fig 1.7. The injected current circulates within the two converters groups and the transformer secondary winding. Selecting the appropriate phase shift and magnitude of the injected current one current harmonic can be eliminated and other harmonics can be reduced significantly. The order of the compensated harmonic is determined by the magnitude of the injected current. The current sources in the developed schemes are connected across the secondary windings of the converter transformer allowing this technique to be applied to any type of converter. This scheme does not suffer from the problems associated with filtering, in particular the effect of system impedance. Although this scheme does not eliminate completely more than one harmonic for a given operating condition, it provides a significant improvement.

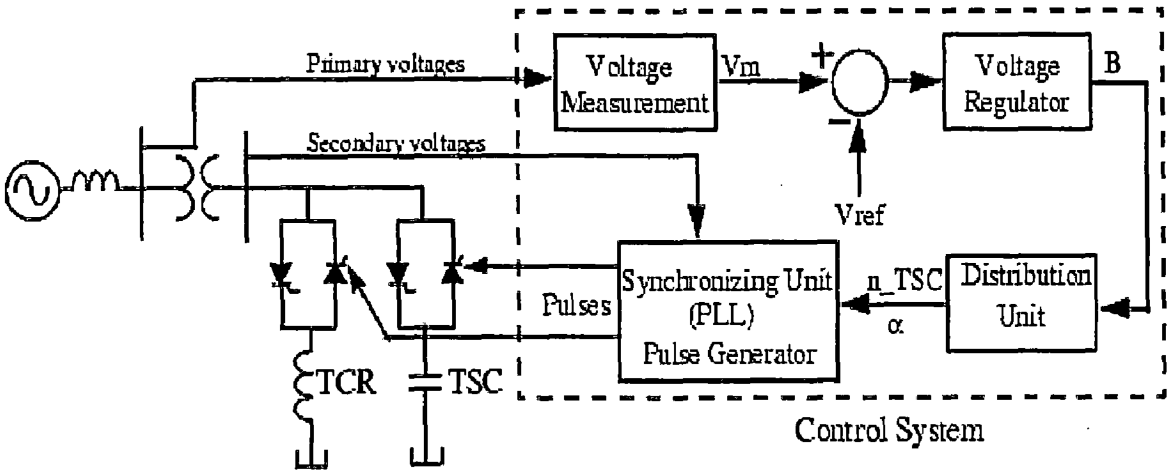


Figure 1.4: - Static Var Compensator

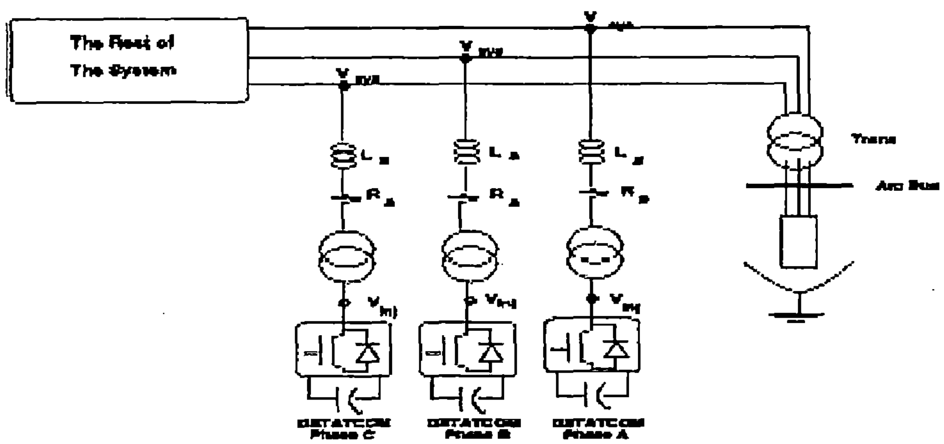


Figure 1.5: - D-STATCOM for flicker mitigation

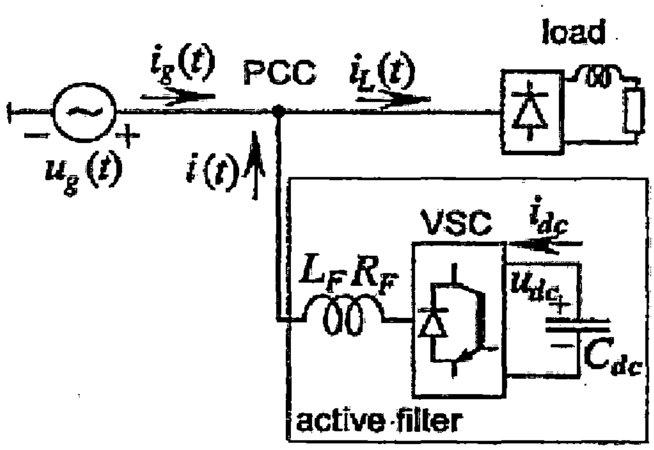


Figure 1.6: - Principle Scheme of Active filtering using VSC

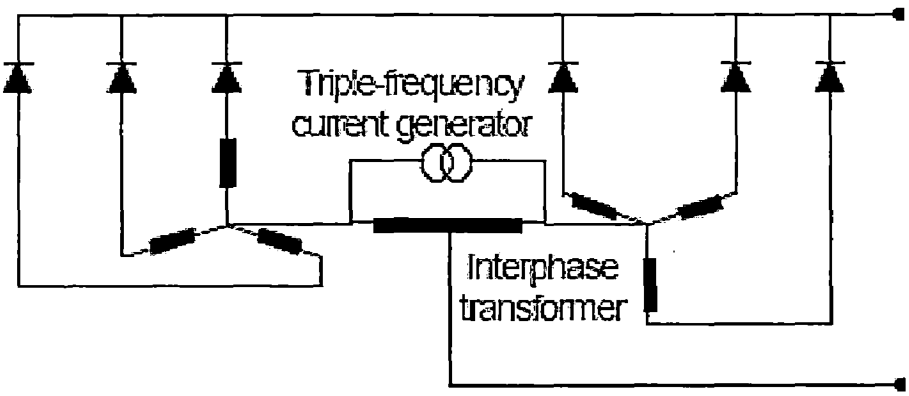


Figure 1.7: - Principle of harmonic elimination by the harmonic injection technique

MODELING OF SMALL HYDRO POWER STATION

2.1 INTRODUCTION

The equipments for power quality improvement are to be tested by simulation. So, it is important to develop a model for Small Hydro Power Plant, which is discussed in this chapter. Hydro power plants are power-generating stations where the potential energy of water is ultimately converted into electrical energy. Small hydro power plants are defined as the plants having generation capacity upto 25 MW where the unit capacity is limited to 5 MW. A unit consists of mainly hydro turbine and generator. Hydro turbine converts the potential energy of the water into mechanical rotation, which is then converted to electrical energy by generator. This electricity is then transmitted to load or grid near by through switchyard situated at the plant. There are other components also, the governor for the hydro turbine and the exciter for the generator. These constitute the main components of a hydro power plant. These are shown in the block diagram below in Fig 2.1.

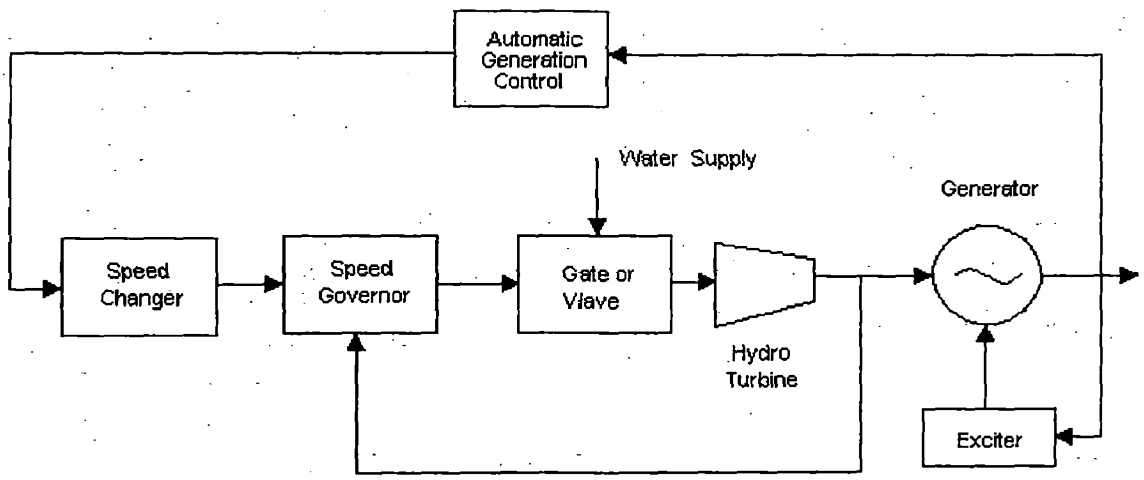


Figure 2.1: - Basic components of power generating unit with controller

The turbine is sometimes referred as prime mover also. The prime mover governing system provides a means of controlling active power and frequency, which is referred as load frequency control or Automatic Generation Control (AGC). Here the role of the speed changer is to determine the sensitivity of the governor.

2.2 MODELING OF MAIN COMPONENTS OF HYDRO POWER STATIONS

The dynamic modeling of the main components, namely Hydraulic Turbine, Governor, Exciter, Generator; of a power plant is being done by the IEEE committee. In 1973 the committee suggested a report named as "Dynamic Models for Steam and Hydro Turbines in Power System Studies", which includes hydraulic models suitable for wide range of studies. It includes modeling of two important components as given below

(i) Prime movers including water supply conduit

(ii) Prime mover speed control (governor).

Both linear and non-linear model of the prime mover has been described. Non-linear models are required for the situations where speed and power changes are large, such as in islanding, load rejection and system restoration studies. Models of the main components, which will be used for the simulation, are described below.

2.2.1 Hydraulic Turbine [10]

The dynamic characteristics of a simple hydraulic turbine with penstock can be represented by the block diagram as shown in Fig 2.2. For the purpose of simplification in developing this model two assumptions are taken as described below

(i) The penstock is modeled assuming an incompressible fluid and rigid conduit

(ii) No Surge Tank.

From the laws of momentum, the rate of change of flow in the conduit is

$$\frac{d\overline{q}}{dt} = \left(\overline{h}_0 - \overline{h} - \overline{h}_l\right) g \, A/L \tag{2.1}$$

where, $\overline{q}$ = turbine flow rate m^3/sec

$\overline{h}_0$ = static head of water column, m

$\overline{h}$ = head at the turbine intake, m

$\overline{h}_l$ = head loss due to friction in the conduit, m

g = acceleration due to gravity, m/sec^2

A = penstock cross section area, m^2

L = length of penstock, m

The equation (2.1) can be written in per unit as

$$\frac{dq}{dt} = \frac{\left(1 - h - h_l\right)}{T_w} \tag{2.2}$$

where the h_{base} is defined as the static head of the water column above the turbine.

T_w is called the water time constant or water starting time, and can be expressed as

$$T_w = \left(\frac{L}{A}\right) \frac{q_{base}}{h_{base}\, g} \quad \text{secs.} \tag{2.3}$$

q_{base} is chosen as the turbine flow rate with gates fully open and head at the turbine equal to h_{base}.

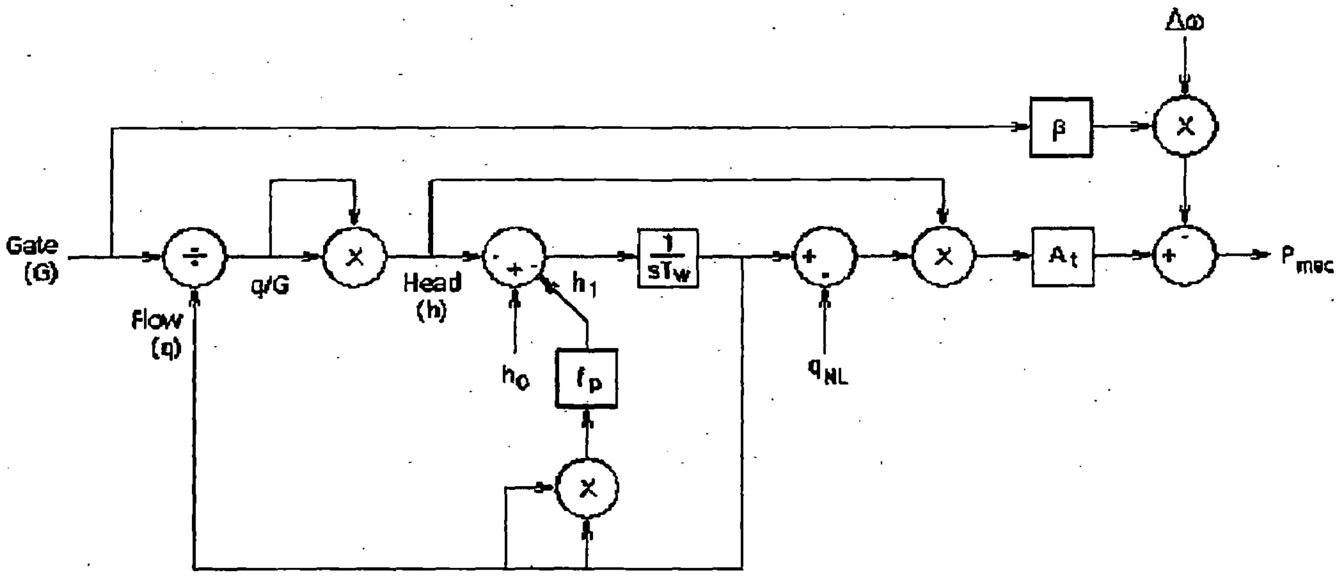


Figure 2.2: - Transfer function block diagram of Turbine

Different parameters shown in the block diagram are defined as below

A_t = Turbine Gain Factor Flow

f_p = Penstock Head Loss Coefficient [p.u.]

G = Gate Position [p.u.]

q = Turbine Flow Before reduction by Deflector and Relief valves [p.u.]

q_{nl} = No load water flow [p.u.]

T_w = Water Starting Time [s]

β = Speed deviation Damping Constant

Δw = speed deviation

The input and output for this model are

Input: - G = Gate position;

Output: - P_{mach} = Mechanical power

The per unit flow rate through the turbine is given by

$$q = G\sqrt{h} \tag{2.4}$$

In an ideal turbine, mechanical power is equal to flow times head with appropriate conversion factors. The fact that the turbine is not 100% efficient is taken into account by subtracting the no load flow from the actual flow giving the difference as the effective flow, which multiplied by head produces mechanical power. There is also a speed deviation damping effect, which is a function of gate opening. Per unit turbine power, P_m on generator MVA base is thus expressed as,

$$P_m = A_t h(q - q_{nl}) - DG\Delta w \tag{2.5}$$

The no load flow q_{nl} is accounted for turbine fixed power losses. A_t is a proportionality factor and is assumed constant. It is calculated using turbine MW rating and generator MVA base.

$$A_t = \frac{\text{Turbine MW rating}}{(\text{Generator MVA rating})h_r(q_r - q_{nl})} \tag{2.6}$$

where, h_r is the per unit head at turbine at rated flow and q_r is the per unit flow at rated head. Sometimes this factor A_t is used to convert the actual gate position to the effective gate position, i.e. $A_t = 1/(G_{fl} - G_{nl})$. Then separate factor is used to convert the power from turbine rated power base to that of the generator volt-ampere base.

The mechanical torque (T_m) can be derived from the mechanical power (P_{mach}) as

$$T_m = \frac{P_{mach}}{w} \tag{2.7}$$

where, w = speed of the turbine runner.

This mechanical torque (T_m) is the input to the generator.

2.2.2 Hydraulic Turbine Governor

The speed of the rotating part of Turbine-Generator unit changes with load. However, to produce the rated output voltage and frequency the speed should be constant. For the purpose of maintaining the speed constant with varying load, the governors are used with the turbines. The hydraulic turbine governor is such of a kind, which consists of a speed governor, a pilot valve, PID controller and servomotor. A functional block diagram of hydraulic turbine governing system is shown in Fig 2.3 below. The same is being used in the simulation presented here.

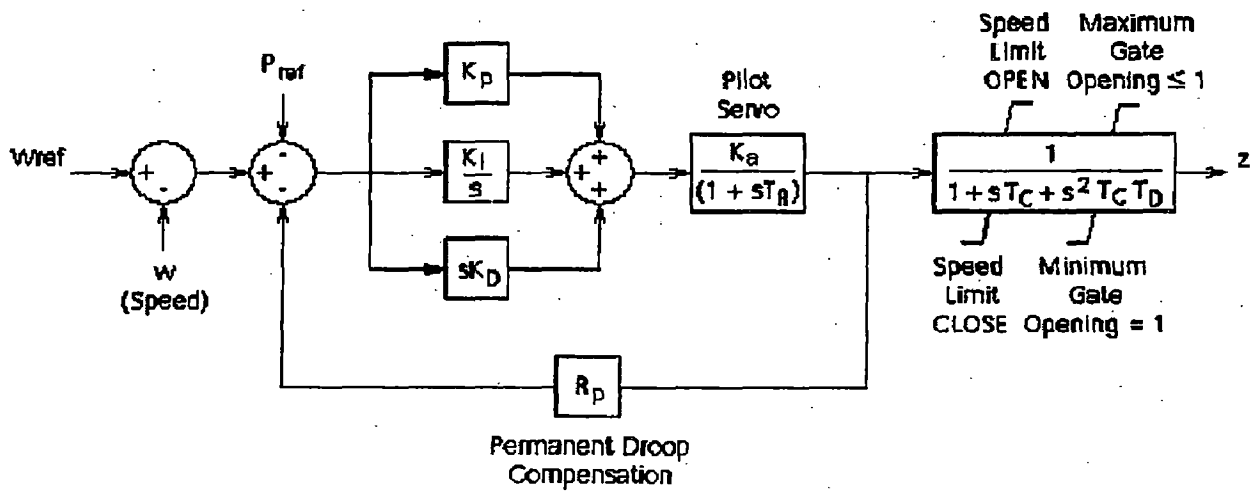


Figure 2.3: - Hydraulic Turbine PID Governor

Different parameters shown in the block diagram are defined as below

K_D = Derivative Gain [p.u.]

K_I = Integral Gain [p.u.]

K_P = Proportional Gain [p.u.]

K_a = Servo gain [pu]

T_A = Pilot Servomotor Time Constant [s]

T_C = Gate Servo Gain [s]

T_D = Gate Servomotor Time Constant [s]

R_P = Permanent Droop [p.u.]

The input and output for this model are

Input: - W_{ref} = Speed reference [p.u.] , W = speed [p.u.]

Output: - z = Gate position

The governor shown in Fig 2.3 above also includes a PID controller and Permanent droop compensation. The permanent droop determines the speed regulation under steady state conditions. It is defined as the speed drop in percent or per unit required to drive the gate from minimum to maximum opening without any change in speed reference.

