VOLTAGE FLICKER MITIGATION USING FORTY PULSE VOLTAGE SOURCE CONVERTER BASED DSTATCOM

A Dissertation submitted in fulfillment of the requirements for the Degree
of

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in
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Submitted by

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "VOLTAGE FLICKER MITIGATION USING FORTY PULSE VOLTAGE SOURCE CONVERTER BASED DSTATCOM", in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is as authentic record of my own work carried under the supervision of Dr.PARAGNIJHAWAN.It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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

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LIST OF ABBREVIATIONS

AC = Alternating Current

CPF = Cumulative Probability Function

DC = Direct Current

DSTATCOM = Distribution Static Compensator

EAF = Electric Arc Furnace

FACTS = Flexible AC Transmission Systems

FCTCR = Fixed Capacitor Thyristor Controlled Reactor

GTO = Gate Turn off Thyristor

HVDC = High Voltage Direct Current

IEC = International Electrotechnical Commission

IGBT = Integrated Gate Bipolar Transistor

IGCT = Integrated Gate Commuted Transistor

PCC = Point of Common Coupling

PI = Proportional Integral

PLL = Phase Lock Looped

PWM = Pulse Width Modulation

STATCOM = Static Synchronous Compensator

SVC = Static VAR Compensator

TCR = Thyristor Controlled Reactor

THD = Total Harmonic Distortion

UIE = International Union for Electroheat

VSC = Voltage Source Converter

VSI = Voltage source Inverter

NOMENCLATURE

I_{FL} = Instantaneous flicker level

P_{ST} = Short term flicker severity index

P_{LT} = Long term flicker severity index

$P_{0.1}$ = Flicker level corresponding to 0.1%

N = Number of observations

Sccf = Short circuit level of arc furnace at PCC

Sccn = Fault level of network

V_{dc} = DC input voltage

D = Duty ratio

f = Rated frequency

MI = Modulation index

Vd = Direct axis voltage

Vq = Quadrature axis voltage

ABSTRACT

With the universal grid integration of non-conventional energy and increased transmission of power to geographically inaccessible and rural areas over the period of time, the importance of enhancing the power quality at both the generation end and distribution end has increased substantially. But, the greater degree of use of non-linear loads and other external factors has led to the increased deterioration in power quality and introduction of unacceptable phenomena like harmonics, voltage sags and swells and induced voltage flicker. Voltage flicker pose a serious threat to power system. It is characterized by sharp change in voltage level accompanied by increase in harmonic distortion and is common in highly inductive loads like electric arc furnace. Though it lasts for the shorter interval of time, it is regarded as potentially hazardous for load as well as supply, jeopardizing the safety of electric devices connected to the power system. For this reason its mitigation is of utmost importance. For mitigation of this phenomenon, FACTS devices like DSTATCOM are extensively used in power industry. This thesis presents the impact of using conventional six-pulse and multi-pulse converter circuit configured DSTATCOM. In the proposed work a non-conventional ten-pulse inverter is simulated which is non-integral multiple of six. Then a forty-pulse inverter is designed using ten-pulse inverter as the building block. The effectiveness of proposed DSTATCOM for flicker mitigation is established using MATLAB/SIMULINK.

CHAPTER-1

OVERVIEW

1.1 INTRODUCTION

Improved standard of living and growth in industrial sector has led to the greater degree of pressure on the energy providers. Trends of consumers of electrical energy being merely acceptors, is vanishing. Fluctuations and voltage disturbances that used to be a part of deal are no longer allowable. Today electrical energy is a product that can be predicted, measured, improved and guaranteed. The various environmental constraints and financial needs have obliged to look for the means to fully utilize the available resources and look for the techniques to enhance the performance of existing power system.

Utilities all over the world are concerned about the improvement of so called the power quality. The term power quality is characterized by "the quality of supply voltage in reference with voltage flicker, harmonics and transient breaks. Poor quality of power deteriorates performance and life span of the end-user equipment".

The concern of consumers regarding the electric power or to say the quality of voltage waveform which they receive is increasing. Increase in competition among the electrical utilities in a deregulated market has led to customer satisfaction become the matter of prime importance. Modern electrical as well as electronic equipments with their sophisticated design are quiet sensitive to poor voltage quality, which may cause the device to mal-operate or cease to operate.

With the greater degree of automation and modernization in industries, application of microprocessor and power electronic based devices is increasing which is the main reason behind the power quality problems. There are both internal and external factors affecting the quality of power. Power contamination in the form of harmonic generation is the main consequence when power electronics switches are used. Integrated renewable energy resources like a wind turbine, photo-voltaic or fuel cell to an electric utility grid is characterized by interface provided by the power electronic converter based devices which further amplify the power quality problems.

Voltage flicker is one of the critical power quality problems found in non-linear loads like electric arc furnace (EAF). It behaves as a variable resistance with constant reactance. Voltage flicker has earned interest of both, utilities as well as researchers. Voltage flicker is the variation in the illumination intensity as an outcome to voltage fluctuations. Voltage sag initiates voltage flicker; inrush current is generated due to sudden voltage drop which can affect sensitive equipments. Voltage flicker can cause damage to the highly sensitive loads; hence its mitigation is a necessity.

Flexible AC Transmission System (FACTS) devices have the capability to overcome this power quality problem. The integration of FACTS devices in power system helps in enhancing the reliability and power quality. FACTS devices help in distribution of electrical energy in an economical manner aiming for better utilization of existing system.

Voltage source inverter (VSI) based FACTS devices are quiet promising due to no harmonic contamination, fast response, small size and cost effectiveness. VSI is widely adopted as next generation reactive power controller replacing traditional VAR compensators in power system. FACTS devices can be applied to different spheres to improve power system operation like power system stability improvement and voltage stability and control enhancement. This can be achieved with suitable voltage magnitude and phase angle control. With the recent advancements, multi-pulse voltage source inverter is gaining attention from scientists. They are designed for total harmonic distortion (THD).

The proposed work presents the impact of using conventional six-pulse and multi-pulse converter circuit configured DSTATCOM for voltage flicker mitigation. DSTATCOM is chosen for flicker mitigation because of its easy controllability and fast response. Traditional six-pulse inverter based DSTATCOM has been used in industries but is associated with low order harmonics. However, for high power, sinusoidal voltage with minimal distortion is required which is achieved by using multi-pulse inverter along with the magnetic interface provided by zig zag phase shifting transformer (PST). The effectiveness of the proposed DSTATCOM for flicker mitigation has been established.

1.2 LITERATURE REVIEW

The power quality definitions and terminology is introduced in detail by A. Ghosh *et. al* [1]. A useful overview of power quality terminology with reference to standards and other valuable information is given by IEEE and IEC [2] where power quality impacts and problems are also widely described.

Math Bollen *et. al* [3] has discussed about various solutions and methods for improving power quality which can be implemented, independent of any standardization. Roger *et. al* [4] has emphasised over the significance of power quality. Continuous growth in application of high efficiency devices has led to the increase in harmonic content in power system. IEEE 519 [5] specifies the maximum harmonic current and voltage levels at the PCC.