2.2.3 Synchronous Generator [11]

Synchronous generators are mostly used in all kinds of hydropower Plants. The performance of these generators are considered to be better than induction machines. The simulation of small hydropower station is done here with synchronous generator. The derivation of the generator model is done by its representation using per unit quantities and equivalent circuit on d- and q- axes. The d- and q-axes equivalent circuit models of synchronous generator are shown in Fig 2.4(a) and 2.4(b) below.

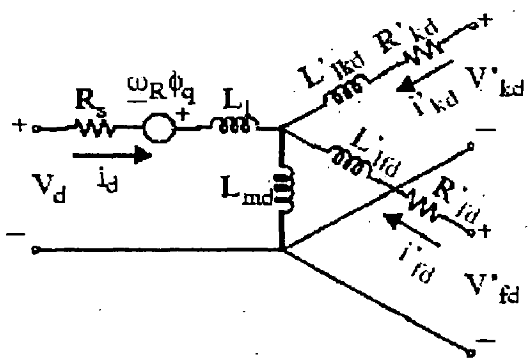


Figure 2.4(a): - d-axes equivalent circuit of Synchronous Generator

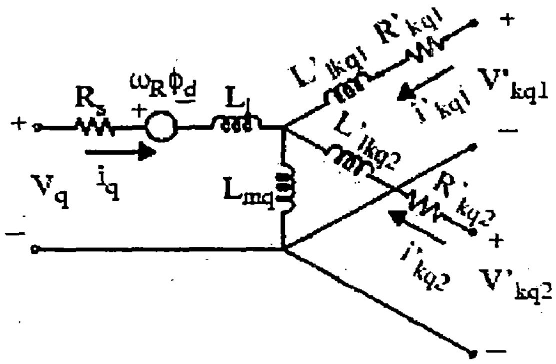


Figure 2.4(b): - q-axes equivalent circuit of Synchronous Generator

The components of the equivalent circuit above are described below.

L = inductance in H

R = Resistance in Ohm

V= Voltage in Volt

i = Current in Amp

ϕ = flux in Weber

ω = speed of the rotor in rad/s

The suffixes used in the equivalent circuit above are described as below.

d,q: - d and q axis quantity

R,s: - Rotor and stator quantity

l,m: - Leakage and magnetizing inductance

f,k: - Field and damper winding quantity

The governing differential equations of the synchronous generator are given below.

$$V_d = R_s i_d + \frac{d}{dt}\varphi_d - \omega_R \varphi_q \tag{2.8}$$

$$V_q = R_s i_q + \frac{d}{dt}\varphi_q + \omega_R \varphi_d \tag{2.9}$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\varphi'_{fd} \tag{2.10}$$

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\varphi'_{kd} \tag{2.11}$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\varphi'_{kq1} \tag{2.12}$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\varphi'_{kq2} \tag{2.13}$$

$$\varphi_d = L_d i_d + L_{md}\left(i'_{fd} + i'_{kd}\right) \tag{2.14}$$

$$\varphi_q = L_q i_q + L_{mq} i'_{kq} \tag{2.15}$$

$$\varphi'_{fd} = L'_{fd} i'_{fd} + L_{md}\left(i_d + i'_{kd}\right) \tag{2.16}$$

$$\varphi'_{kd} = L'_{kd} i'_{kd} + L_{md}\left(i_d + i'_{fd}\right) \tag{2.17}$$

$$\varphi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q \tag{2.18}$$

$$\varphi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q \tag{2.19}$$

2.2.4 Excitation system [12]

The main objective of the excitation system is to control the field current of the synchronous generator. The field current is controlled so as to regulate the terminal voltage of the generator. As the field circuit time constant is high, fast control of the filed current requires field forcing. Thus exciter should have a high ceiling voltage, which enables it to operate transiently with voltage levels that are 3 to 4 times the normal. The rate of change of voltage should also be very fast. There are different types of excitation system. However, the IEEE Type 1 excitation system is one, which is widely used.

The block diagram representation of the AC excitation system is shown in Fig 2.5. This one is IEEE Type 1 without saturation function and with Transient Gain Reduction (TGR).

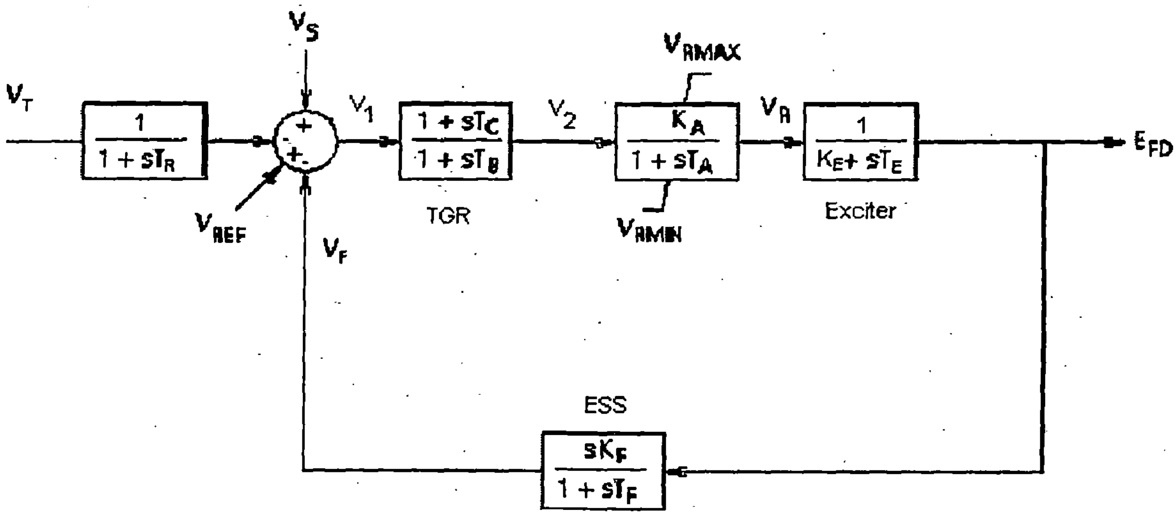


Figure 2.5: - Excitation system IEEE Type 1

Different parameters shown in the block diagram are defined as below

V_T = Terminal voltage of synchronous generator [p.u.]

T_R = Time constant of filter [s]

V_{Ref} = Voltage regulator reference (determined to satisfy initial conditions) [p.u.]

V_S = Combined power system stabilizer and possibly discontinuous control output after any limits or switching, as summed with terminal voltage and reference signals [p.u.]

T_B, T_C = Transient Gain Reduction time constants [s]

V_F = Excitation system stabilizer output [p.u.]

V_{AMAX}, V_{AMIN} = Maximum and minimum regulator output limits [p.u.]

K_A = Voltage regulator gain [p.u.]

T_A = Voltage regulator time constants [s]

V_R = Voltage regulator output [p.u.]

T_E = Exciter time constant [s]

K_E = Exciter constant related to self-excited field [p.u.]

K_F = Excitation control system stabilizer gain [p.u.]

T_F = Excitation System Stabilizer time constant [s]

E_{FD} = Exciter output voltage [p.u.]

The terminal voltage of synchronous generator is measured and transformed in to ac quantity by passing it through a filter. The filter may be complex, but it is usually modeled as a single time constant T_R. the Excitation System Stabilizer (ESS) block in the feedback path is used for increasing the stable region of operation of the excitation system and permit higher regulator gains. The feedback control system often requires lead/lag compensation or derivative feedback. Instead of feedback compensation for ESS, a series connected lead/lag functional block can also be used. This block, as shown in Fig 2.5, is known as TGR or Transient Gain Reduction. The objective of TGR is to reduce the transient gain at higher frequencies, thereby minimizing the negative contribution of the regulator to system damping. The governing equations of excitation system in frequency domain are shown below.

$$V_1 = V_{ref} + V_S - V_F - V_T\left(\frac{1}{1+sT_R}\right); \quad \text{with } V_T(0) = 1 \text{ [pu]} \tag{2.20}$$

$$V_2 = V_1\left(\frac{1+sT_C}{1+sT_B}\right); \quad \text{with } V_1(0) = \frac{K_E . V_T(0)}{K_A} \tag{2.21}$$

$$V_R = V_2\left(\frac{K_A}{1+sT_A}\right); \quad \text{with } V_2(0) = K_E V_T(0) \tag{2.22}$$

$$E_{FD} = V_R\left(\frac{1}{K_E + sT_E}\right); \quad \text{with } V_R(0) = K_E V_T(0) \tag{2.23}$$

$$V_F = E_{FD}\left(\frac{sK_F}{1+sT_F}\right); \quad \text{with } E_{FD}(0) = V_T(0) \tag{2.24}$$

2.3 SIMULATION OF A SMALL HYDRO POWER STATION

The simulation of a Small Hydropower station is done with Hydro Turbine, Mechanical Hydraulic Governor, Synchronous Machine and IEEE Type 1 exciter. The turbine generator unit is having a rating of 625 kVA and the synchronous generator is generating power at 415 volt. It is then stepped up to 11 kV to connect to 11 kV grid. The grid is being modeled as a 3-phase source of 11 kV with high base MVA (10000 MVA). The transformer are considered to be ideal, i.e., non-saturable core. PI model of transmission line has been used here. A 300 kW load is connected at distance of 20 km. The model is being shown in Fig 2.6.

2.3.1 Simulation Parameters

2.3.1.1 Synchronous Generator model parameters

Rated Output = 625 kVA

Rated Power Factor = 0.8

Rated RPM = 750

Run away Speed in RPM = 2175

Voltage = 415 Volt

Frequency = 50 Hz

Moment of inertia = 77.7 kgm^2

d-axis synchronous reactance (X_d) = 0.6 pu.

d-axis transient reactance (X_d') = 0.06643 pu

d-axis sub-transient reactance (X_d'') = 0.03178 pu

q-axis synchronous reactance (X_q) = 0.33571 pu

q-axis sub-transient reactance (X_q'') = 0.03143 pu

d-axis short circuit transient time constant (T_d') = 0.23 s

d-axis short circuit sub-transient time constant (T_d'') = 0.011 s

q-axis open circuit sub-transient time constant (T_{qo}'') = 2.2 s.

2.3.1.2 Hydro turbine and governor turbine model parameters

Derivative Gain (K_D) = 0

Integral Gain (K_I) = 0.015 [p.u.]

Proportional Gain (K_P) = 1.163 [p.u.]

Servo gain (K_a) = 3.5 [pu]

Pilot Servomotor Time Constant (T_A) = 0.07 [s]

Permanent Droop (R_P) = 0.05 [p.u.]

Water starting Time (T_w) = 2.67 s

Speed deviation damping constant (β) = 0

2.3.1.3 Exciter model parameters

Time constant of filter (T_R) = 20×10^{-3} [s]

Maximum and minimum regulator output limits (V_{AMAX}, V_{AMIN}) = 11.5, -11.5 [p.u.]

Voltage regulator gain (K_A) = 300 [p.u.]

Voltage regulator time constants (T_A) = 0.001 [s]

Exciter time constant (T_E) = 0 [s]

Exciter constant related to self-excited field (K_E) = 1 [p.u.]

Excitation control system stabilizer gain (K_F) = 0.001[p.u.]

Excitation System Stabilizer time constant (T_F) = 0.1 [s]

Transient Gain Reduction time constants (T_B, T_C) = 0,0 [s].

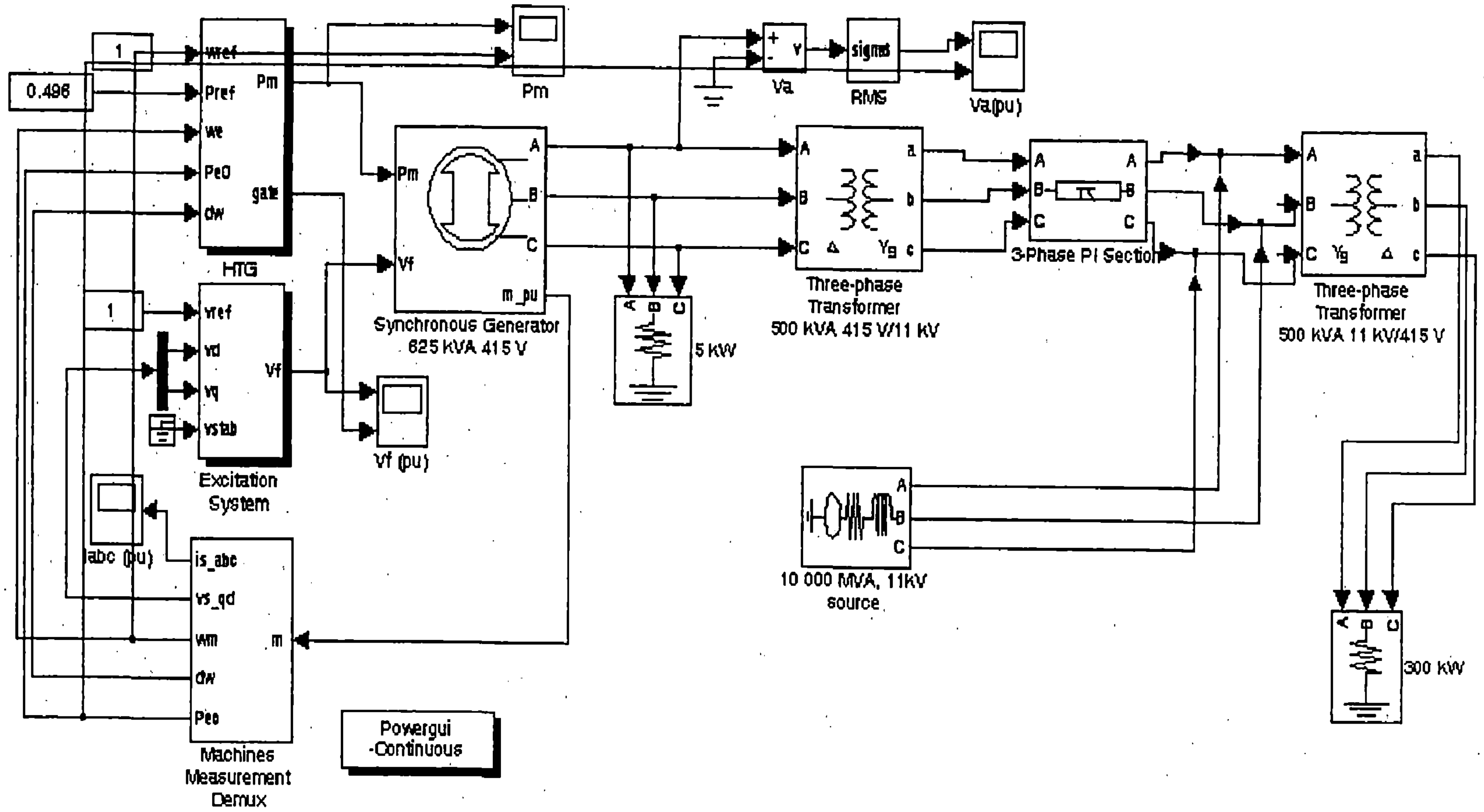


Figure 2.6: - Simulink model of Small Hydropower station with Transmission line and Load

2.3.1.4 Initial conditions for simulation in steady state

To start the simulation of the small hydro power station model developed in MATLAB/SIMULINK, the initial conditions for different parameters are required. Initial value of the parameters are required for solving the differential equations used for developing models of different components. For this purpose the load flow study of the system is done. The value of the initial conditions are determined from load flow study and then updated to the model.

2.3.2 Simulation Results

The simulation results are shown by plotting the graph of the following quantities as listed below.

(a) Synchronous generator terminal voltage (V_t)

(b) Mechanical power (P_m)

(c) Field voltage (V_f)

(d) Speed of the rotor (ω_m)

(e) Gate opening (G)

(f) Electrical output power

The model is simulated for different normal and abnormal situation and for each case the plot of above mentioned quantities are done. At no load condition, the gate opening and mechanical power are very nearly equal to zero. The electrical power is zero and the speed and field voltage are 1 p.u. Small gate opening or mechanical power is required to supply for the frictional losses. Terminal voltage is at rated value, i.e., 240 volts.

In the 2nd condition load is suddenly rejected from 300 kW to 0 at 1 sec. The mechanical power and gate opening are getting reduced sharply. While the terminal voltage remains almost constant. The speed increases first and then settles down to a value, which is nearly equal to 1 p.u. Transients are observed in the field voltage and it also settles to steady state after few cycles.

In the 3rd condition a three phase to ground fault has been created at the transmission level at 3 sec. The fault is cleared at 3.1 sec. Transients are being observed in all quantities. But after a few cycles all the quantities settle down to steady state.

The results are shown in Fig 2.7 to Fig 2.24. The results show that the developed model of SHP station is working properly under normal and abnormal conditions.