The influence of power quality over customers, utility and manufactures has been captured by C. Sanskaran [6]. IEEE 100 [7-8] describes power quality as “concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment.” The subject of power quality and its problems has been discussed in [9]. The increasing competition in electrical market is creating greater commercial awareness with respect to power quality [10-12].

D. Czarkowski et. al [13] have analysed about the voltage flicker and has mitigated it using the pulse width modulation based STATCOM. J. Mckim *et. al* [14] have discussed about the UIE flickermeter. The author highlighted that voltage variations become quiet perceptible at frequency range of 10 Hz and relative magnitude of 0.26%.

R. collantes *et. al* [15] have discussed about modelling of three phase arc furnace. According to author, huge non-linear industrial loads, welding machines, rolling mills, pumps are the main source of flicker. M. Zouiti *et. al* [16] have investigated electronic based equipment for flicker mitigation. S. Saadate *et. al* [17] investigated the concept of reactive power control for voltage flicker mitigation.

J.R. Clouston *et. al* [18] have investigated regarding field demonstration of a DSTATCOM for voltage flicker mitigation. In this type of compensation, the reactive power consumed is maintained constant at a particular level. M.W. Marshall *et. al* [19] have proposed the application of series capacitor to mitigate voltage flicker.

J. Dolezal *et. al* [20] have analysed about various topologies of active filter to reduce voltage flicker. L. Gyugi *et. al* [21] have investigated static shunt compensation for the purpose of power factor correction and voltage flicker reduction. SVC is the frequently used devices as quoted from his paper.

Y. Hamachi *et. al* [22] have analysed the voltage fluctuation elimination using thyristor controlled capacitor. Thyristor switched capacitor is also used for flicker suppression. Frank *et. al* [23] have applied thyristor controlled capacitor for power factor correction of an arc furnace. Device based on FCTCR is also used for voltage flicker mitigation.

Hingorani [24] has provided with the concept of custom power. FACTS and custom power technology has created most challenging advancement and achievements to meet the operating challenges that power system faces today. T. Muni *et. al* [25] have performed voltage flicker mitigation using fixed capacitor thyristor controlled reactor (FCTCR) and a 3-phase, 4-wire inverter STATCOM, establishing the effectiveness of STATCOM for voltage flicker mitigation.

R. Cai *et. al* [26] have investigated dual vector controller of DSTATCOM for voltage sag mitigation and applied it to low voltage and medium voltage system to obtain results. Using dual vector controller technique, DSTATCOM can achieve high dynamic performance. W. Chang *et. al* [27] have designed a micro-computer based voltage flicker teaching. Three interesting experiments are proposed for learning flicker related problems. M. Joorabian *et. al* [28] have discussed the application of voltage source converter based DSTATCOM. An adaptive arc furnace model is designed by T. Zheng *et. al* [29]. The model is divided into supply system model, non-linear load model and controller model. The model is compared with the traditional model to mark its suitability. A. Y azdani *et. al* [30] has introduced a non-linear control for STATCOM for reduction of electric arc induced oscillations on power system. This technique is compared to the traditional PI controller to prove its effectiveness.

FACTS and high voltage direct current (HVDC) systems implement multi-pulse converters for their robust control [31]. Power electronic equipments such as custom power devices and FACTS implement voltage source inverter based technology [32]. The high performance capabilities of these technologies have resulted in improved power quality [33]. Harmonics are the major factor governing the poor power quality. Harmonics can be treated either by filtering or cancellation [34] and [35].

Attempt has been made to reduce the harmonics using controlled converters [36]. Passive filters with different configurations have been used for the purpose but they suffer from resonance problems, heavy filter elements and bulky in nature [37]. Active filter have also been applied but they are complex and costly [38]. Hybrid filters though overcome these problems but are complex in construction [39] and not easily available with the manufacturer [40].

Gonzalez *et. al* [41] have proposed the shunt passive filters for harmonic mitigation. Along with harmonics, shunt passive filters also compensates for reactive power with lesser amount of losses. The design of passive filter using transfer function approach is presented in [42]. Peng *et. al* [43] have investigated series hybrid active filter topologies which consist of shunt passive filter and a series active filter.

The multi-pulse converter deals with reduction in harmonics. Pulse width modulation techniques have been accorded in VSI [44] to obtain variable voltage and frequency supply. A hexagonal auto transformer arrangement has been proposed in [45] to maximize the efficiency of 12-pulse AC to DC converter. Akagi *et. al* [46] have proposed the instantaneous reactive power theory based on d-q-0 transformation to design the controller for voltage source converter.

In [47] power factor correction in an isolated bridgeless AC-DC converter for welding load has been investigated. Fast dynamic response and unity power factor has been achieved. Even during load variations, THD is less than 5% and input current is in phase with input voltage. Voltage and current waveform distortion produces power losses, harmonic distortion and high frequency noise. In [48] minimization of THD on multi-level inverter with reference current generation has been discussed. Microcontroller or digital signal processing based controllers are preferred over analog controller for implementing SPWM scheme for multi-level inverters.

In [49] design and development of SPWM based voltage source inverter has been discussed. Most commonly used modulating techniques are carrier based PWM and SVPWM. The SPWM has been tested for voltage source inverter using MATLAB for different loads at different carrier frequencies. Sinusoidal pulse width modulation can be realized digitally quiet conveniently. As the carrier frequency is increased, THD in output current decreases upto 13 KHz.

For high power DC arc furnace, integrated gate bipolar transistor (IGBT) or integrated gate commuted transistor are used. They have capability of reducing flicker and increase productivity as discussed in [50]. These systems have benefits over the other conventional rectifiers like efficiency, improved power factor, fast dynamic response and low output ripples as discussed in paper [51]. IGBTs are employed for large currents [52]. Multi-pulse converters along with phase shift transformers are used to meet IEEE standards [53].

Transformers used for high currents can have different winding arrangements as explained in [54] like star, delta, zig-zag, fork, polygon etc. Burgos et. al [55] have analysed some winding arrangement for 18-pulse autotransformer based converter. In [56] it is suggested to use high pulse configuration for AC-DC converters to meet IEEE 519 requirements in reference to the power quality. J. Rodriguez *et. al* [57] have discussed about different topologies of a multi-level inverter like diode-clamped, cascaded- clamp and cascaded multi-cell with separate DC source. Multi-level inverter can be used for shunt active filter [58]. Sun Hui *et. al* [59] discuss multi-level inverter for active power filter. SVPWM technique is used for 3-phase voltage source inverter. Space vector based current controller for two level pulse width modulation based inverter is discussed in [60]. Application of high power multi-pulse inverter has been discussed in [61]. A multi-pulse inverter gives a staircase wave as output resembling a sine wave.

Flicker from different sources have been reported and analysed in literature [62-64]. It is done by flicker power direction analysis and Interharmonics power flow. In [65], method for flicker evaluation for wind power generator is proposed. In [66] performance analysis of DSTATCOM for voltage stability and reactive power compensation is highlighted. DSTATCOM contains IGBT based voltage source converter. The simulation is performed in MATLAB. A relationship between flicker assessment criteria and short-term flicker is established in [67]. Analytical calculations and on-site measurements are performed to evaluate the ratio between two indices.