2.3.2.1 At no load condition

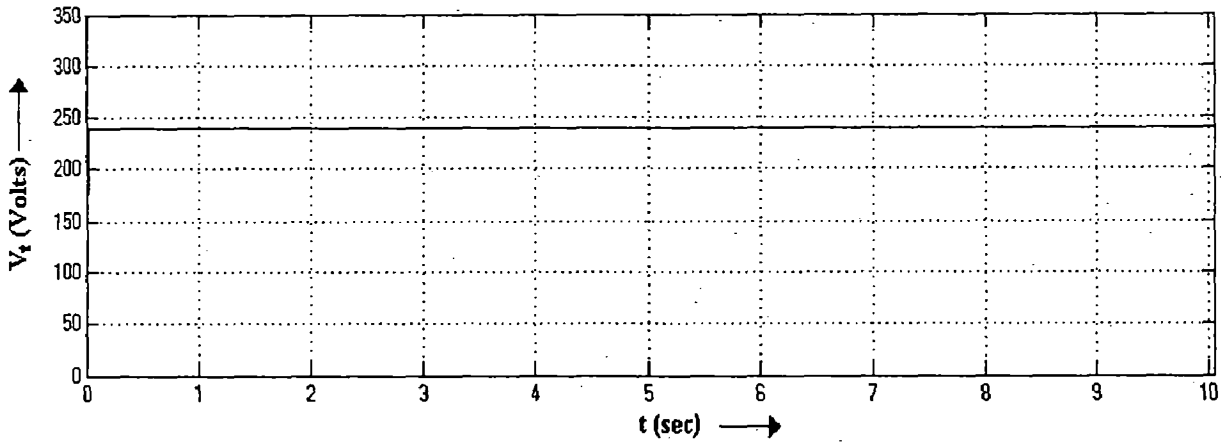


Figure 2.7: - Synchronous generator terminal voltage (r.m.s.) at no load

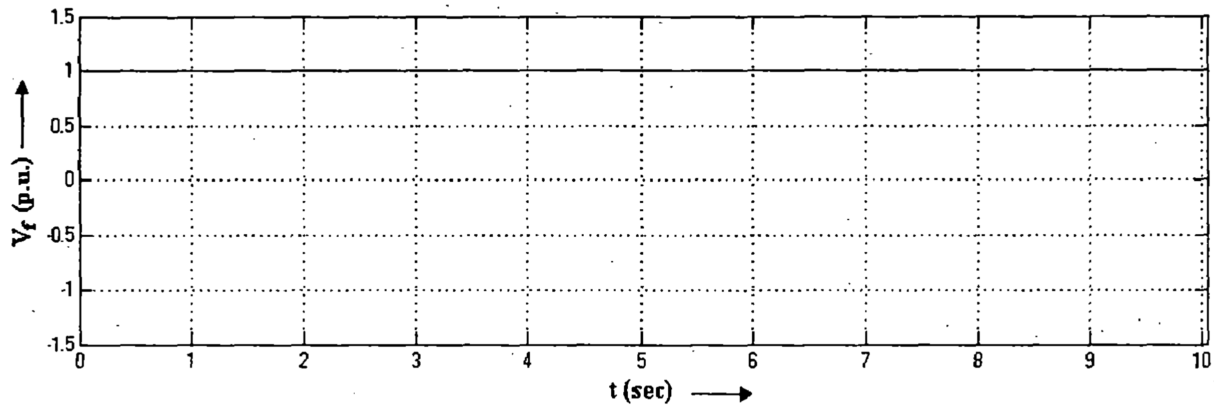


Figure 2.8: - Field voltage at no load

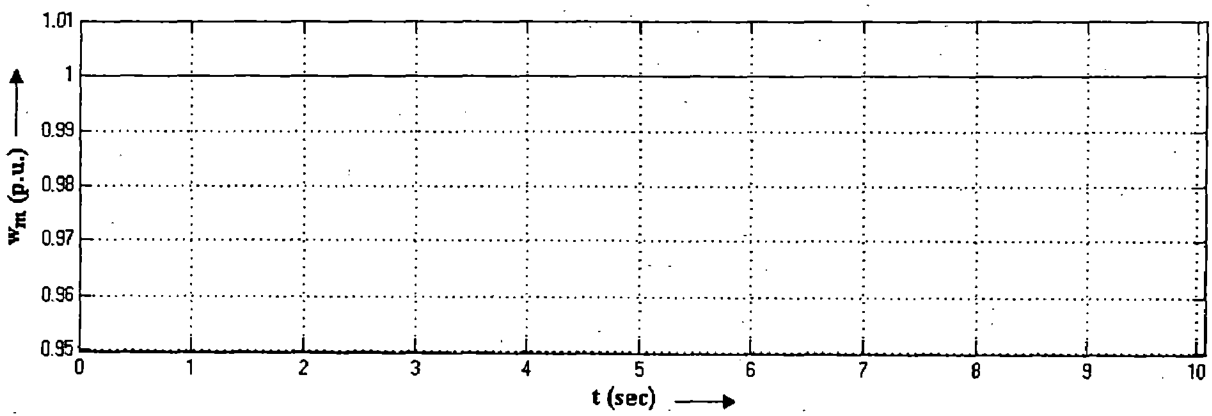


Figure 2.9: - Rotor Speed at no load

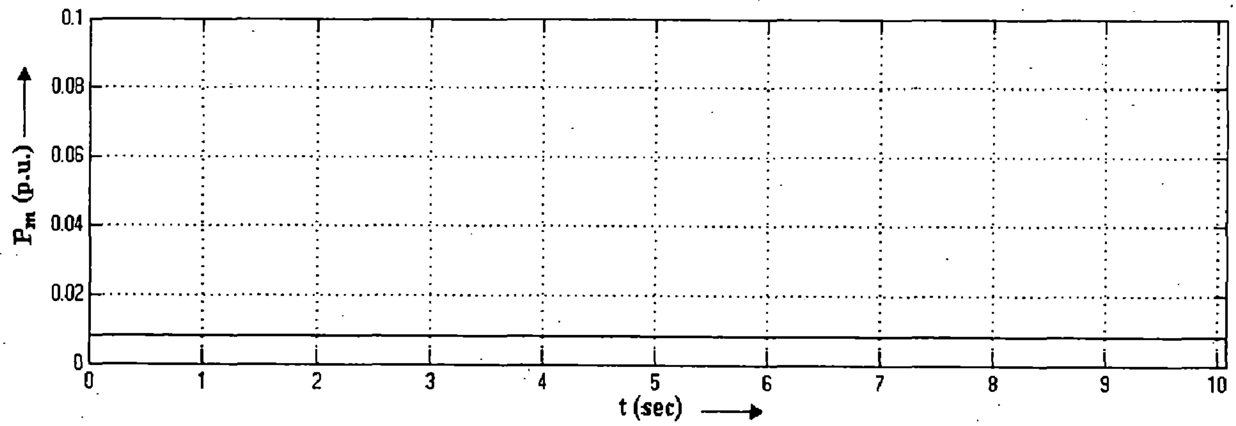


Figure 2.10: - Mechanical power at no load

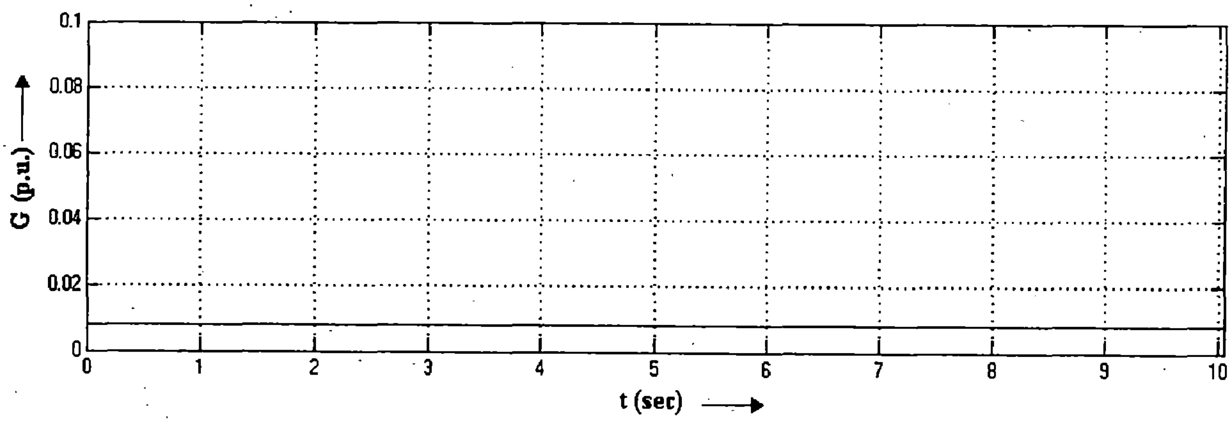


Figure 2.11: - Gate opening at no load

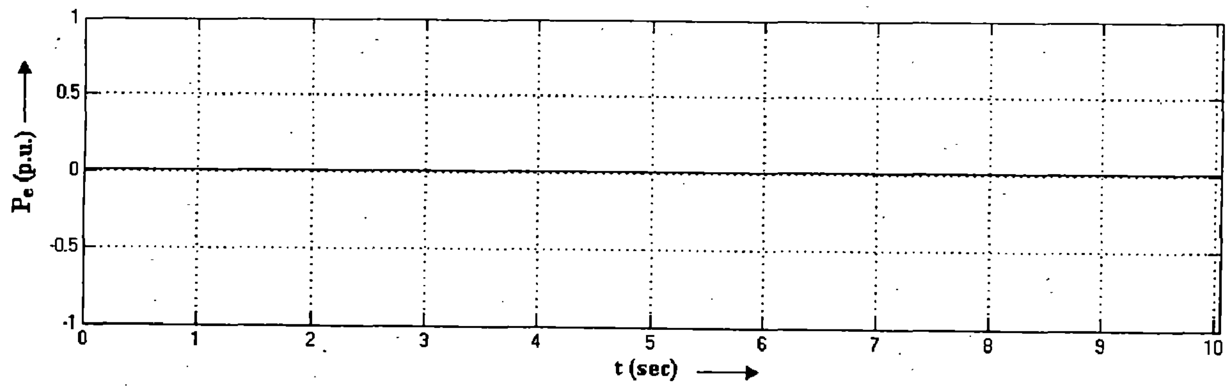


Figure 2.12: - Electrical power output at no load

2.3.2.2 Load rejection from 300 kW

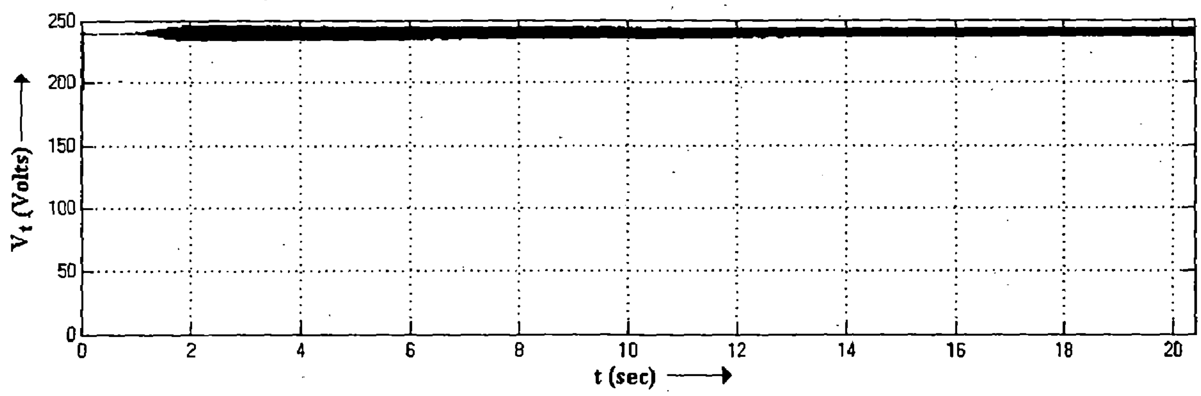


Figure 2.13: - Synchronous generator terminal voltage (r.m.s.) at load rejection

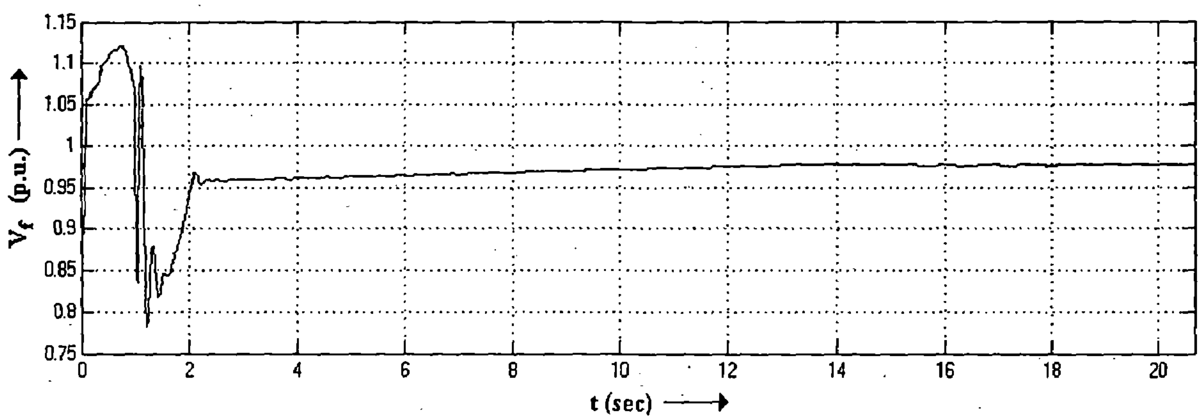


Figure 2.14: - Field Voltage at load rejection

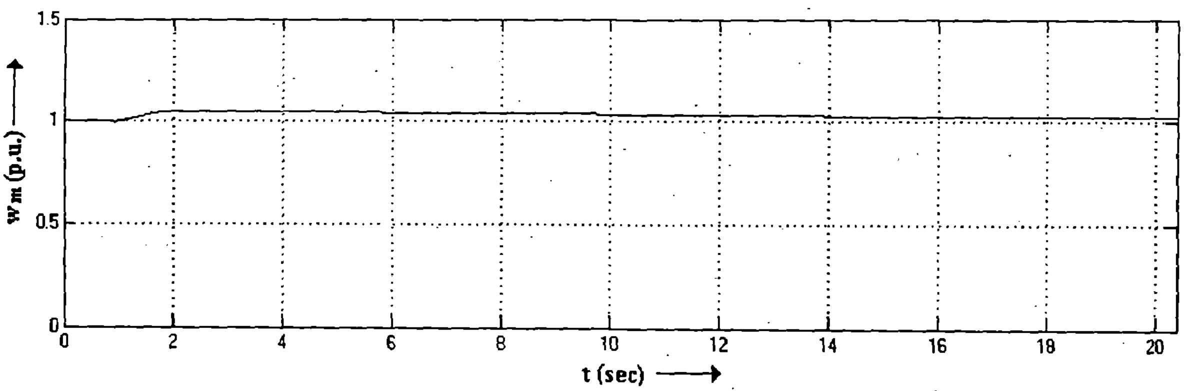


Figure 2.15: - Rotor Speed at load rejection

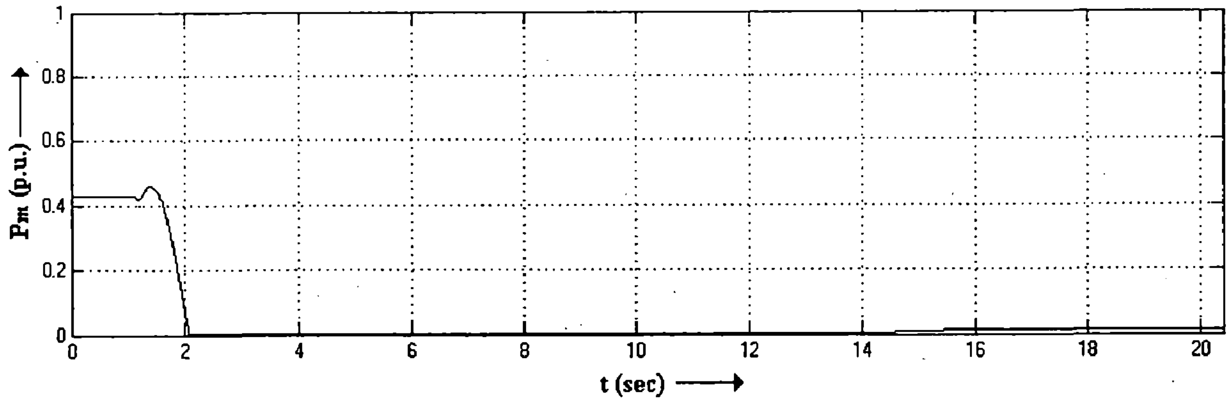


Figure 2.16: - Mechanical power at load rejection

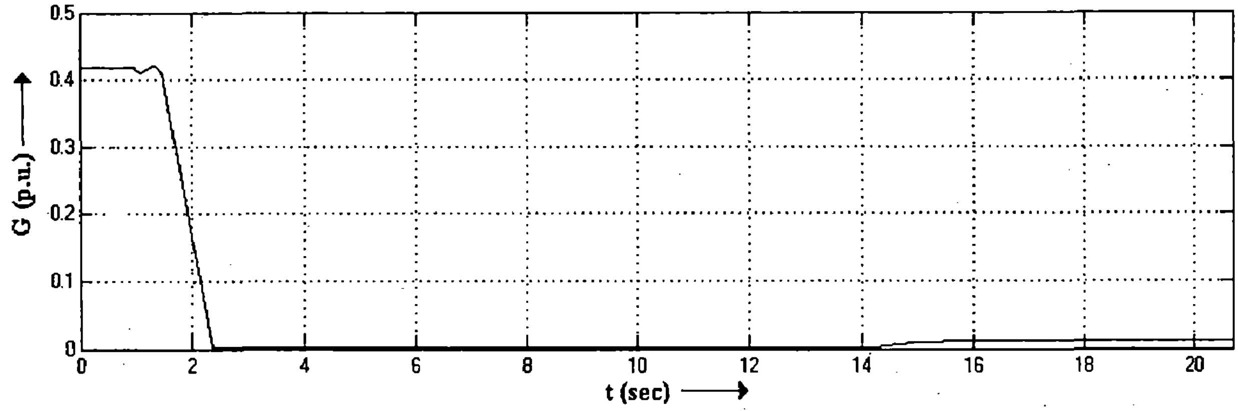


Figure 2.17: - Gate opening at load rejection

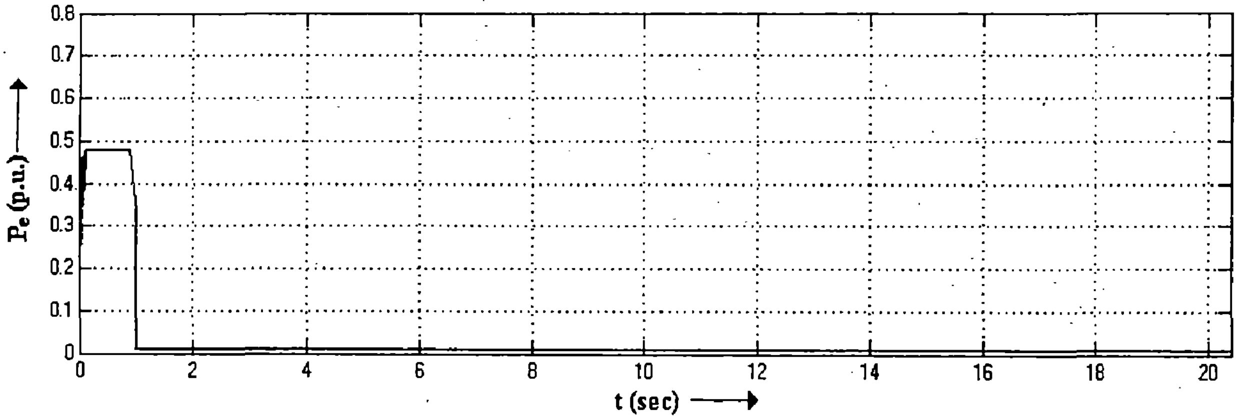


Figure 2.18: - Electrical power output at load rejection

2.3.2.3 Three phase to ground fault

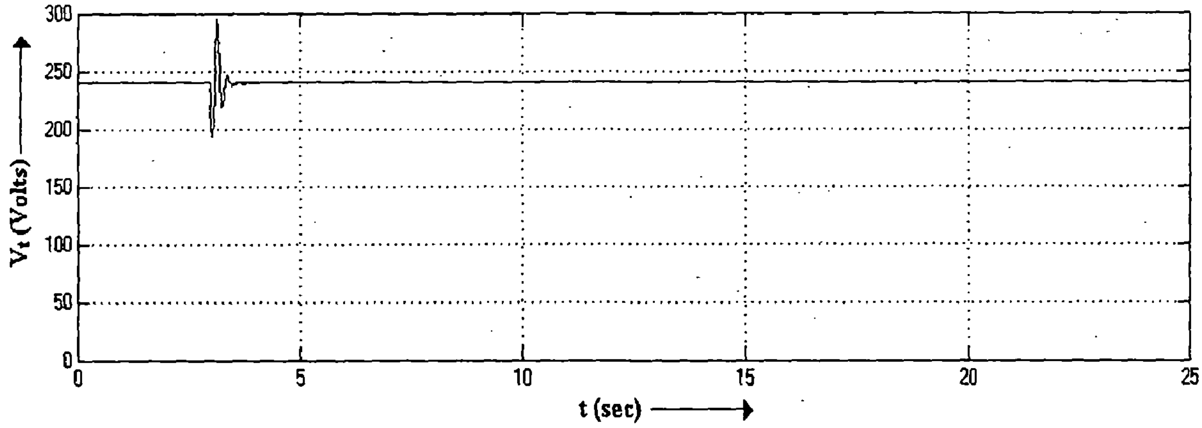


Figure 2.19: - Synchronous generator terminal voltage (r.m.s.) at 3-phase fault

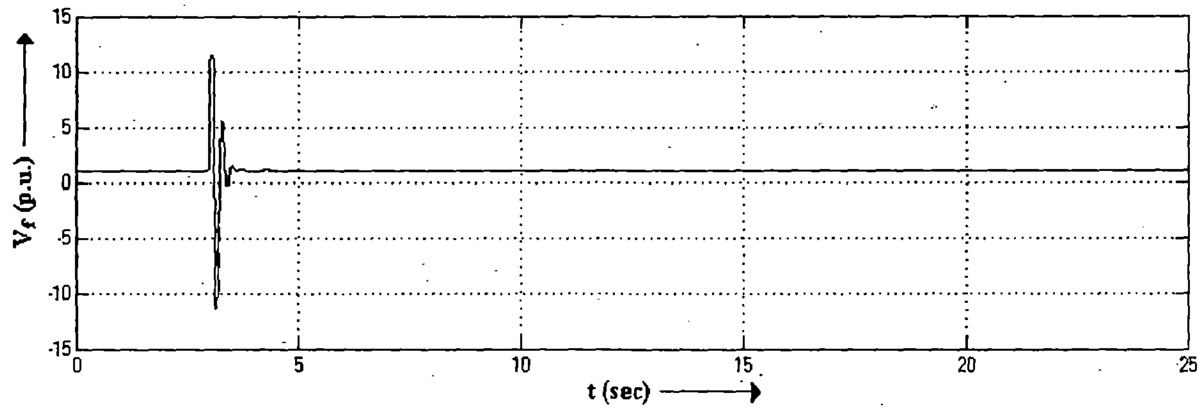


Figure 2.20: - Field voltage at 3-phase fault

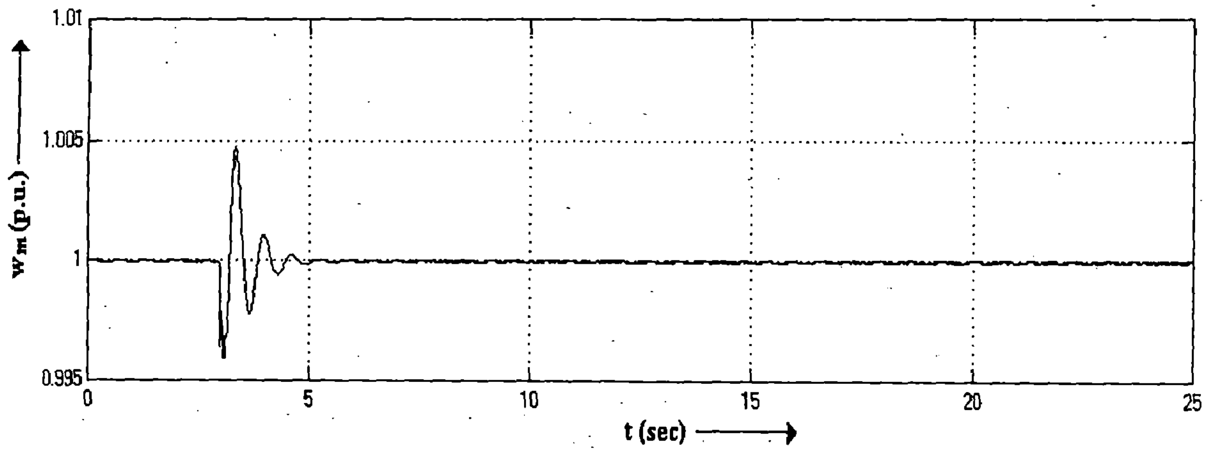


Figure 2.21: - Rotor speed at 3-phase fault

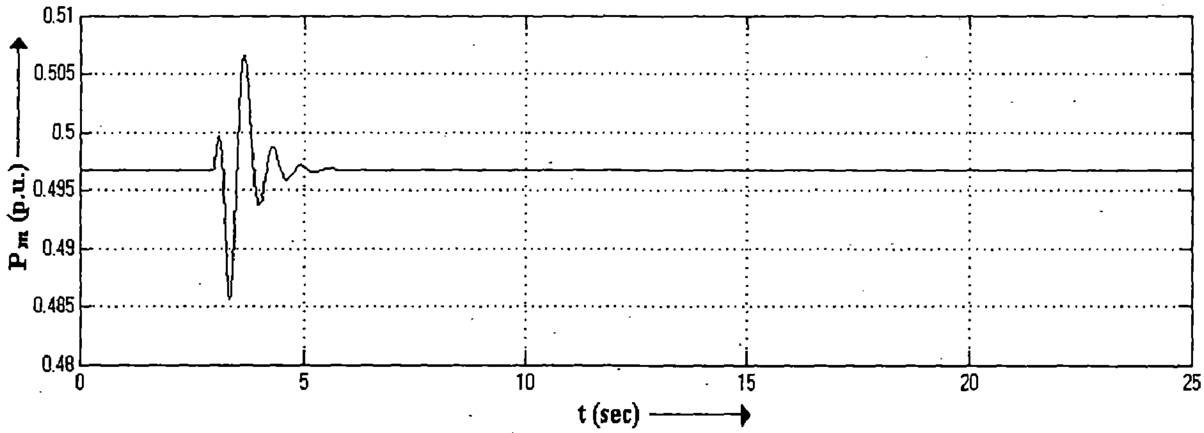


Figure 2.22: - Mechanical power at 3-phase fault

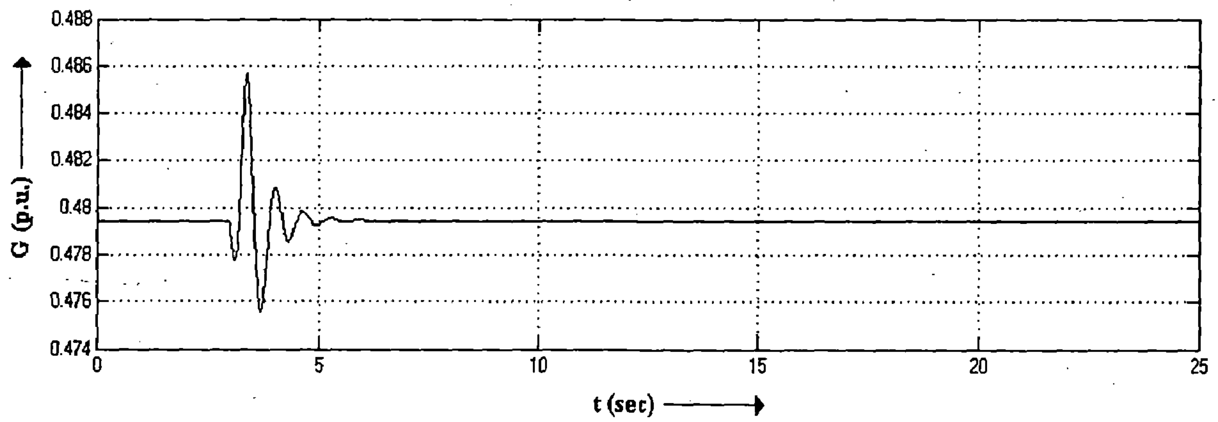


Figure 2.23: - Gate opening at 3-phase fault

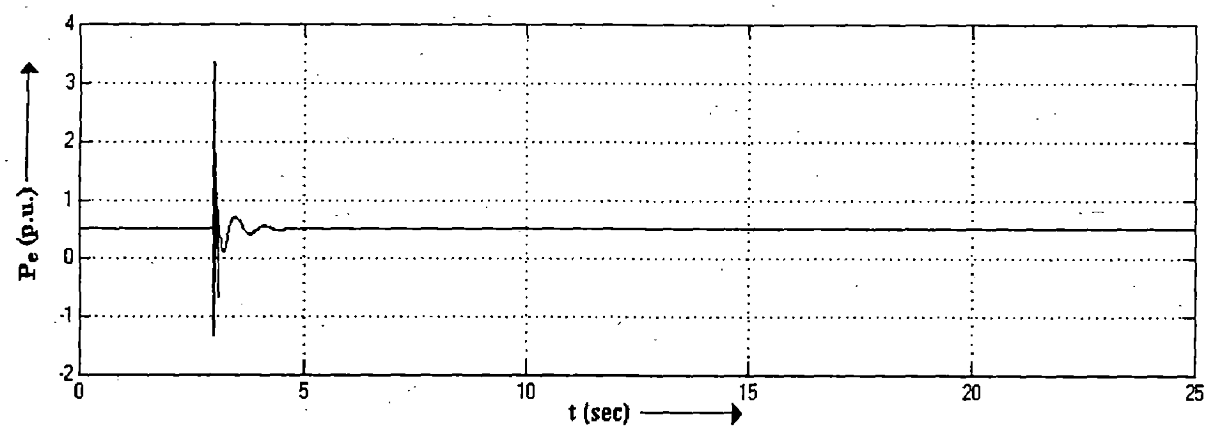


Figure 2.24: - Electrical power output at 3-phase fault

DYNAMIC VOLTAGE RESTORER FOR VOLTAGE SAG MITIGATION

3.1 INTRODUCTION

Significant deviations from the nominal voltage are a problem for sensitive consumer in the grid system. These problems are sometimes referred as voltage sags. Voltage sags are characterized by a reduction in voltage with the load connected to the supply. Voltage sags have in several cases been reported as a threat to sensitive equipments and have resulted in shutdowns, loss of production and hence a major cost burden. Voltage sag has already been discussed in chapter 1, section 1.4.1. Different mitigation techniques are also discussed in chapter 1, section 1.6.1. Here the mitigation of voltage sag through Dynamic Voltage Restorer (DVR) has been discussed in detail. A simulation study in MATLAB/SIMULINK has also been presented.

3.2 DVR PRINCIPLE

A DVR consists of an energy storage system, a Pulse Width Modulated (PWM) Voltage Source Inverter, control system, filter circuit and coupling transformer [13]. A typical schematic diagram (single line view) is shown in Fig 3.1. The energy storage system can be a DC link capacitor or simply a Dc voltage source. The primary of the coupling transformer is connected in series with the distribution line approaching a sensitive load, and the secondary is connected to the output of PWM Voltage Source Inverter. The secondary of the coupling transformer can be connected in delta or wye. The inverter output is filtered before feeding to the coupling transformer in order to nullify switching frequency harmonics. The PWM inverter plays an important role of generating appropriate voltages to be injected in series with the distribution line. The injected voltage by the inverter depends on the accuracy and dynamic behavior of the PWM voltage synthesis and control system adopted. DVRs can compensate upto 70% voltage sag. However, the compensation capacity is limited by the size of the energy storage system.

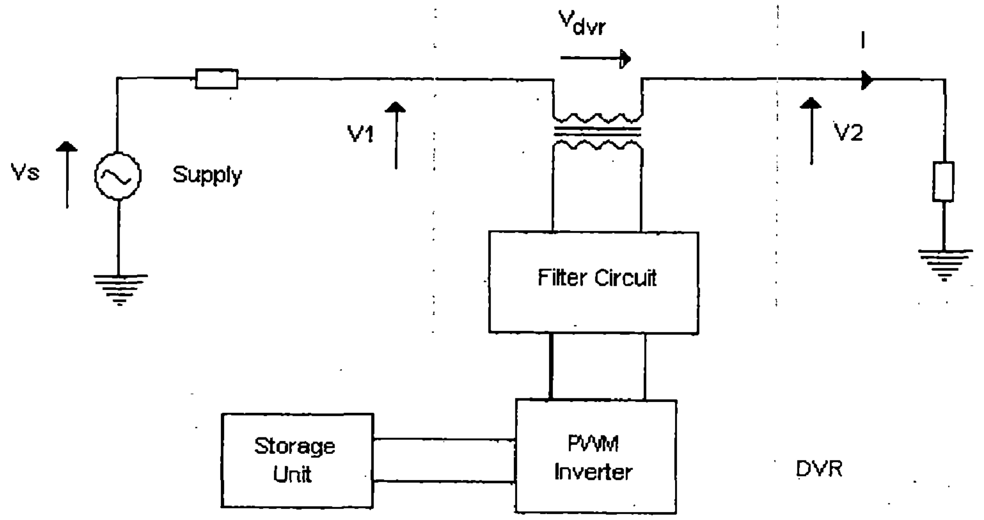


Figure 3.1: - Schematic Diagram of DVR

3.3 CONVENTIONAL CONTROL STRATEGIES

The proper control method and compensation strategy of the DVR is determined by the characteristics of the sensitive load. The linear loads are not sensitive to phase angle jump, only voltage magnitude is important. But his is not case for a non-linear load. The control techniques should also consider the limitations of the DVR such as the voltage injection capability (converter and transformer rating) and energy storage system limitation. Three conventional control strategies are described below.

3.3.1 Pre-sag Compensation Strategy

The most nonlinear loads such thyristor-controlled loads, which use the supply voltage phase angle as a set point, are sensitive to phase jumps [14]. To overcome this problem, this control technique compensates the difference between the sagged and the pre-sag voltages by restoring the instantaneous voltages to the same phase and magnitude as the nominal pre-sag voltage. The drawback is the capacity limitation of energy storage device for the injection of real power.

3.3.2 In-phase Compensation Strategy

In this strategy the restored voltage is in phase with the measured supply voltage. The advantage of this method is that the magnitude of the injected voltage is minimum. Therefore, for a given load current and voltage sag the apparent power of DVR is minimized.

3.3.3 Energy Optimal Compensation

In this method the energy storage system is fully utilized. The information about the load current is used to minimize the depletion of the energy storage.

3.4 MODELING AND SIMULATION OF POWER SYSTEM WITH DVR

The model is developed here for a simple power system with DVR feeding a single load. The model is developed in MATLAB/SIMULINK software environment. The Hydropower station here is replaced by a three-phase source of same rating, for the sake of simplicity. The same model of DVR can also be implemented with a Hydropower station model. The entire model of the system is shown in Fig 3.2. Different components of the model are separately discussed. The source used in this model is of 50 Hz and 415 Volt rms (phase-phase). The load used here is a 3-phase parallel RC type with 1 kW active and 0.1 kVAr capacitive reactive power. Different simulation parameters are also described.

3.4.1 Voltage Source Inverter

A 6-pulse bridge inverter configuration is used for the purpose of modeling of Voltage Source Inverter as shown in Fig 3.3. Gate Turn Off Thyristors (GTO) has been used as power electronic switches with diodes connected in anti-parallel. GTOs are effective power switches, which can be turned off by sending a '0' pulse to its gates, thus eliminating the requirement of separate commutation circuit. Snubber circuits are also used with the GTOs in parallel.

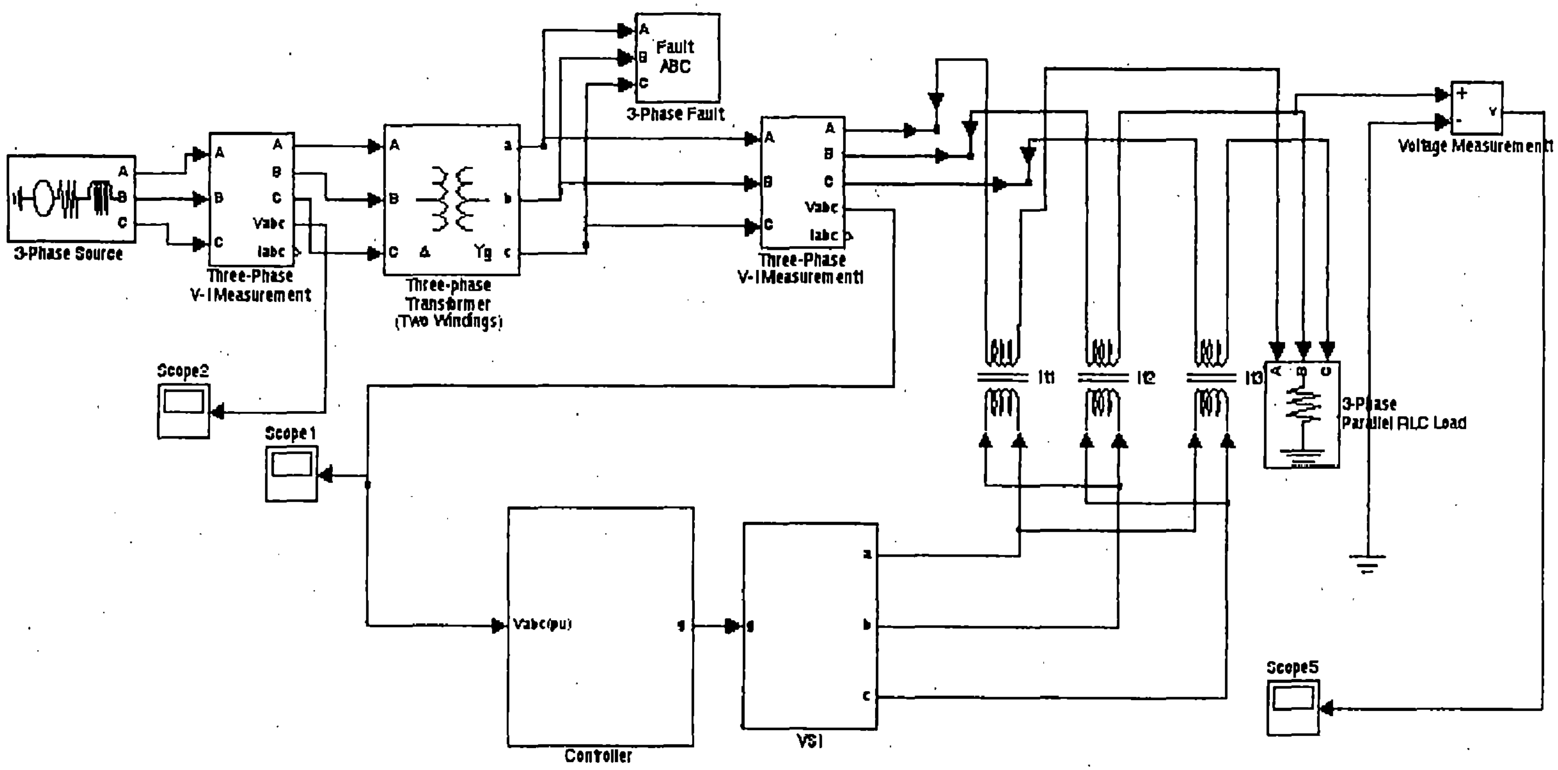


Figure 3.2: - Simulink model of a DVR

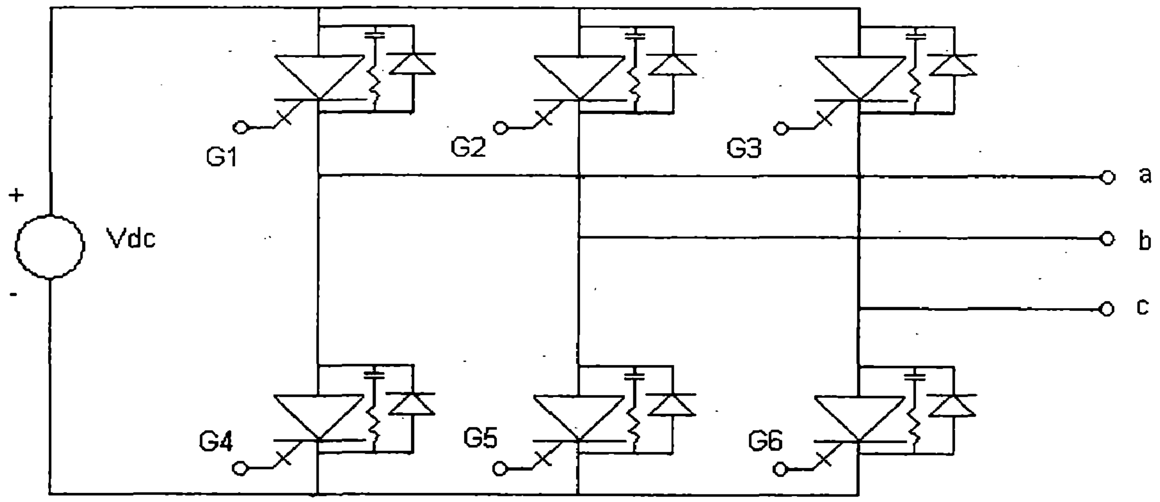


Figure 3.3: - 6-Pulse Bridge Inverter

A dc source is used here as energy storage system. Different parameters are listed below.