P. Nijhawan *et. al.* [68] discusses the performance of carrier phase shift pulse width modulation multi-level inverter based DSTATCOM with inductance furnace load and compared it with pulse width modulation inverter based DSTATCOM. MATLAB/SIMULINK is used for illustration of results.

In [69] application of DSTATCOM in a distribution network with inductance furnace load is discussed. Induction furnace is the cause of appreciable amount of harmonic distortion which depend upon configuration and operation of furnace. Harmonics also affect other loads connected in power system. Here DSTATCOM with PI controller for harmonic mitigation due to arc furnace load is presented. P. Mereado *et. al.* [70] have discussed the DSTATCOM coupled with a flywheel energy storage system to mitigate wind generation related problems. A dynamic model of DSTATCOM is discussed with the technique to control active power exchange between power system and the device.

1.3 SCOPE OF THE WORK

From the above discussed literature review it is quite evident that, work in the field of voltage flicker mitigation is quiet broaden over the horizon. However, much attention has been paid to improve power quality using conventional converter topology based devices. There is scope to investigate the effectiveness of various non-conventional multi-pulse inverter topologies to mitigate voltage flicker.

From the literature survey it can be emphasised that there is scope in analysing statistical aspect of voltage flicker along with harmonics which has been made possible using digital flickermeter.

1.4 RESEARCH MOTIVATION

The successful performance of the loads depends mainly on the level of voltage at which the power is being supplied to them. Power quality is more complex than in past because new loads are not only sensitive to power quality but also adversely affect the quality of electrical energy. In power system, power quality issues arise due to faults, sudden switching and even transients cause distortion in the voltage and frequency levels. In order to maintain stable and standard voltage at of common coupling point, custom power device is required to be connected at PCC. In the proposed work, analysis of DSTATCOM for the mitigation of voltage flicker has been carried out.

1.5 OBJECTIVE OF THESIS

The dissertation proposes the digital simulation of voltage source inverter based DSTATCOM using MATLAB/SIMULINK for the purpose of voltage flicker mitigation. The major objectives are summarized as follows-

- To study and investigate voltage flicker and its causes.
- To study and analyse the effect of voltage flicker on power system.
- To simulate the necessary test system to investigate voltage flicker.
- To model a device best suited for voltage flicker mitigation.
- To achieve mitigation of voltage flicker using traditional techniques and control the device such that desired performance is obtained.
- To simulate the model using non-conventional techniques for voltage flicker mitigation.
- To enhance the model of device for application in various domains
- To perform the comparative analysis of the conventional and non-conventional technique for voltage flicker mitigation and establish the effectiveness of the latter.

1.6 ORGANIZATION OF THESIS

The main body of the report present in a number of chapters, starting with Introduction and ending with results and conclusions. This report is divided into six chapters. Each part deals with different aspects which are described as following-

Chapter 1

This chapter includes the introduction to the thesis work and the literature survey. It also includes the scope of work, objective of thesis along with research motivation and organization of thesis.

Chapter 2

This section deals with the power quality and issues associated with it. It also includes various measures that can be adopted and implemented to improve the power quality of distribution network.

Chapter 3

This chapter discusses voltage flicker in detail. Classification of voltage flicker along with measurement of voltage flicker has also been covered in this section.

Chapter 4

This section includes the study of DSTATCOM for the purpose of voltage flicker mitigation. Its basic model along with applications has been discussed.

Chapter 5

This chapter presents the methodology along with the simulation and associated observations.

Chapter 6

This section includes conclusions of work presented in the dissertation. It also presents the future scope of this approach.

CHAPTER-2

POWER QUALITY

2.1 INTRODUCTION

With the modifications in electric power network over the interval of time, it faces many challenges in order to deliver qualitative power ensuring reliability of supply. As per IEEE 1100 [71], power quality is characterised “as the idea of controlling and establishing the touchy supplies in a manner that is suitable for the operation of the gear” [71].

With growing usage of sensitive loads, the power quality is receiving more importance. Among many factors load is the main reason of power quality degradation. Automation of industries has led to the use of computers, microprocessors and other communication based devices. These equipments are very sensitive to disturbance in power network. The consequence of power quality degradation can be regarded in terms of vulnerability and susceptibility. Where former is due temporary malfunctions, like in computing devices. The latter is said to be the case when electric transient exceeds insulation withstand level. This trend is observed in rectifier which fails if it is subjected to transient voltage exceeding the threshold limit [72].

As per IEEE, power quality is “the concept of powering and grounding sensitive electronic equipments in a manner that is suitable to operation of that equipment” [73].

2.2 IMPLICATIONS OF POWER QUALITY

The power quality has some serious implications for electrical utilities, costumers and equipment manufacturers. The power quality problem [74] is influencing consumers from all the spheres like commercial, industrial and even resident. In deregulated market as the competition between electrical utilities is increasing, customer satisfaction is becoming the matter of concern. The suppliers have to take decisions regarding including features into devices for improving power quality adding to the cost of equipments. It is required to know the level of power disturbances in order to determine the tolerance limit of the device. The effect of user generated disturbance on other consumer’s and utility’s equipment is also taken into consideration.

2.3 IMPORTANCE OF POWER QUALITY

- Microprocessor based control and power electronic devices for newer generation load equipments are sensitive to generated power quality.
- In order to achieve maximum power system efficiency, the application of power electronic based devices has expanded, causing the increased harmonic levels on power system.
- Modern networks are complex and interconnected. Integration process means failure of one component can have its consequences on entire network.
- Integration of non-conventional energy resources with electrical utility grid require interface which is suitably provided by power electronic based converter system which also contribute to power quality problems.
- Increase in awareness among the consumers regarding power quality issue and thus challenging suppliers to ensure higher degree of quality and reliability of electric supply.
- Increased dependency of society on electrical power causes heavy economic losses and discomfort [73].

2.4 POWER QUALITY ISSUES

As discussed in the previous section, the basic reason for power quality problem is electromagnetic phenomena [75] classified by IEC as follows-

- Conducted low frequency phenomena
- Radiated low frequency phenomena
- Conducted high frequency phenomena
- Radiated high frequency phenomena
- Electrostatic discharge phenomena (ESD)
- Nuclear electromagnetic pulse (NEMP)

The various spectral content, duration and magnitude for different electromagnetic phenomena is available in literature [75]. An overview of different power quality problems with their causes of occurrence is presented below-

2.4.1 Short Duration Variations

Variations which occur for less than one minute are called short duration variations. These variations depend on the location of fault and system conditions. The main cause of the variations is load which requires high starting currents or unsecure connections in power wiring. These variations can cause voltage sags, swells or interruptions which are described as follows-

- **Voltage Sag-**

According to IEC voltage sag is defined as voltage dip. It is the "decrease in root mean square voltage to a value lying between 0.1 to 0.9 pu which lasts for the duration of 0.5 cycles to one minute". This is the most common power quality problem occurring due to system faults lasting for duration of 3 cycles to 30 cycles based on the fault clearing period. The magnitude of voltage sag depends upon on nature of fault and fault impedance. The magnitude of voltage sag depends upon the distance of fault location from bus where sag is measured and also on nature of fault and fault impedance. Starting of large induction motor is the primary cause of voltage sag as the motor draws current which is ten times the full load current during starting [74]. Heavy loads connected to power system are also responsible for voltage sag. Fig. 2.1 shows the phenomena of voltage sag.