DC source voltage (V_{dc}) = 415 V

GTO on Resistance (R_{on}) = 0.01 ohms

GTO on Inductance (L_{on}) = 1 μH

GTO forward voltage (V_f) = 0.8 V

Diode on Resistance (R_{on}) = 0.01 ohms

Diode on Inductance (L_{on}) = 0 H

Diode forward voltage (V_f) = 0.8 V

Snubber Resistance (R_s) = 10 ohms

Snubber Capacitance (C_s) = 0.01 μF

The output of the inverter can contain some harmonic components. Filtering of the output voltage of the inverter is then required. In this model the filtering is being done by the leakage reactance of the coupling transformer. It is set to 0.1 pu.

3.4.2 Control System and PWM Generator

The pre-sag compensation strategy has been used in this model of shunt active power filter. In this model amplitude modulation technique of the sinusoidal signal used for PWM is used. To fulfill this purpose a three reference sinusoidal signals (for three phases) has been generated internally, whose amplitude is 1 and it is in phase with the pre-sag nominal load voltages. The load voltages measured are converted into per unit quantities. The sinusoidal reference signals are compared with these measured per unit load voltage. In normal operating condition the output of the comparator is zero as the load voltages at normal condition are also having amplitude as 1 per unit. When voltage sag occurred the magnitude of load voltage goes down. Hence, the comparators give the difference between the reference signal and per unit load voltage. The error signals thus produced are also sinusoidal, whose magnitude depends upon the deference between the reference signal and per unit load voltage. Thus the amplitude modulation of the error signal is accomplished. The plot of reference signal, measured load voltage (p.u.) and error signal are shown in Fig 3.5, Fig 3.6 and Fig 3.7 respectively. The control system model is shown in Fig 3.4 below.

The error signals generated are then compared with a triangular signal to generate PWM pulses for the GTOs. The frequency of the sinusoidal control signals is same as system frequency, i.e., 50 Hz and that of the triangular signal is 900 Hz. Therefore, the frequency modulation index (m_f) is 18. The logic of generating PWM pulses is as follows, if magnitude of sinusoidal signal (Phase a) $\geq$ magnitude of triangular wave, GTO1, i.e., the upper GTO of the phase arm a turns on. If magnitude of sinusoidal signal (Phase a) $<$ magnitude of triangular wave, GTO4, i.e., the lower GTO of the phase arm a

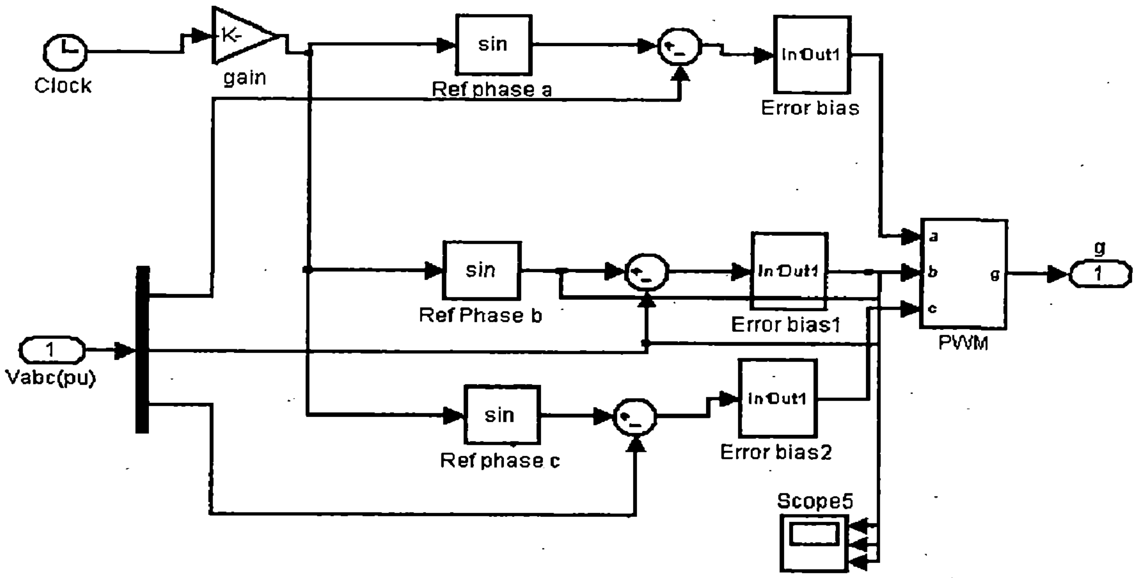


Figure 3.4: - Control System of DVR

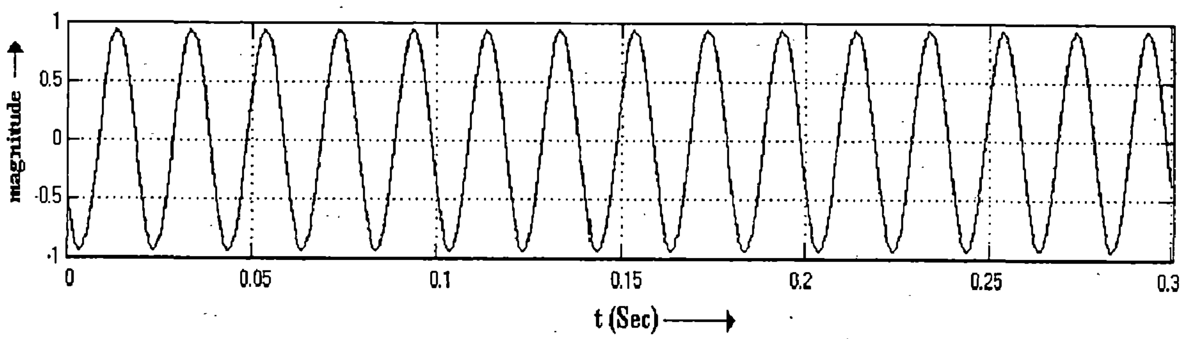


Figure 3.5: - Reference signal

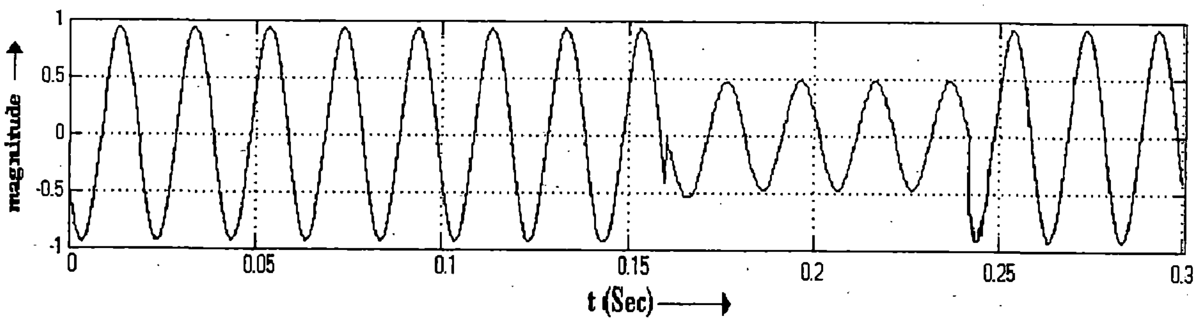


Figure 3.6: - Measured voltage at fault point (p.u.)

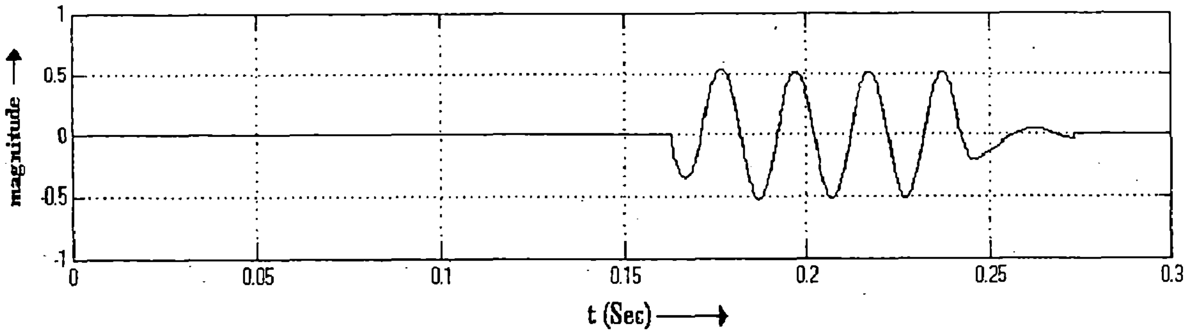


Figure 3.7: - Error signal

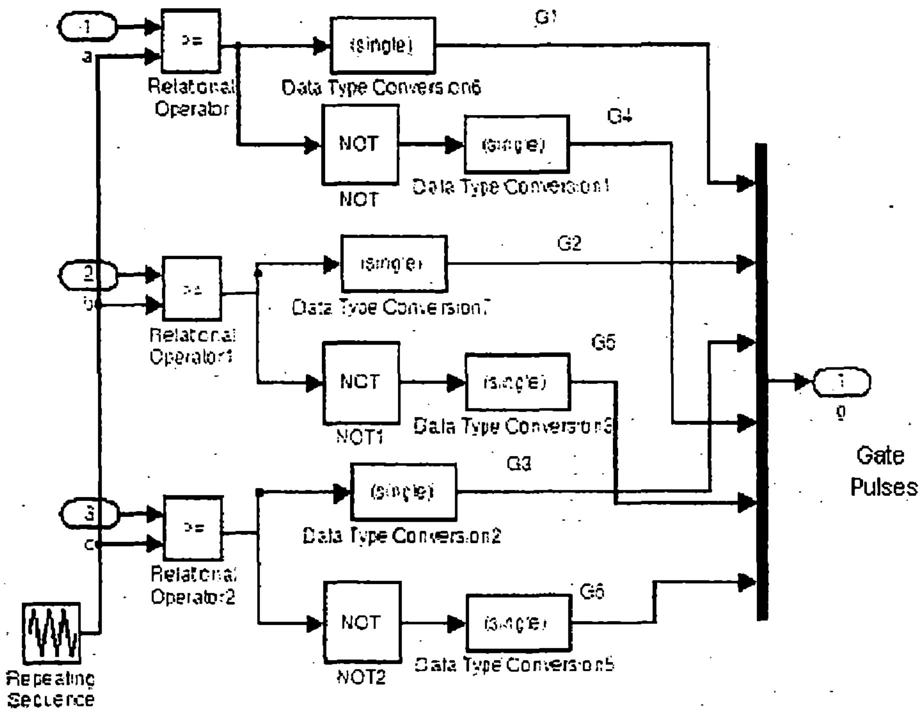


Figure 3.8: - PWM pulse generation model of DVR

turns on. The logic goes same for the other phases also. The PWM pulse generation model is shown in Fig 3.8.

To generate a sag in the distribution line a three phase to ground fault has been created in the model from 0.16 to 0.24 seconds. The fault typically has a fault resistance of 15 ohm and fault to ground resistance as 10 ohm.

3.5 SIMULATION RESULTS

The simulation results are shown in Fig 3.9 and fig 3.10. In Fig 3.9 the instantaneous load voltage is shown. It is clearly seen that due to the 3 phase to ground fault created at the distribution level the load voltage has gone down during the period of fault and a sagged voltage appears across the load. Comparing the value of the sagged voltage with the pre sag nominal voltage it has been calculated that the sag is almost 50%. When the system is simulated with DVR connected the sagged voltage is compensated. When the fault occurred, the load voltage follows a sag. This sagged voltage is almost 50% of the pre sag nominal voltage and has a phase shift of 52.8° from the pre-sag nominal voltage. This sag voltage, after normalizing, is compared with the reference signal and an error signal is generated which is in phase with the DVR voltage, which is to be injected in series with the sag voltage in order to restore the load voltage to its nominal value. This error signal is then used to produce proper PWM pulse signals, which is used by voltage source inverter. The inverter generates the voltage wave, which is to be injected in series through coupling transformer. The plot of restored load voltage is shown in Fig 3.10. From Fig 3.10 it is clearly seen that during fault period, i.e., 0.16 to 0.24 sec the required voltage is supplied by the inverter and the resultant load voltage is as same as pre sag condition. A careful observation shows that the tips of the voltage waveform during the period 0.16-0.24 sec are a little bit sharp as compared to other portion. This is due to the harmonics present in the inverter output. A little harmonics remains in the output voltage of the inverter even after filtering it through the leakage inductance of the coupling transformer.

3.6 IMPLEMENTATION OF DVR MODEL WITH SHP STATION MODEL

After the successful operation of DVR with the test system it has been implemented with the SHP station model as developed in chapter 2. The entire model is shown in Fig 3.11. A 3 phase to ground fault has been created at the transmission level in order to produce a voltage sag of about 30%. The voltage at the fault point with 30% sag is shown in Fig 3.12. The DVR operates at this condition and injects voltage in series with the sag voltage to compensate the sag. The load voltage with DVR is shown in Fig 3.13. From this figure it can be seen that the load voltage is fully restored after the sag. Careful observation shows that the DVR injected voltage contains a little harmonics. The output of the voltage source inverter is filtered by the leakage inductance of the coupling transformer; still a little harmonics are coming.

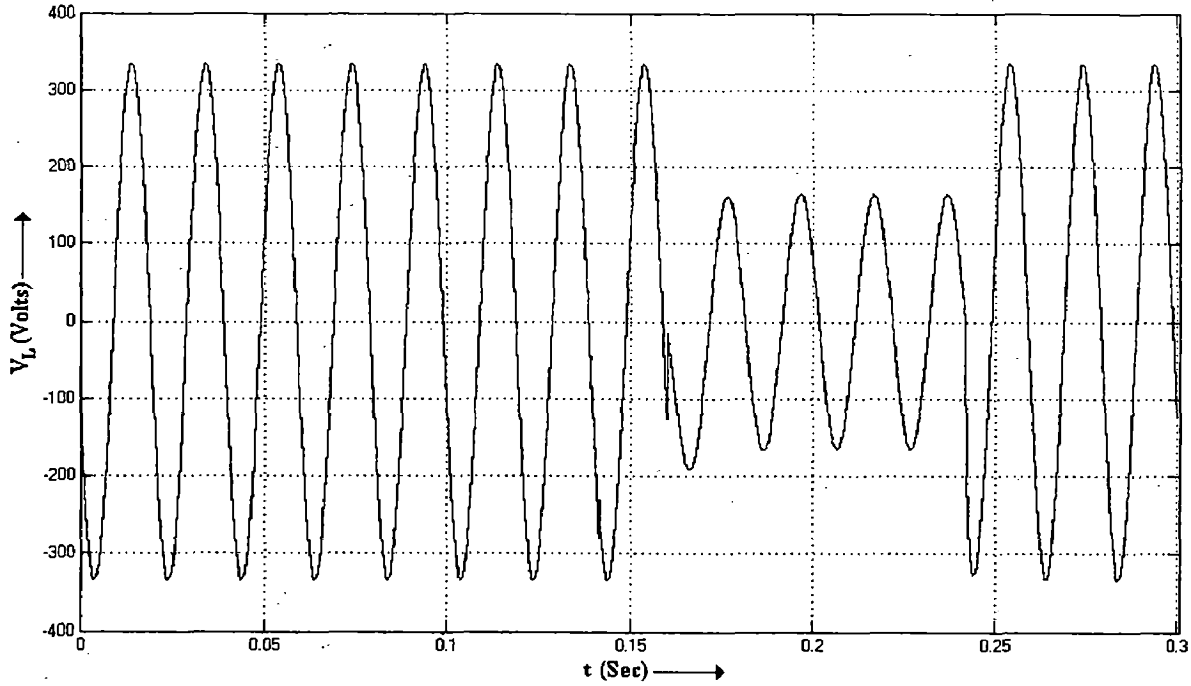


Figure 3.9: - The load voltage sag during a fault

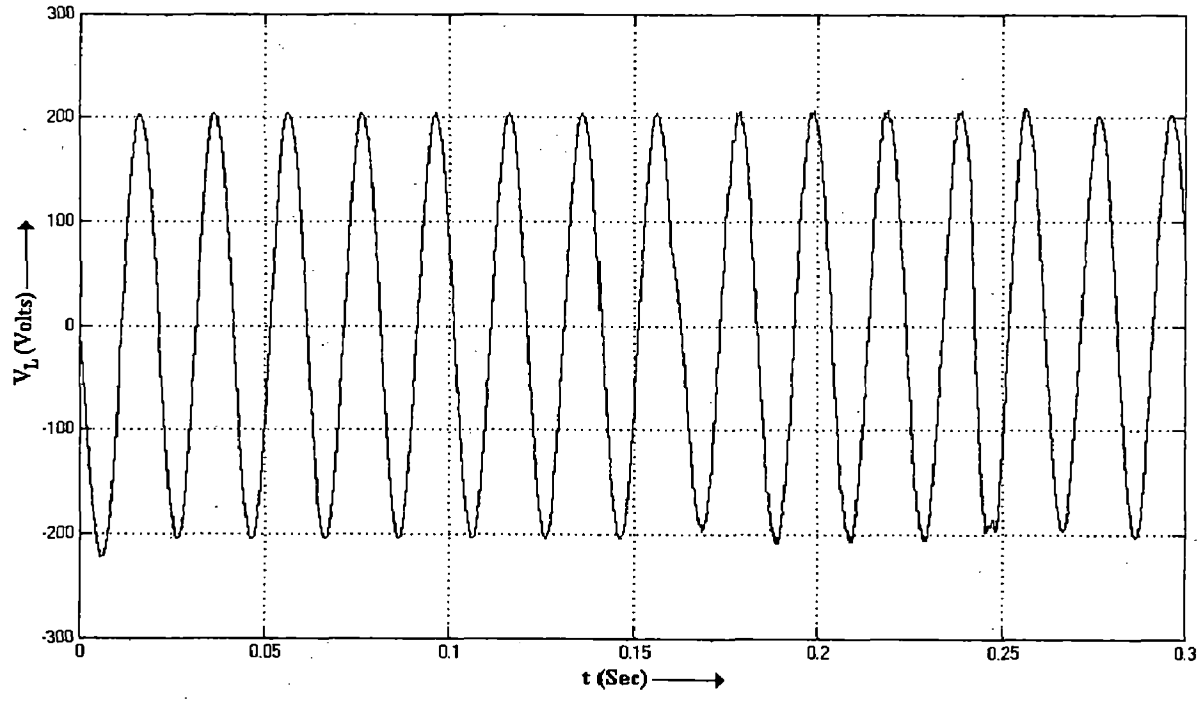


Figure 3.10: - The restored load voltage after connecting a DVR

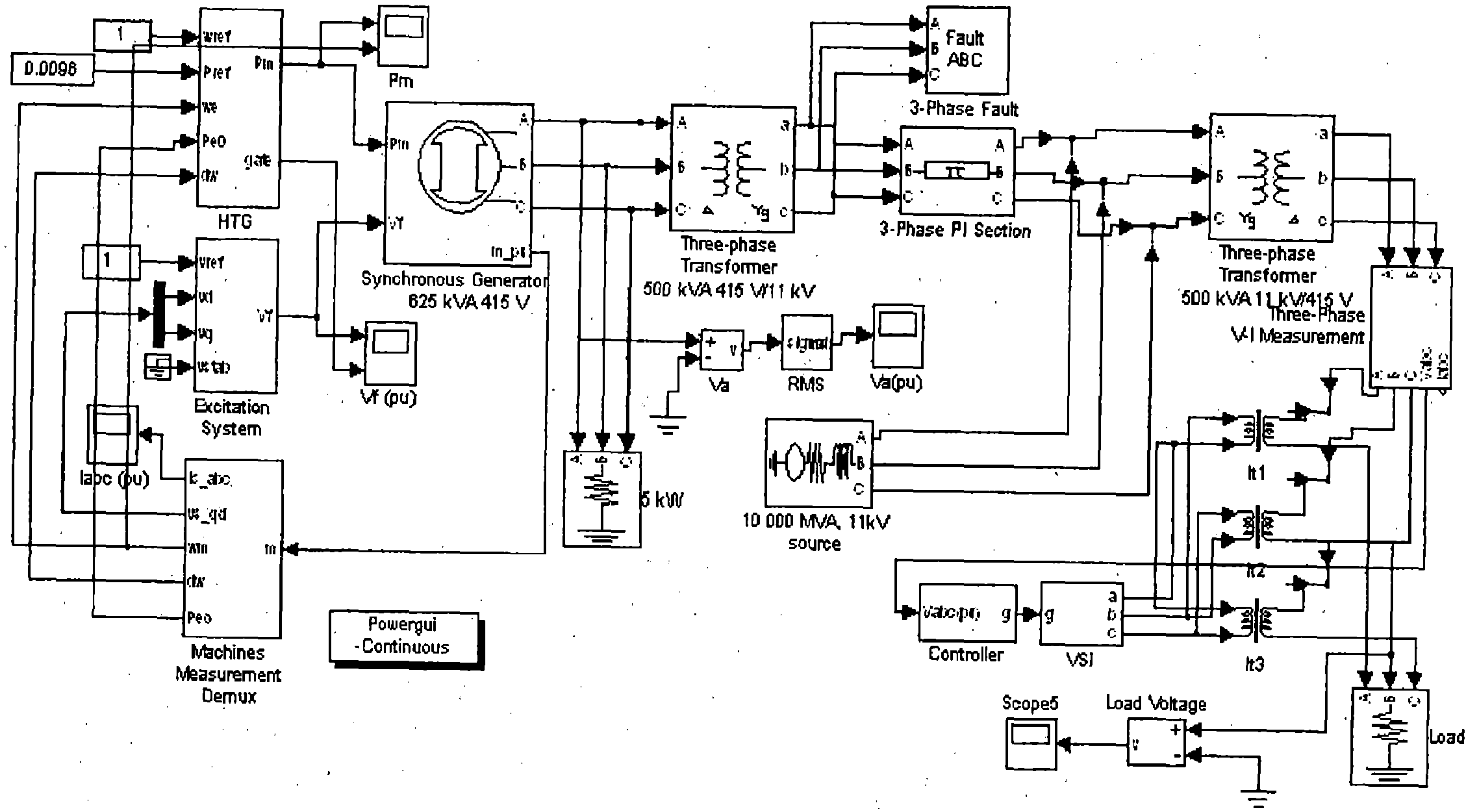


Figure 3.11: - SHP station model with DVR

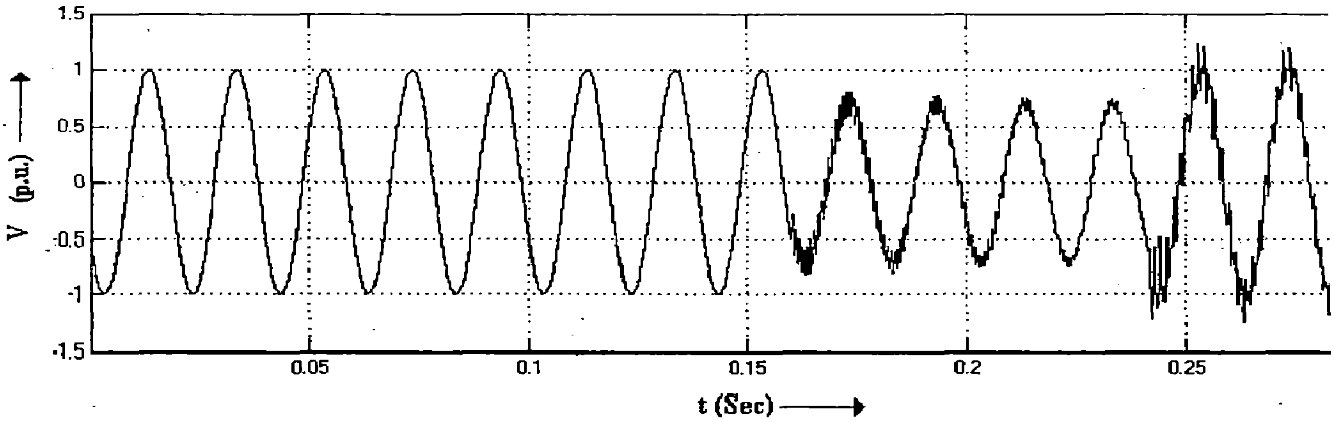


Figure 3.12: - Voltage at the fault point

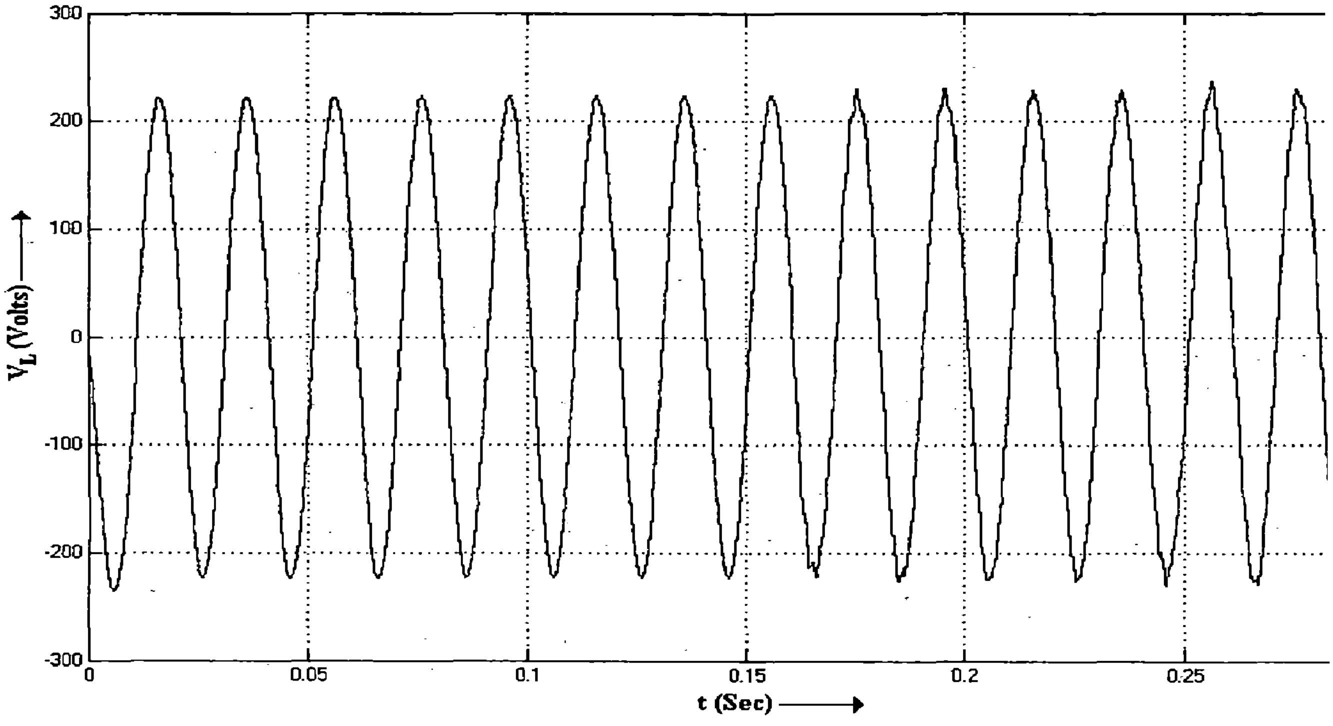


Figure 3.13: - Restored load voltage

HARMONICS REDUCTION BY ACTIVE FILTERS

4.1 INTRODUCTION

The use of power converters and other non-linear loads in industry and by general consumer has contributed to a great deal to the deterioration of the power system voltages and currents waveforms. This problem is known as harmonics. The presence of harmonics in power lines leads to a number of problems like power losses in distribution system, problem of electromagnetic interference with communication systems, operation failure of protection equipments, electronic equipment and industrial processes etc. Harmonics, its source and effects have already been discussed in Chapter 1, section 1.4.7. Different mitigation techniques have also been discussed in Chapter 1, section 1.6.3. In this chapter harmonics reduction techniques through active filters, its configuration and control strategy is discussed. A simulation study of Active Power Filter in MATLAB/SIMULINK has also been presented in this chapter.

An Active Power Filter (APF) provides a good solution to mitigate the problems of harmonics produced by non-linear loads. The shunt active filter acts as a harmonic compensator and injects the current, which is in anti-phase with the harmonic components of currents present in the line. The series active filter functions in a different way, as a harmonic isolator. Hence, the required rating of series active filter is much smaller than conventional shunt active filter. These filters have succeeded to provide the required harmonic filtering and shown better control performance in comparison to conventional passive filters and static var compensators consisting of capacitor banks and thyristor-controlled reactors.

4.2 SHUNT ACTIVE POWER FILTER

Shunt or parallel active filters have been realized as a feasible solution to current harmonics and reactive power compensation. The shunt active filters connected in parallel with distribution system can be implemented with a voltage source inverter. The functions of the shunt active filters are operating as a current source, generating current harmonics required by the nonlinear loads, and regulating dc-link of the voltage source inverter. Hence, it draws either leading or lagging reactive power from the supply. The conventional six-switch three-phase voltage source inverter is the most common circuit to implement shunt active power filter. For the sake of simplicity the dc-link has been replaced by a dc voltage source in this model. A schematic diagram of shunt active power filter implemented in a distribution system is shown in Fig 4.1 below.

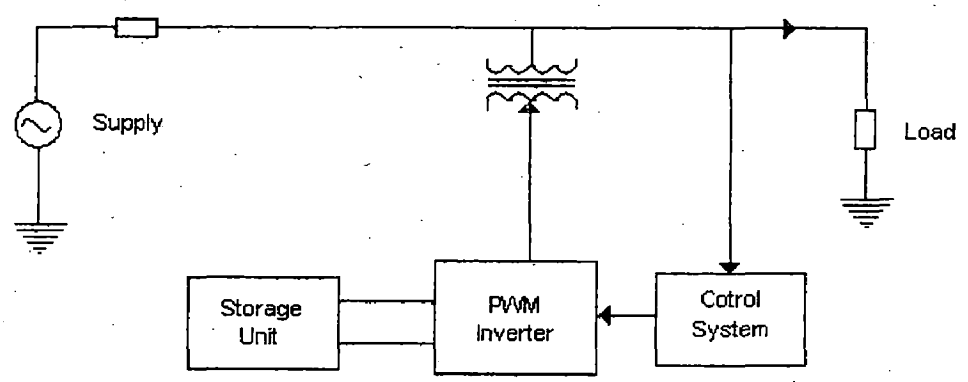


Figure 4.1: - Schematic diagram of shunt Active Power Filter

As the principle of operation of APF is based on the injection of the current harmonics required by the non-linear loads, the characteristics of the harmonic compensation are strongly dependent on the filtering algorithm employed for the calculation of the load current harmonics. Hence, implementation of a suitable current regulator is required. Hysteresis current regulators have been successfully used for active filter applications because of their high bandwidth and simple structure. Hysteresis current regulator compares the measured filter currents with the filter reference currents and generates gate pulses for the voltage source inverter. For generating filter reference current a control system based on p-q theory has been implemented in this model as discussed below.

4.2.1 The p-q Theory Based Control System

The p-q theory has been applied in the control of three-phase active power filters. This theory is based on time domain, which makes it valid for operation in steady state as well as transient state [15]. According to this theory three phase instantaneous voltages and currents are converted into quantities of another stationary reference frame known as α-β orthogonal coordinate system. This transformation is known as Clark's Transformation. According to this transformation rule the voltages and currents in this coordinate system are calculated as follows.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{4.1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4.2}$$

The instantaneous real and imaginary power can be calculated from these voltages and currents in α-β system as given below.

$$p = v_\alpha i_\alpha + v_\beta i_\beta \tag{4.3}$$

$$q = v_\alpha i_\beta - v_\beta i_\alpha \tag{4.4}$$

The real power is obtained by multiplying the voltages and current of same axis. The real power calculated thus is equivalent to the three phase real power and has the same unit, i.e., Watt. The imaginary power is being obtained here by multiplying the voltages and currents of two orthogonal axes. Hence, this is not the conventional reactive power and has the unit IVA (Imaginary Volt Ampere), unlike conventional reactive power. The real power p and imaginary power q have components as shown in equation (4.5) and (4.6).

$$p = \overline{p} + \widetilde{p} \tag{4.5}$$

$$q = \overline{q} + \widetilde{q} \tag{4.6}$$

The physical interpretations of the components are given as follows [16].

- $\overline{p}$: - Mean value of the instantaneous real power. This is equivalent to the power that is transferred to the load in the a-b-c coordinate system.
- $\widetilde{p}$: - Alternated value of the instantaneous real power. This is equivalent to the power, which is being exchanged between power supply and load through an a-b-c coordinates.
- $\overline{q}$: - Mean value of the instantaneous imaginary power, equivalent to conventional reactive power.
- $\widetilde{q}$: - Alternated value of the instantaneous imaginary power. This component is not responsible for exchange of any energy between supply and load but it causes to circulate undesirable currents between system phases.

The mean values of the p and q are developed due to the positive sequence components of the load currents and alternated values of p and q are developed due to the harmonics components. The shunt active power filter is operated to suppress the harmonics component of real and imaginary power ($\widetilde{p}, \widetilde{q}$) and compensates reactive power ($\bar{q}$) of the nonlinear load. The system of equation as given in (4.3) and (4.4) can be written as

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_b & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \tag{4.7}$$

In a reverse way equation (4.7) gives the currents. If we put only the alternated components of real and imaginary power ($\tilde{p}, \tilde{q}$) in place of p and q in equation (4.7), the calculated currents will be the harmonics components only. This will constitute the reference currents for compensation as given below by equation (4.8).

$$\text{or, } \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ -v_b & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \tag{4.8}$$

The reference currents in α-β system values can be transformed to a-b-c coordinate system as given below.

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \tag{4.9}$$

These reference currents are being compared with the filter currents in a Hysteresis current controller to generate gate pulses. The Hysteresis controller is explained as follows.

4.2.2 The Hysteresis Current Controller

The Hysteresis Current Controller provides the fastest control and requires minimum hardware and software. The schematic of a Hysteresis current controller is shown in Fig 4.2, where i_a^*, i_b^* and i_c^* are the reference currents and i_{fa}, i_{fb} and i_{fc} are the measured filter currents respectively. In this method of control the filter currents track the reference currents within a hysteresis band, HB. The control logic is given as, if $i_{fa} < (i_a^* - HB)$ the upper switch of the phase a arm is off and lower switch of phase a arm in on. If $i_{fa} > (i_a^* + HB)$ the upper switch of the phase a arm is on and lower switch of phase a arm is off. This is same for other phase arms also. The generation of PWM pulses by hysteresis current controller is shown in Fig 4.2 below.

4.2.3 Modeling and Simulation of Shunt Active Power Filter

The model of a shunt active power filter, to implement it with a grid connected small hydro power plant, is done by using MATLAB/SIMULINK software package. The entire model is shown in Fig 4.3 below.

For the sake of simplicity in the model, the hydro power plant has been replaced by a three-phase source with resistance and inductance in series with it. This model can also be implemented along with the plant model as presented in chapter 2. The non-linear load has been modeled as a resistive load with three-phase thyristor bridge converter, which converts the ac voltage into dc. This load draws a non linear from the mains. In Fig 4.4 the model of the non-linear load is shown.