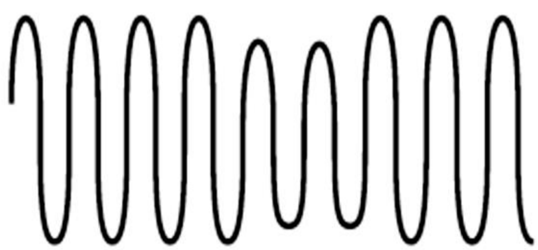

Fig. 2.1: Voltage Sag

- **Voltage Swell**

It is increase in root mean square voltage between 1.1 to 1.8 pu at the power frequency for the duration of 0.5 cycles to one minute. Periodic starting and stopping of heavy loads is the basic cause for voltage to swell. Energizing of large capacitor banks, line faults and incorrect tap settings of tap changers are other reasons for voltage swells. It depends upon fault location, system impedance and grounding [74]. Fig. 2.2 shows the voltage swell phenomena.

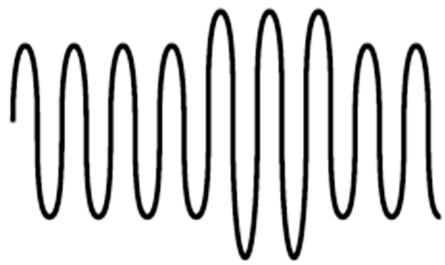

Fig. 2.2: Voltage Swell

- **Interruptions**

Decrease in supply voltage or load current to less than 0.1 pu for the time duration of not more than one minute is called interruption. The main cause of interruption is equipment failure, control malfunction and system fault. Fig. 2.3 shows the example of interruptions.

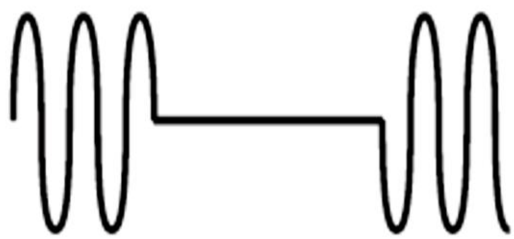

Fig. 2.3: Interruptions

2.4.2 Long Duration Variations

The variation in root mean square value of voltage or current occurring at power frequency for a time interval exceeding one minute is called long duration variations. They are basically of two types described as follows:

- **Overvoltages**

Increase in root mean square AC voltage greater than 1.1 pu at the power frequency is called overvoltage. Overvoltages are produced due to lightning, switching off loads, incorrect tap settings on transformers, energizing of capacitor banks, Ferroresonance, insulation failure etc.

- **Undervoltages**

Decrease in root mean square AC voltage lesser than 0.9 pu at the power frequency is called undervoltage. Undervoltages are produced as result of switching in loads or switching off a capacitor bank.

- **Sustained Interruptions**

If the voltage supply remains interrupted for the time period of more than one minute, such variations are called as sustained interruptions. They are more of a permanent in nature and require human interference to restore the system to its normal condition. Sometimes it also synonymies outage by utility.

2.4.3 Transients

It synonymies ‘surge’. “That part of the change in variable that disappears during transition from one steady state operating condition to other is called transient [2]”. It is characterized by high currents or voltage magnitude. The basic source of transient are-

1) Lightning strikes
2) Switching of circuit breakers and capacitor banks
3) Reclosing operations
4) System instability

Transients are broadly classified as follows-

- **Impulsive Transients**

An impulsive transient is a sudden non-power frequency change that is unidirectional and is characterized by decay and rise time. It mainly occurs due to lightning discharge or opening and closing of circuit breakers. Transient can lead to equipment malfunction or even a permanent damage if the level is quiet high. Fig. 2.4 shows the impulsive transients.

Fig. 2.4: Impulsive Transients

- **Oscillatory Transients**

A sudden non-power frequency change that is bi-directional is called oscillatory transients. Oscillatory transients are shown in Fig. 2.5. Oscillatory transients are classified based on their frequency as-

1) High frequency (> 500 kHz) – caused due to response of network to an impulsive transient.
2) Medium frequency (5-500 kHz) – caused due to back to back capacitor energization or cable switching.
3) Low frequency (<5 kHz) – caused due to capacitor bank energization.

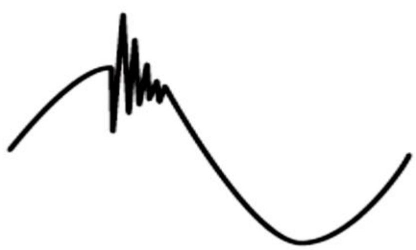

Fig. 2.5: Oscillatory Transients.

2.4.4 Voltage Imbalance

The ratio of negative sequence component to positive sequence component measures imbalance. When the three phase voltage has unequal magnitude, voltage imbalance takes place. The phase difference may or may not be equal. Fig. 2.6 shows the phenomena of voltage imbalance.

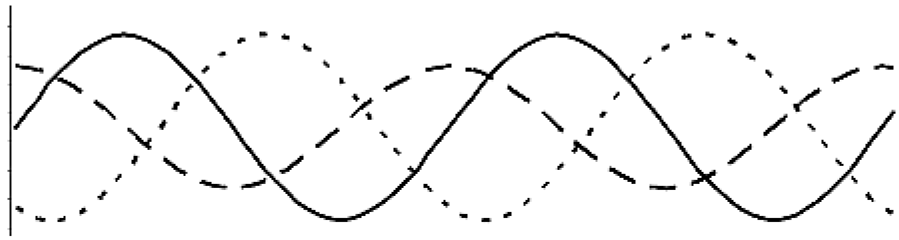

Fig. 2.6: Voltage Imbalance

The main cause of voltage imbalance is single phase load on three phase circuit, fuse is blown in one phase of three phase capacitor bank and if transposition of overhead lines is not executed.

2.4.5 Voltage Fluctuations

Symmetric and random change in voltage envelope in the range of 0.9 to 1.1 pu due to variations in real and reactive power drawn by load is called voltage fluctuations. Fig. 2.7 shows the voltage fluctuations. Loads that draw fluctuating currents like electric arc furnace is the basic cause of voltage fluctuations. Loads that produce voltage fluctuation are

1) Electric arc furnace
2) Arc welders
3) Rolling mills
4) Car shredders
5) Mine hoists

Fig. 2.7: Voltage Fluctuations

2.4.6 Power Frequency Variation

The deviation of the system frequency from its specified nominal value like 50 Hz or 60 Hz is called power frequency variation.

2.4.7 Waveform Distortion

A steady-state deviation from an ideal sinusoidal wave of power frequency is called waveform distortion. It is broadly classified as following-

- **DC Offset**

The presence of DC component in form of voltage or current in AC power system is called DC offset.