The control strategy based on p-q theory to generate reference current for compensation is shown in Fig 4.5.

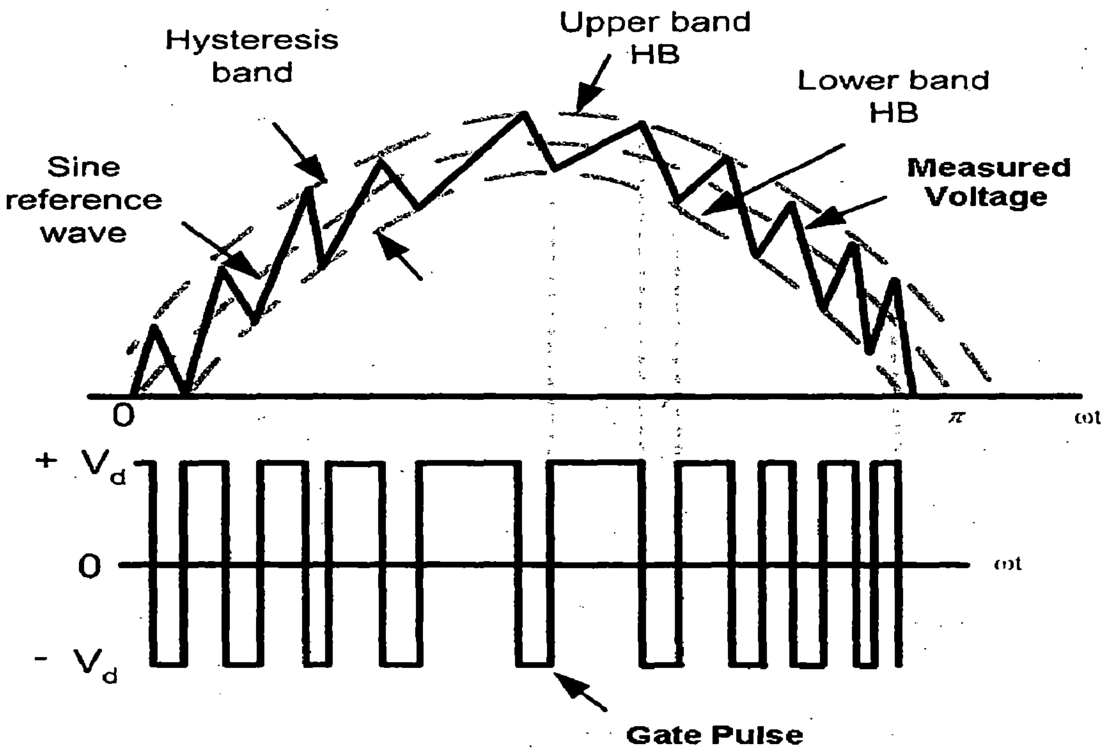


Figure 4.2: - PWM technique using Hysteresis Current controller

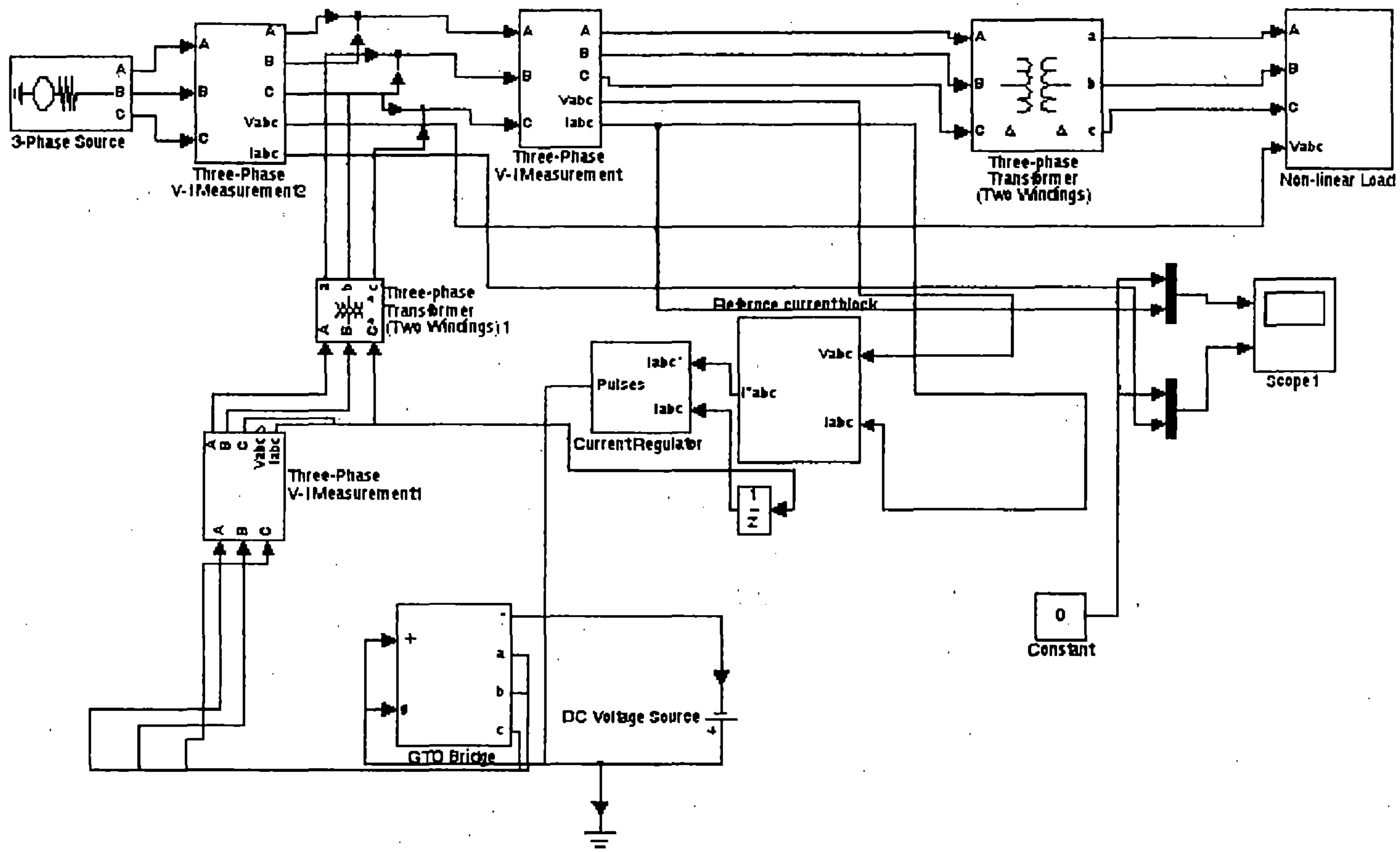


Figure 4.3: - The simulink model of a shunt active power filter in distribution system

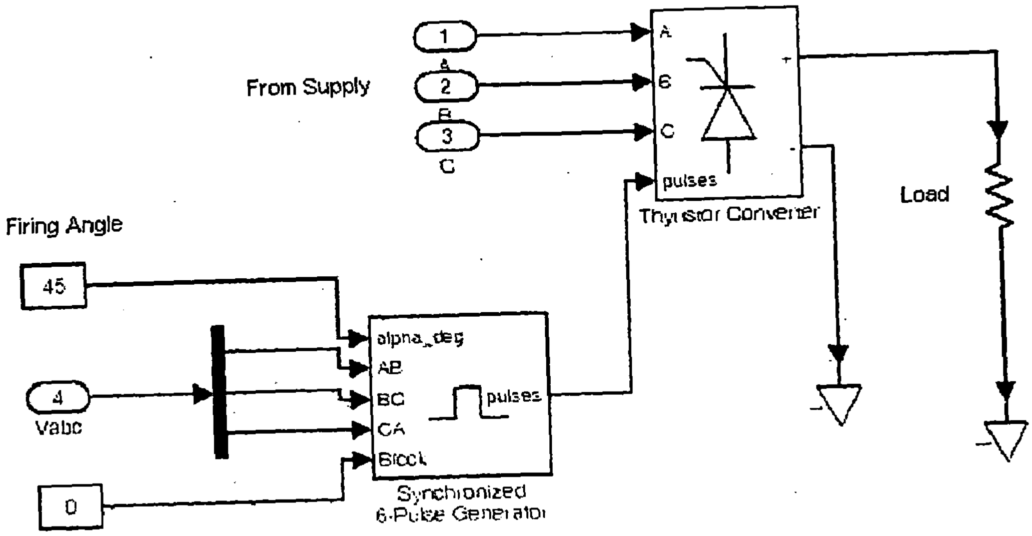
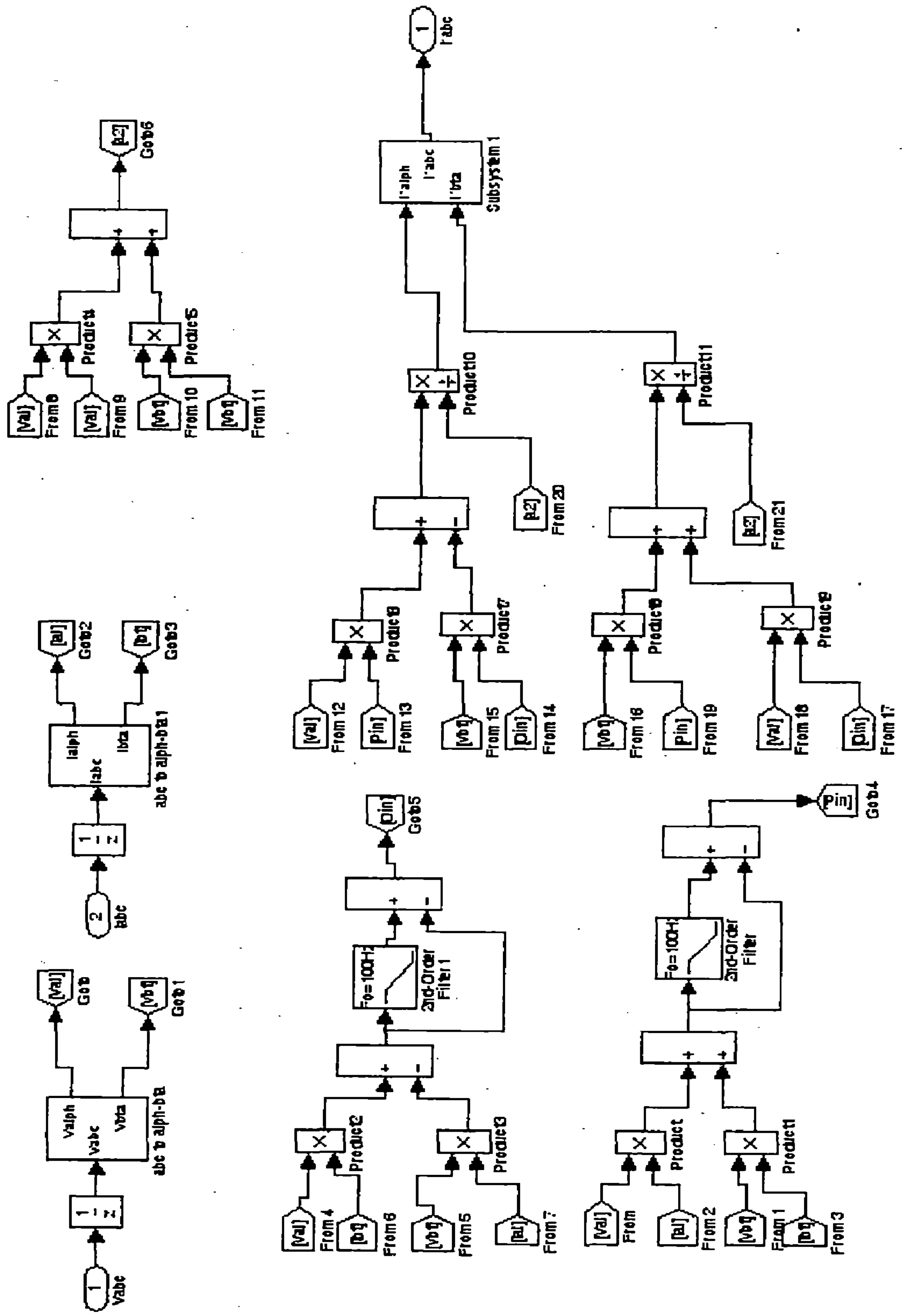


Figure 4.4: - Non-linear load used in the model


Vabc
abc to alph-bta
Valph
Vbta
Goto
Goto1
Iabc
abc to alph-bta1
Ialph
Ibta
Goto2
Goto3
Goto4
Goto5
Goto6
3rd-Order Filter
3rd-Order Filter1
Fo=100Hz
Product
Product1
Product2
Product3
Product10
Product11
Subsystem1
I'alph
I'abc
I'bta
I'abc

4.2.4 Simulation Results

The results of the simulation are shown in Fig 4.6 to 4.9. First the model is simulated with out the active power filter model. In this situation the harmonics coming in the load current and source current as shown in Fig 4.6 and 4.7 respectively.

From Fig 4.6 and 4.7 it is clear that the non-linear load is drawing harmonics currents, which distort the source currents. The shunt active power filter is compensating these harmonics. The load current and source current after implementing a shunt active power filter is shown in Fig 4.8 and 4.9 respectively. The harmonic content in the source current are increased by increasing the firing angle of the thyristor converter. To show the dynamic behavior of the model the firing angle has been changed from 30° to 45° during the simulation.

From figure 4.9 it is clear that the harmonics from the source current are compensated by the active power filter, while the non-linear load is drawing harmonics currents. The Total Harmonic Distortion (THD) is a measure to show the reduction in harmonics. THD increases as the firing angle of the thyristor converter load increases. THD of source current at different firing angle with and without active power filter are shown in Table 4.1 below. The results are also shown in the graph in Fig 4.10.

Table 4.1: - THD of source current at different firing angle

Sl. No.	Firing angle (in degree)	Load Current without filter (Amps)	THD without filter (%)	THD with filter (%)
1	30	20	3.4	2.6
2	45	16	10.6	4.7
3	60	11.5	19.5	6.6
4	75	6.5	31.24	6.9

4.3 IMPLEMENTATION OF SHUNT ACTIVE POWER FILTER WITH SHP STATION MODEL

After the successful operation of shunt active power filter model it has been implemented with the SHP station model developed in chapter 2. The entire MATLAB/SIMULINK model of the system has been shown in Fig 4.11. In this figure the SHP station block includes the detail modeling of SHP station as developed in chapter 2. The non linear load is simulated with a firing angle of 45°. Simulation results are shown in Fig 4.12 and Fig 4.13. In Fig 4.12 the three-phase load currents are shown. It can be seen from the figure that the load is drawing harmonic currents with a THD of 10.6%. The waveforms of the currents are distorted. Fig 4.13 shows the source current after compensated by the shunt active power filter. After implementation of the filter the THD has come down to 4.7%. The waveforms of the currents are also become smooth, as seen from Fig 4.13.

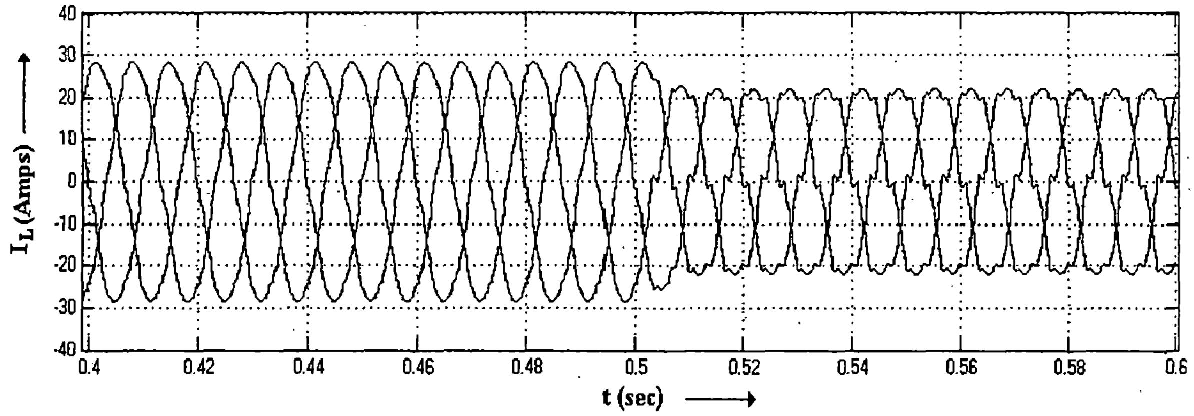


Figure 4.6: - Three phase load currents without shunt active power filter

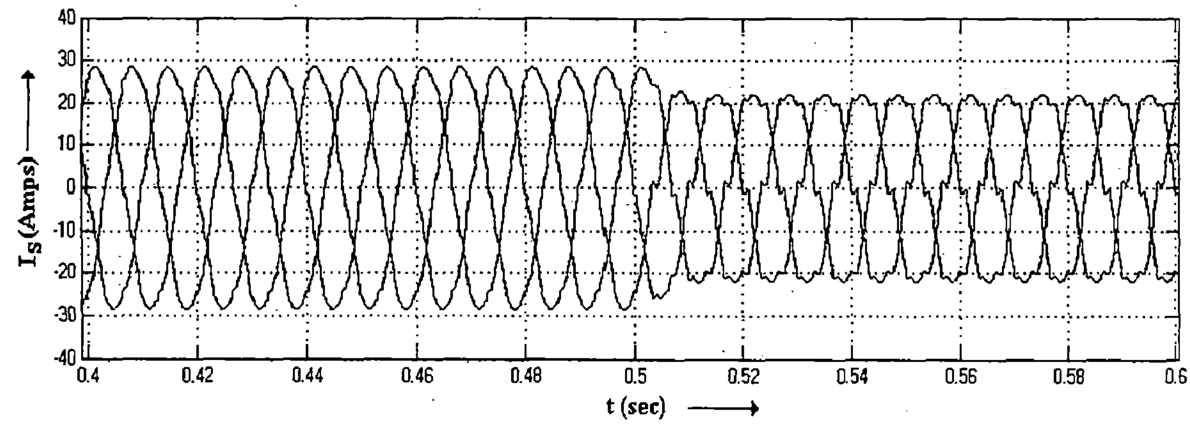


Figure 4.7: - Three phase source currents without shunt active filter

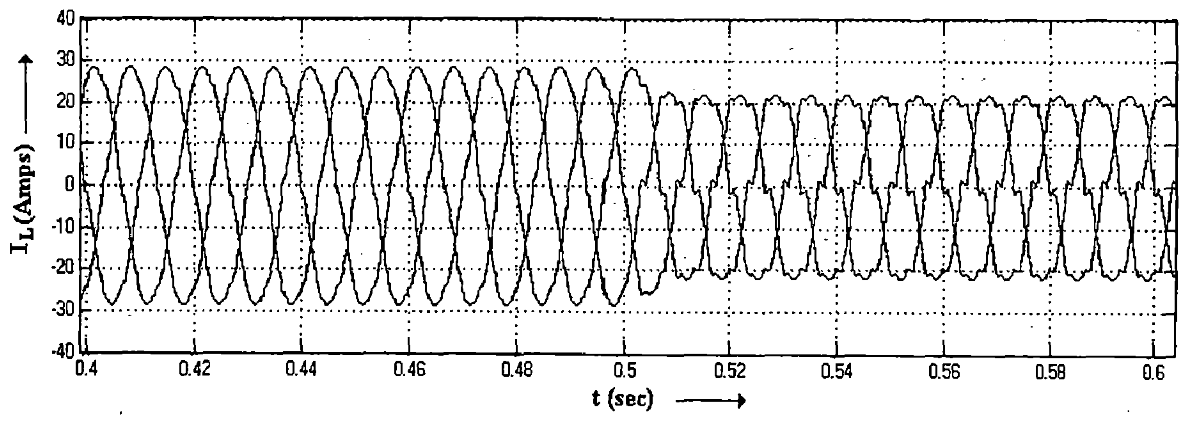


Figure 4.8: - Three phase Load currents with shunt active power filter

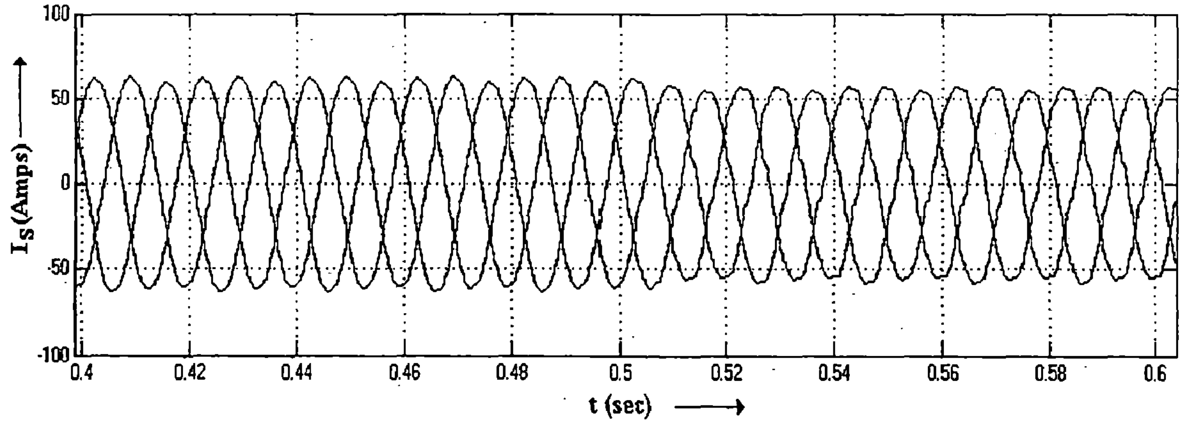


Figure 4.9: - Three phase source currents with shunt active filters

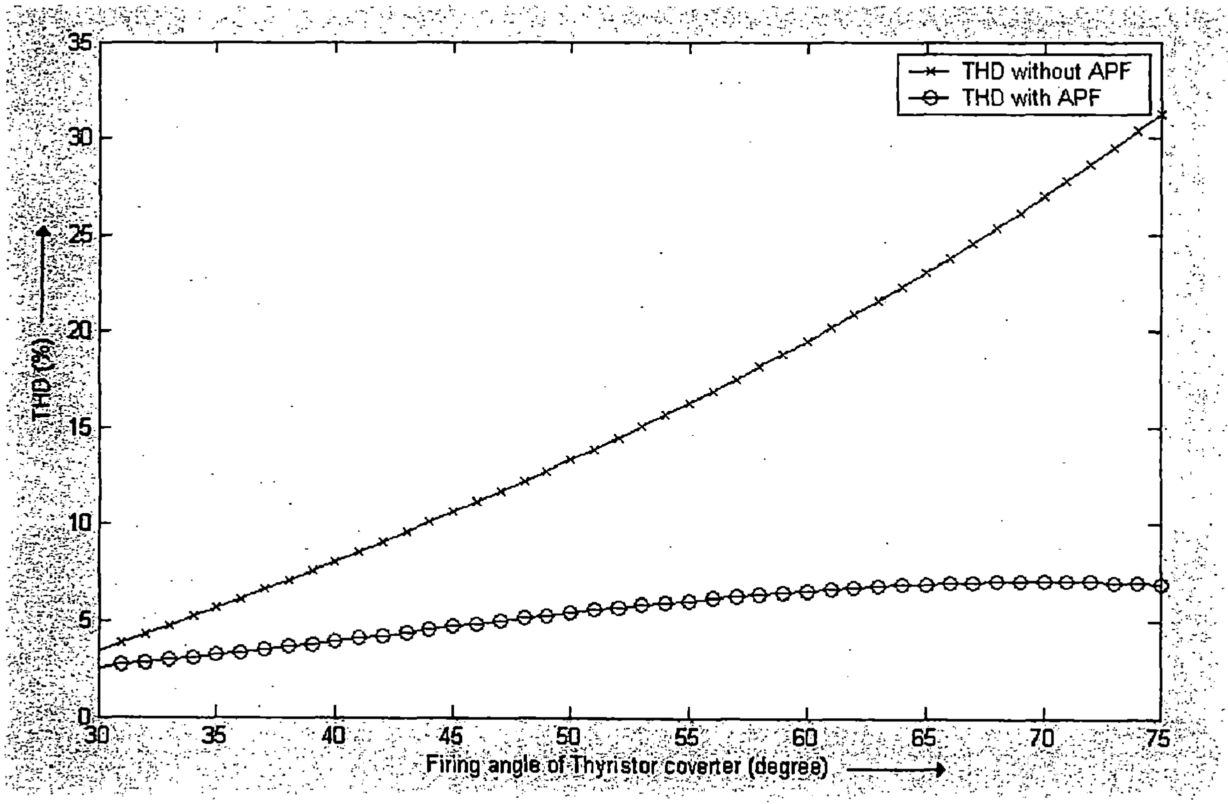


Figure 4.10: - THD at different firing angle with and without active power filter

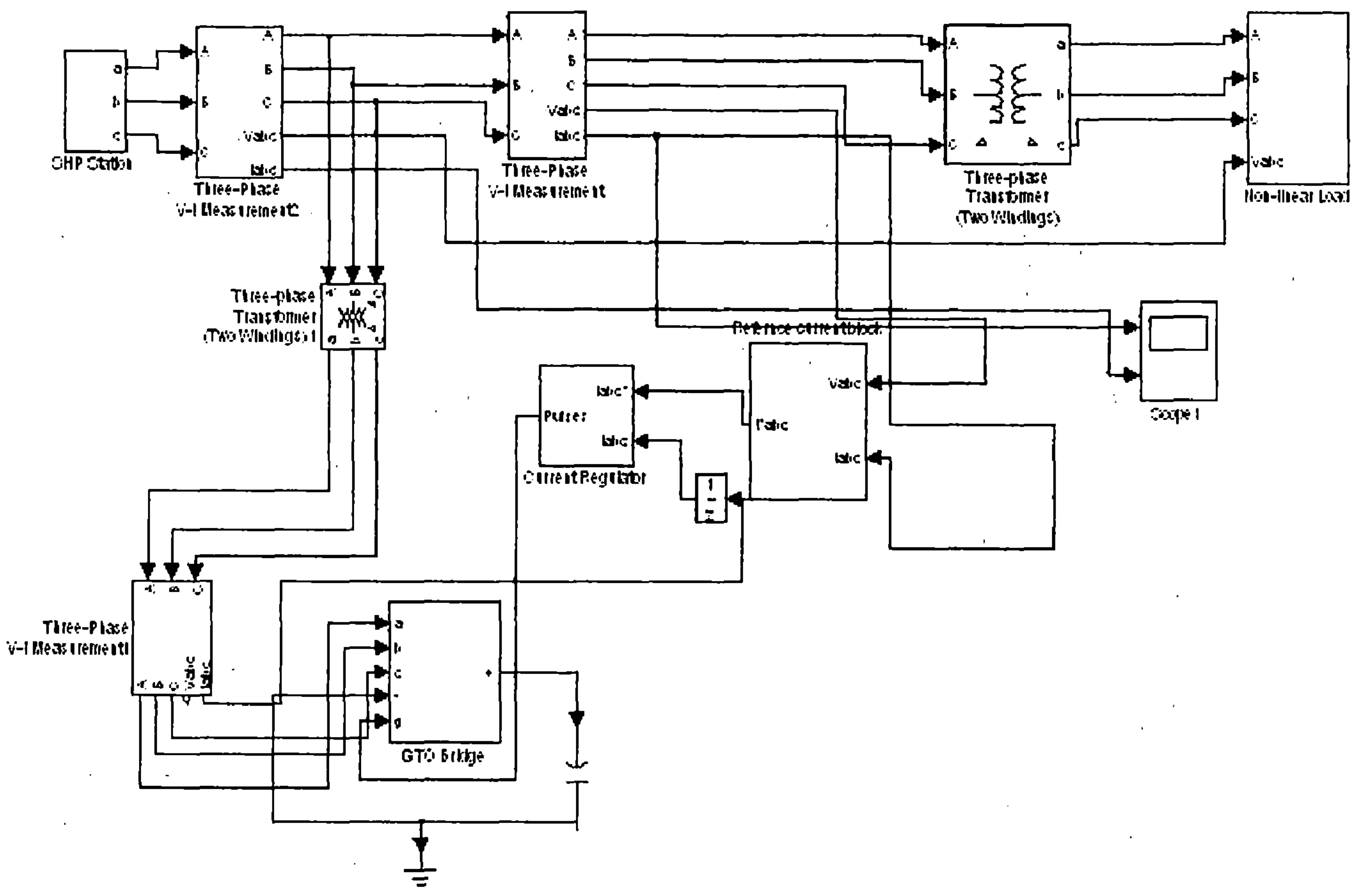


Figure 4.11:- Simulink model of shunt APF implemented with SHP station

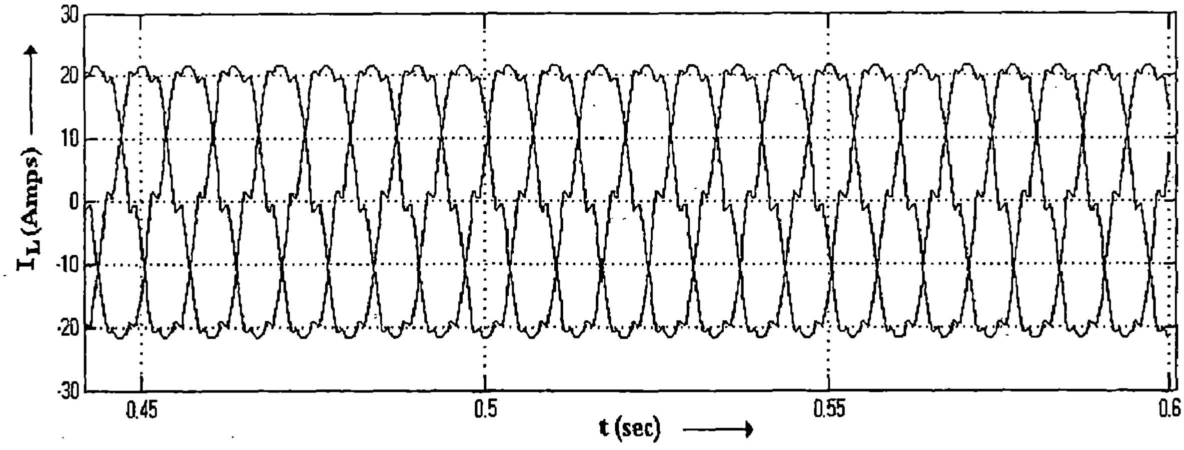


Figure 4.12: - Three phase load currents

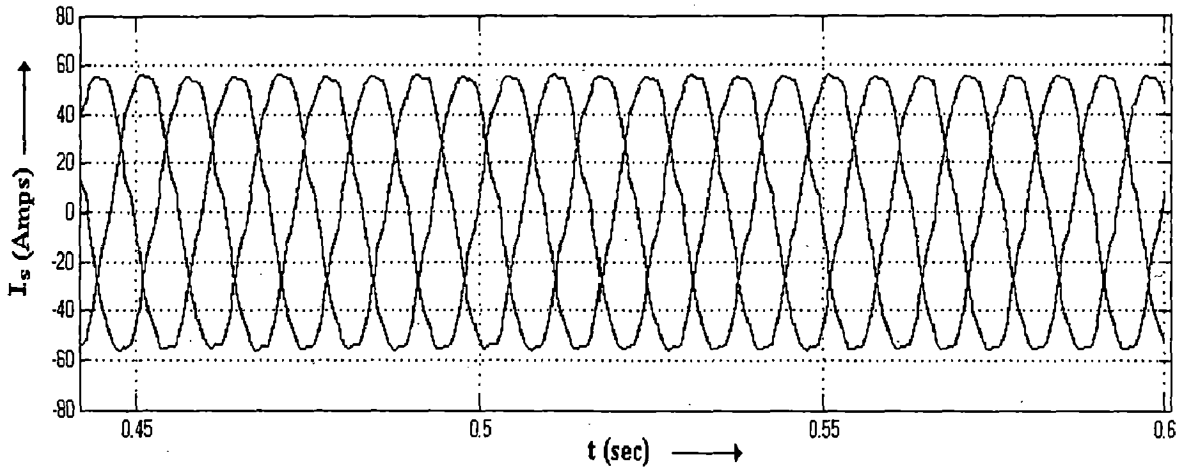


Figure 4.13: - Three phase currents currents

RESULTS AND CONCLUSIONS

5.1 DISCUSSION

. Small hydro power plants are located in remote places, where the distribution system is comparatively weak. Deterioration of power quality is a very common phenomenon in these areas. To solve this problem the distribution system should be strengthened by extending the network. But sometimes it becomes difficult to extend the distribution system in those areas. At this situation custom power devices are the only solution to this problem. In this dissertation work two important power quality issues are considered namely voltage sag and current harmonics. These two are very common in power system.

In chapter 2 the model of a small hydro power plant is developed using power system toolbox of MATLAB/SIMULINK software package. The importance of developing this model lies in the fact that any device developed for power quality improvement of small hydro power plant can be tested on this model. The results show that the model is working properly. But it needs proper initial conditions for the differential equations used to model different components of small hydro power plant. The initial conditions are given from the result of a load flow analysis. The operation of the model is tested for different normal and abnormal conditions and plots of different parameters are shown accordingly.

Voltage sag is one of the most common phenomena in power system. So, the mitigation of this problem draws greater attention. The DVR modeled in chapter 3 solves this problem. Comparison of the graphs shown in Fig 3.9 and Fig 3.10 shows that it is working efficiently. The DVR has successfully restored the load voltage from a 50% sag. Theoretically it can work efficiently upto 70% sag. But ultimately the capacity of restoration is limited by the energy storage system. The control strategy adopted here is to bring the sag voltage to pre sag value, in magnitude and phase both. It is important because the supply voltage waveform is used by the power electronic converter as a reference to generate firing signals with required firing angle. During the fault period DVR injects a voltage with required magnitude and phase in series with the supply voltage to restore the load voltage to pre sag value. DVR uses a voltage source inverter to generate this voltage, which is to be injected in series. After the successful modeling and testing of DVR it has been implemented with SHP station model developed in chapter 2. a sag of about 30% has been created by occurring a three phase to ground fault at the transmission level. The voltage at fault point and restored load voltage are shown in Fig 3.12 and 3.13 respectively. Fig 3.13 shows that the output voltage of inverter contains harmonics, whose value depends upon the switching frequency of the power electronic devices. In the model developed here GTO has been used as power switches. It performs well at high switching frequency, thus producing less harmonics. To reduce harmonics in the output voltage of DVR the leakage reactance of the coupling transformer is utilized as a filter. Still some amount of harmonics are coming in the output voltage of the DVR. Actually, these types of devices contribute harmonics to the supply line and deteriorates the waveform of the voltage coming from power plants. Then it becomes necessary to compensate those harmonics. The solution to harmonics problem is discussed in chapter 4.

Harmonics reduction by active power filter is widely used in power system industry. The shunt active power filter injects the harmonic components of current required by the non-linear load. The strategy for harmonics reduction using shunt active power filter adopted in this dissertation work is based on p-q theory. The simulation results show the successful implementation of this theory. The non linear load is modeled as a thyristor controlled resistive load. Total Harmonic Distortion (THD) depends on the firing angle of the thyristor bridge. The more the firing angle, more the distortion of the load currents take place. The model of non-linear load presented in this work is with a thyristor bridge, whose firing angle is dynamically changed from 30° to 45°. This is causing an appreciable harmonics in the line as seen from Fig 4.8 in chapter 4. But with the implementation of shunt active filter the harmonics content of the source current gets reduced and the THD comes down, as seen from Fig 4.9. From Table 4.1 it is clear that with the application of shunt active power filter total harmonic distortion can be reduced to 6.9% from 31.24%. A plot of THD vs firing angle of thyristor is shown in Fig 4.10. THD is plotted for with and with out shunt active filter. Comparison of the two plots shows that the THD is reduced considerably after implementing the shunt active power filter. After successful modeling and testing of the shunt active power filter, it is implemented with the SHP station model developed in chapter 2. The firing angle of the thyristor controlled load is set to 45° during simulation. Reduction in harmonics can be observed by studying the plots of three phase currents as shown in Fig 4.12 and 4.13. The control strategy for shunt active power filter plays an important role in the filter performance. In the control strategy of the shunt active power filter, 2nd order high pass filters with a characteristic frequency of 100 Hz has been used to separate the alternated real power (harmonic component) from the fundamental mean real power. This alternated real power is used to calculate the reference current for filter current controller. Hence, the ability to compensate for harmonics of shunt active power filter depends upon the operation of the high pass filter.

5.2 SCOPE FOR FUTURE WORK

The Flexible AC Transmission (FACTS) devices are playing an important role now a day to improve the power quality. The DVR and shunt active power filter developed in this dissertation work are working successfully. Still they have some limitations. Like, in DVR the ability of restoration of load voltage is limited by the capacity of the energy storage system. A new FACTS device, named Unified Power Flow Controller (UPFC), is coming into the picture gradually. It can be used to mitigate the problem with supply voltage flicker/imbalance, reactive power, negative-sequence current and harmonics [17]. It is a combination of shunt and series converters connected by a common dc link. The series converter injects a voltage in series with the supply line at required magnitude and angle. The shunt converter controls the real power exchange between the supply system and the device and also controls the voltage of the common dc link [18]. Thus, it optimizes the capacity of the energy storage system. But this device is beyond the scope of this dissertation work.

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