- **Harmonic**

The voltage or current waveform having frequencies which are whole number multiple of nominal frequency at which power system is designed to operate is called harmonics. The fundamental frequency is usually 50 Hz or 60 Hz. Harmonics are generated during application of arc furnace, UPS, SMPS, rectifier, variable frequency drive, welding machine and other power electronic based equipments. Fig. 2.8 shows the phenomena of harmonics. Total harmonic distortion is a measure for harmonic distortion and is defined as-

$$THD = \frac{\sqrt{\sum_{h=2}^{hmax} Mh^2}}{M_1}$$

Where M_h is the RMS value of harmonic (h) component of M.

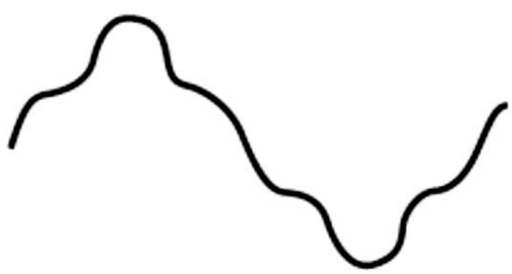

Fig. 2.8: Harmonics

Harmonic distortion causes-

1) Losses and heating of rotating machines and capacitors, thereby reducing efficiency.
2) Overvoltages due to resonance.

3) Interference in control system used in demand side management.
4) Interference in telephone lines.
5) Overloading of the neutral
6) Skin effect.

- **Interharmonics**

Those frequencies that are not integer multiple of system frequency are called Interharmonics. The source of Interharmonics are cycloconverters, HVDC links (back to back), static frequency converters. Interharmonics can cause visual flickering in CRT.

- **Notching**

Periodic disturbance induced in voltage waveform during current commutation from one phase to another in a power converter is called notching. It is a steady state phenomenon. Notching results in momentarily short circuit across the two phases during commutation. Notching cause digital clock to run faster.

- **Noise**

An unwanted electrical signal super imposed on the voltage or current signal with broadband spectral less than 200 kHz is called noise. Noise is caused by following factors-

1) Arcing equipments
2) SMPS and power converter based devices
3) Corona
4) Radiations due to welding machines
5) Control circuit
6) Improper grounding

Noise effect electronic equipments and can be mitigated using filters, isolation transformers and line conditioners.

2.5 POWER CONDITIONING

Power conditioning includes voltage monitoring and regulating devices to improve power quality. Some of these are as follows-

i. Line-voltage regulator
ii. Motor-generator set
iii. Magnetic synthesizers
iv. Static VAR compensators (SVC)
v. Uninterruptible power supply (UPS)
vi. Superconducting magnetic energy storage (SMES)
vii. Custom power devices

CHAPTER-3

VOLTAGE FLICKER

3.1 INTRODUCTION

According to IEC standards, flicker is "Impression of unsteadiness of visual sensation induced by light stimulus whose luminance or spectral distribution fluctuates with time." It is one of the most concerning power quality problem affecting both utility and consumers. When the observer is subjected to change in illumination intensity, a sensation is experienced. Voltage flicker observed in a lamp is generally due to the variations in the input voltage to the lamp. Large non-linear industrial loads cause voltage distortions by introducing harmonics causing voltage fluctuations in the distribution system. To limit the effect of these loads, flicker mitigation devices have to be connected at point of common coupling (PCC). Devices can be connected in series, shunt or as a combination of both. "The voltage flicker with frequency from 1 Hz to 10 Hz can affect the life of incandescent lamps, television and sensitive electronic equipments [76]". It can also decrease the efficiency of an electric motor.

3.2 CAUSES OF VOLTAGE FLICKER

The causes of voltage flicker are given below [77]:

- Starting of Large Motors
- Electric Arc Furnace
- Reciprocating Pumps or Compressors
- Electric Shovels
- Other Loads like Electric welders, strippers, rolling machines also cause the voltage flicker.

It must be ensured that special measures must be taken so that voltage fluctuations should not cross the flicker limit and if they do, certain corrective action are needed to be adopted for its mitigation.

3.3 CLASSIFICATION OF VOLTAGE FLICKER [77]

The flicker phenomena can be divided into cyclic flicker and non-cyclic flicker [78]. Cyclic flicker is caused by periodic voltage fluctuations and is repetitive in nature. Cyclic flicker occurs due to operation of loads like arc welders, spot welders or compressors. Non-cyclic flicker is caused by occasional voltage fluctuations like starting of large motors. Loads like AC choppers cause both cyclic as well as non-cyclic voltage flicker.

Based on their frequency of occurrence, flicker can be divided into four groups-

- **Cyclic Frequency**

It is visible in reciprocating compressors and pumps, arc furnace and automatic spot welders. The range of fluctuation frequency is 10 per second to 2 per second

- **Cyclic Low Frequency**

Saws, drop hammers, manual spot welders and arc welders fall into this category. The range of fluctuations of frequency is 2 per second to 12 per minute.

- **Non-cyclic Frequent**

The fluctuation frequency ranges from 12 per minute to 1 per minute. Cranes, hoist and single elevators are examples of this category.

- **Non-cyclic Infrequent**

The frequency fluctuates in the range of 1 per minute to 3 per hour. Starting of motors is the most common example of such flicker.

3.4 VOLTAGE FLICKER MEASUREMENT

IEEE standards define flicker as “impression of fluctuating brightness or colour, when the frequency variation lies between few Hertz and the fusion frequency of image.” Many algorithms have been investigated with the aim of measuring flicker and the frequency at which it occurs. A flickermeter measures the flicker produced by fluctuating source voltage in an indirect manner. It measures the flicker and deduce light flicker by considering the following-

- Frequency of occurrence of voltage fluctuations
- Nature of voltage fluctuations
- Type of lamp like incandescent and fluorescent lamps
- Response of eye to light
- Brain's recognition and realization

All these factors are modelled in a modern flickermeter. Unlike the internal complexity, IEEE flickermeter's output is simple. "If the output is greater than 1.0, the flicker is troublesome to humans, if less than 1.0, it is not". Since flicker comes and goes, human irritation to flicker is subjective, there is an objective methodology established by IEEE [79] for measuring with the flickermeter.

"The standardized flickermeter introduced by IEC uses weighing curves, representing the response of human eye to light variations in a 60 W, 230 V, 50 Hz, double coiled filament incandescent lamp [81]". The major parts of the flickermeter are the input, the lamp-eye brain response and the output processing. The output is given as per-unit flicker voltage, where one per-unit is the level responsible for causing "noticeable and annoying light flicker [81]", with the perception of 50% of human population.

The input voltage is obtained using input voltage adapter, which provides normalized rms voltage to the input of demodulator. Adapter contains two filters to eliminate DC component and double frequency ripple. It also includes a calibration generator. Demodulator is provided by the squaring multiplier. It recovers the modulating signal and supresses the main frequency carrier signal using filters. The fluctuating voltage components are obtained using a demodulator followed by a high pass and a low pass filter.

The first filter is the first-order high pass filter with the cut off frequency of 0.05 Hz followed by the sixth-order Butterworth low pass filter with a cut off frequency of 35 Hz. These filters remove the 100 Hz double carrier along with the associated side bands and the DC component. Weighing curve which is the model of human reaction to the fluctuation of lamp luminosity is in the frequency domain. It is represented as a bode plot of band pass filter with transfer function as [74]-

$$H(S) = \frac{k\,\omega_1}{s^2 + 2\lambda + \omega_1^2} \times \frac{1 + \frac{s}{\omega_2}}{\left(1 + \frac{s}{\omega_3}\right) \times \left(1 + \frac{s}{\omega_4}\right)} \tag{3.1}$$

Where, for a 60 W, 230 V incandescent lamp, k = 1.74802 ,$\lambda = 2\pi \times 4.05981$, $\omega_1 = 2\pi \times 9.15494$, $\omega_2 = 2\pi \times 2.7979$, $\omega_3 = 2\pi \times 1.22535$, $\omega_4 = 2\pi \times 21.9$.

The weighing filter gives a band pass response at 8.8 Hz, simulating the response of lamp-eye-brain system for the observer. The filter designed is based on psycho-physiological research on the influence of luminous flux change in human being [74].

The weighing filter is succeeded by a squaring multiplier and a smoothning filter, which is a low pass filter with a cut off frequency of 0.53 Hz and models the fatigue effect of luminous flux change. It implements the remainder of lamp-eye-brain model. Simulation of non-linear eye/brain response characteristics is executed using squaring multiplier, while the filter emulates perceptual storage effects in the brain with time constant of 300 ms [81]. The output of this block is called instantaneous flicker sensation (I_{FL}). Fig. 3.1shows the block diagram of a digital flickermeter and Fig. 3.2 shows the Instantaneous flicker level of a certain voltage signal as obtained from digital flickermeter.

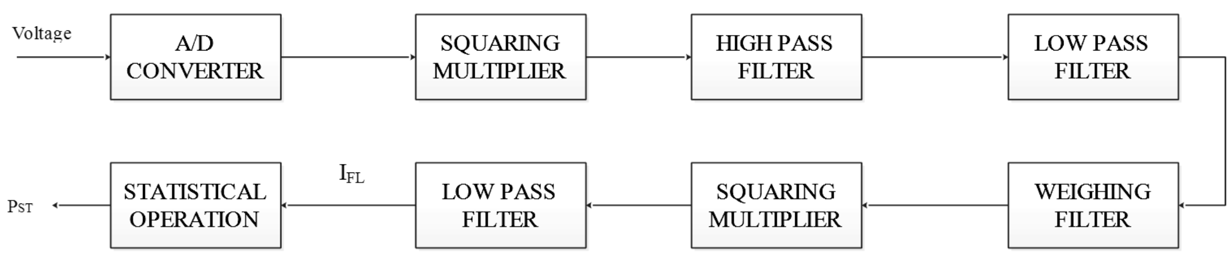

Fig. 3.1: Block diagram of Flickermeter

The instantaneous flicker is given as input to the evaluation block. It constitute of analog to digital converter and a statistical classifier. It computes cumulative probability function based on the samples of I_{FL} collected over an observation time of ten minutes. The classifier translates the output of filter into short-term flicker severity index (P_{ST}) and long-term flicker severity index (P_{LT}).

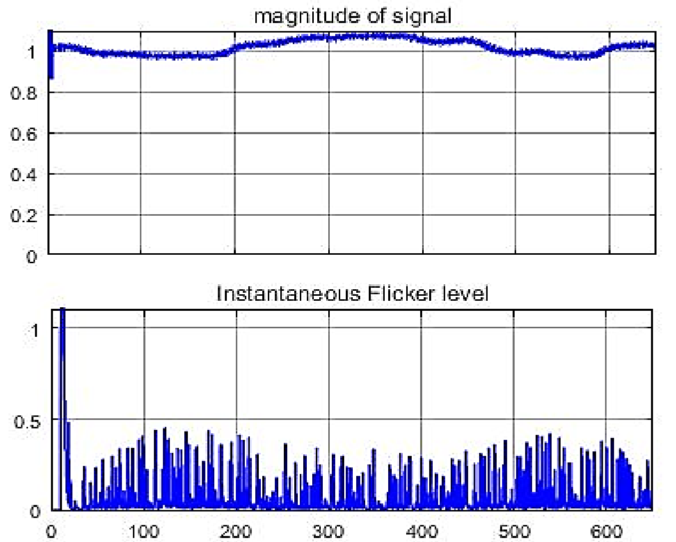

Fig. 3.2: Instantaneous Flicker Level obtained from Digital Flickermeter

As stated above, two major indices are used in evaluation of flicker in power systems. The measure of severity of short term flicker, P_{ST} is then calculated every ten minutes using weighted cumulative probability values of flicker level exceeding 0.1, 1.3.10 and 50% of time using equation (3.2).

$$P_{ST} = [0.0314P_{0.1} + 0.0525P_{1S} + 0.0657P_{3S} + 0.28P_{10S} + 0.08P_{50S}]^{\frac{1}{2}} \tag{3.2}$$

Where, $P_{0.1}$ is the voltage flicker level referred to 0.1%. Same can be said for P_1, P_3, P_{10} and P_{50}. Also,

$$P_{1S} = \frac{P_{0.7} + P_1 + P_{1.3}}{3} \tag{3.3}$$

$$P_{3S} = \frac{P_{2.2} + P_3 + P_4}{3} \tag{3.4}$$

$$P_{10S} = \frac{P_6 + P_8 + P_{10} + P_{13} + P_{17}}{5} \tag{3.5}$$

$$P_{50S} = \frac{P_{30} + P_{50} + P_{80}}{3} \tag{3.6}$$

The possible method for evaluating P_{ST} is direct measurement using flickermeter. People's tolerance to flicker decrease with increase in flicker period. The second index, long-term flicker severity index, P_{LT} is given by equation (3.7) as

$$P_{LT} = \left[\frac{\sum_{i=1}^{N} P_{STi}^{3}}{N}\right]^{1/3} \tag{3.7}$$

Where N is the number of ten minute intervals within the observation time of P_{LT}. The short-term flicker values are required to evaluate long-term flicker severity. Utilities must ensure that flicker level must remain below 1.0. For long-term flicker index, the values should be kept lower as it is more annoying to consumers. Utilities should make sure that flicker indices should not exceed compatibility standards. Compatibility levels for voltage fluctuations are shown in Table. 3.1.

Table 3.1: Compatibility Levels for LV and MV System [82]

P_{ST}	*1.0*
P_{LT}	*0.8*

In some Asian countries (Japan and Taiwan) another criteria for the flicker assessment is adopted by power companies- the voltage flicker index ΔV_{10}, characterizing the actual flicker with respect to an equivalent value of the voltage modulation component with the frequency of 10Hz [83]. It results that the same voltage fluctuations can be acceptable to one flicker criterion and non-acceptable according to another one, resulting in double cost of flicker level verification.

3.5 VOLTAGE FLICKER MITIGATION

Many techniques are available to mitigate the voltage flicker. Some are based on tracking voltage envelope, voltage sag or extracting filter frequency using the notch filter [84]. The various approaches involved for voltage flicker mitigation are-

- Reducing load power variations by using devices like dynamic voltage stabilizers or installing the synchronous machines at the point of common coupling. Synchronous machines are the source of reactive power both leading and lagging. They are required to operate in a closed-loop voltage control system with fast excitation current control to enable the fast rise time of machine's reactive current. Consequently, rms voltage at point of common coupling can be varied. These devices are divided into following categories-

a) Static Var Compensators (SVC)
    - Thyristor Switched Capacitor (TSC)
    - Thyristor Controlled Reactor (TCR)
    - TSR
    - FC-TCR
    - TSC-TCR

b) STATCOM and Distribution STATCOM

c) Saturable Reactor

d) Dynamic Voltage Restorer (DVR)

These devices are the practical solution for reducing fluctuations. The efficiency of these devices depends upon their rated power. Static var compensator (SVC) is commonly used in high power applications for voltage flicker mitigation. However, the main drawback of SVC is poor flicker reduction ratio [85]. SVC also introduces harmonics and requires passive filters which make the arrangement very costly. Voltage source converter (VSC) based STATCOM and DSTATCOM are much more feasible option for voltage flicker mitigation due to its higher flicker reduction ratio [86]. In case of a weak distribution network, DSTATCOM is preferred over an SVC.

- Increasing short circuit power level with respect to load can also reduce flicker levels. This technique is expensive and applied at the designing stage. Short circuit power can be increased by-
    - Installing series capacitors
    - Installing additional lines to reinforce existing lines
    - Connecting the loads at a higher nominal voltage levels
    - Increasing rated power of transformer serving the fluctuating loads
    - Using separate winding of transformer for fluctuating loads and separate for steady loads

Other flicker mitigating techniques include-

- Lowering the motor starting or inrush current by using soft start devices
- Fluctuating loads can be supplied from a decoupled source of the utility system
- Use of isolating transformers to part supply terminal feeding the fluctuating loads from the lightning loads
- Operating of a flicker producing load at a time when it cannot bother people like during the night time.
- Updating and implementing latest equipment design to minimize voltage fluctuations.
- Connecting single phase welder to three phase system for balanced load distribution between phases
- Use of active filter (Custom Power Device)

CHAPTER-4

DISTRIBUTION STATCOM

4.1 INTRODUCTION

A distribution static compensator known as DSTATCOM is a power electronics converter based device which find its application in AC distribution network where, load balancing, harmonics mitigation and reactive current or power compensation is necessary [87]. It provides protection from voltage unbalance to the distribution system. It is shunt connected to the distribution system through a coupling inductance realized using a transformer. The major advantage of DSTATCOM is better dynamic response, ability to generate rated current at any network voltage and use of small capacitor on DC bus resulting in reduction of size and cost of the compensator. DSTATCOM has many topologies but, it is mostly designed based on DC to AC converter which is also called a voltage source inverter (VSI). The voltage source inverter produces a set of controllable, 3-phase output voltage or current at a fundamental frequency of bus voltage from the voltage source like capacitor. The active and reactive power exchange between DC and AC bus takes place by varying the magnitude and phase angles of output voltage and current to regulate AC bus voltage.

The behaviour of DSTATCOM is greatly influenced by the performance of VSI, which is determined by the switching technique and control strategy. Among many ways of controlling, pulse width modulation (PWM) is a standard one. The DSTATCOM has appeared as a promising device for various power quality problems like flicker suppression, voltage stabilization, power factor correction and total harmonic reduction (THD).

4.2 DESIGN OF THE DSTATCOM

The schematic diagram of DSTATCOM is shown in Fig. 4.1. DSTATCOM is connected to 3-phase AC mains supplying three phase loads. Interfacing inductor (L_t) is used for reducing ripples in compensating currents at AC side of voltage source inverter. The harmonic currents are injected by DSTATCOM to cancel out harmonics of the load current. The rating of switches is based on the rating of the VSI for harmonic elimination or reactive power compensation [88]. A small series combination of capacitor and inductor is installed at PCC in parallel with the load and is called ripple filter. It filters the high frequency switching noise of the voltage at point of common coupling.

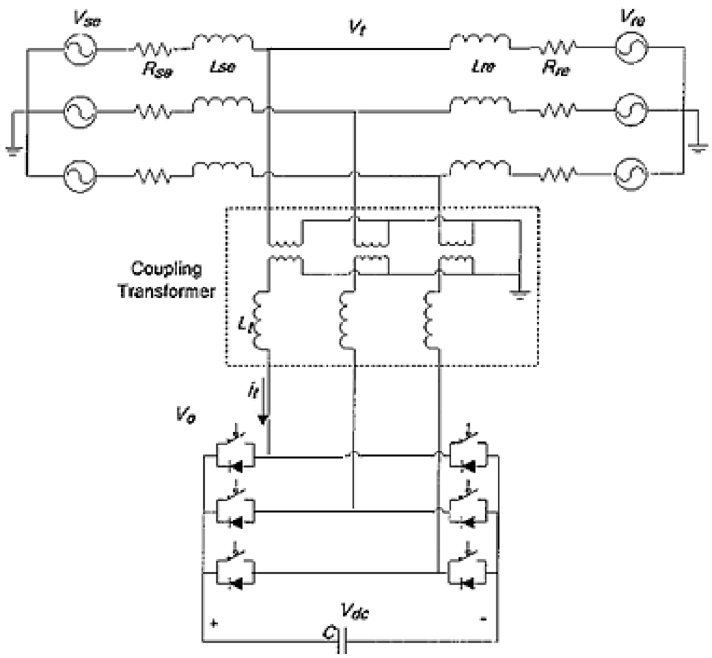

Fig. 4.1: Schematic Diagram of the DSTATCOM

The main components of a DSTATCOM are-

- DC Capacitor
- Voltage Source Inverter
- Coupling Transformer
- Reactor

4.3 OPERATING PRINCIPLE

A DSTATCOM can compensate either line currents or bus voltage. The main role of DSTATCOM is to regulate bus voltage by absorbing or generating reactive power. Hence, it operates either as an inductor or as a capacitor depending upon bus voltage magnitude.

- **Inductive Mode-** If the magnitude of bus voltage is more than the rated voltage, then the system sees DSTATCOM as an inductive reactance connected at its terminals and DSTATCOM sees system as capacitive reactance. The line current flows from AC system to DSTATCOM. DSTATCOM behaves as inductor which absorbs reactive power from the system.

- **Capacitive Mode-** If the bus voltage is less than the reference or rated voltage, then the DSTATCOM sees system as inductive reactance and system sees DSTATCOM as a capacitive reactance coupled at its terminals. The current course from DSTATCOM to the AC system. The DSTATCOM behaves as capacitor generating reactive power.

4.4 PULSE WIDTH MODULATION (PWM)

As mentioned earlier, voltage source inverter is a building block of a DSTATCOM. Out of many configurations of VSI, most standard one is the 3-phase, six-switch VSI. Six switches are made to turn on and off at the allotted intervals by inputting the pre-defined signals in order to convert DC voltage into 3-phase output voltage. Pulse width modulation is most commonly used technique to achieve these characteristics.

In a pulse width modulation technique, input signal is compared with a triangular carrier wave of fixed frequency in order to generate the firing pulses for the voltage source inverter. By varying the magnitude and phase of the modulating signal, phase and magnitude of the fundamental signal can be controlled. In this technique, AC voltage contains the fundamental as well as the harmonic components which are located around the frequency multiples of carrier frequency [91]. Fig. 4.2 shows a one-leg switch mode converter with a DC input source V_{dc}. Switching of signal generator controls the two switches T_{A+} and T_{A-}. V_{AO} is the output voltage of leg A to the ground.

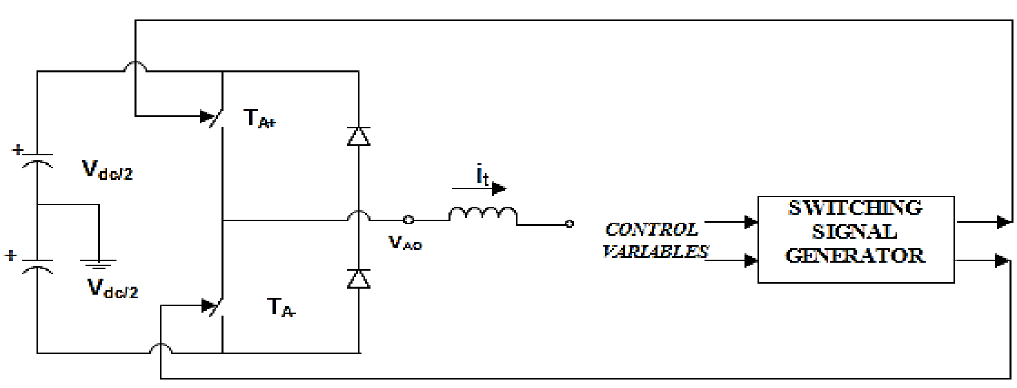

Fig. 4.2: Single-Leg Switch Mode Converter

The output voltage V_{AO} is determined by the status of switches

$$V_{AO} = \frac{V_{dc}}{2} \text{ (when TA+ is on)} \quad (4.1)$$

$$V_{AO} = \frac{-V_{dc}}{2} \text{ (when TA- is on)} \quad (4.2)$$

During the switching period $T_{sw,}$ the average value of output voltage V_{AO} is given as-

$$V_{AO} = (2D - 1)\frac{V_{dc}}{2} \quad (4.3)$$

Where, D is the duty ratio of switch TA+ and is given as-

$$D = \frac{ton}{T} \quad (4.4)$$

In this technique, control signal $V_{control}$ is compared to a triangular carrier wave $V_{tri.}$ When $V_{control}$ > $Vtri$, T_{A+} is on. When $V_{control} < V_{tri}$, T_{A-} is turned on. The duty ratio D, is determined by the ratio of $V_{control}$ to peak value of V_{tri} as both V_{dc} and V_{tri} are fixed.

Therefore,

$$V_{AO} = \frac{V_{control}}{V_{tri}}\frac{V_{dc}}{2} \quad (4.5)$$

$$V_{AO} = \frac{V_{dc} \times V_{control}}{2V_{tri}} \quad (4.6)$$

The average output voltage V_O changes linearly with $V_{control}$. Therefore, converter acts as a linear amplifier. In case, control signal being sinusoidal in nature, instead of DC, the output voltage V_{AO} is the series of pulses with discrete widths. Since the carrier frequency f_{tri} is greater than the control signal frequency f_1, the control signal during the switching period is approximately constant and Eq. 4.6 could be applied here. The pulse width modulation varies linearly with ratio of control signal to the peak value of carrier signal as shown in Fig. 4.3. The square wave is composed of fundamental component at frequency f_1 and harmonic components.

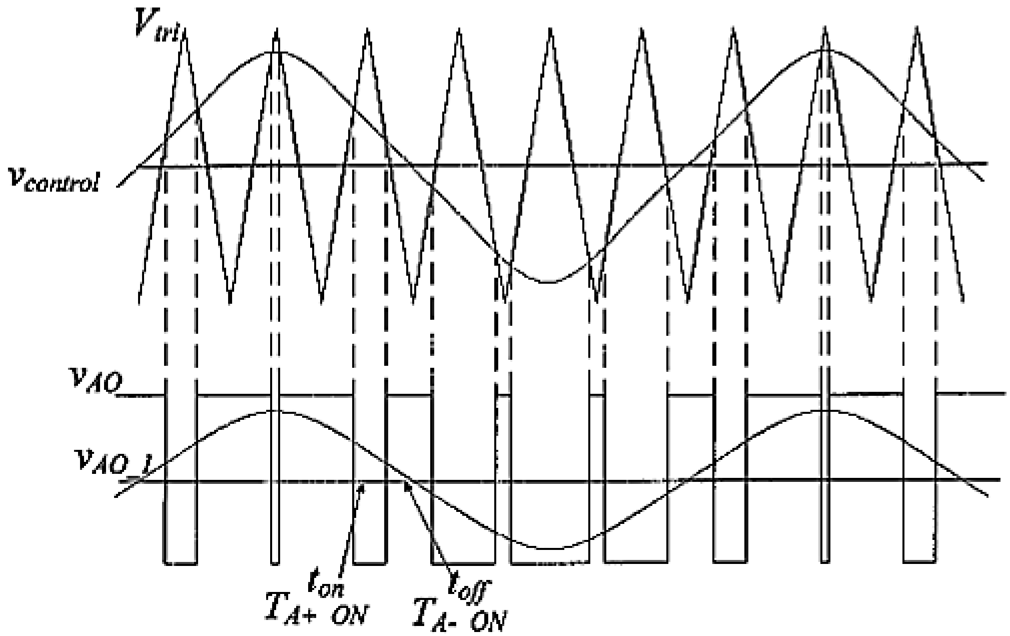

Fig. 4.3: Sinusoidal Pulse Width Modulation (SPWM)

Harmonic components are located close to multiple of f_1. The modulation index MI is defined as-

$$MI = \frac{Vcontrol}{V_{tri}} \tag{4.7}$$

Here, $V_{control}$ is the peak value of the control signal. The frequency of modulation ratio m_f is given as-

$$m_f = \frac{ftri}{f_1} \tag{4.8}$$

Where, f_{tri} equals to switching frequency f_{sw}. The peak value of fundamental component is –

$$V_{AO-1} = \frac{V_{dc} \times V_{control}}{2V_{tri}} = MI\,\frac{V_{dc}}{2} \tag{4.9}$$

4.5 CONTROL STRATEGY

In a DSTATCOM, when voltage at the point of common coupling is more than the rated voltage or reference voltage, then the DSTACOM produces reactive power and when voltage at point of common coupling is less than the reference or rated voltage, it absorbs or takes the reactive power from the system. To obtain this principle, firing pulses applied to the pulse width modulated voltage source inverter are controlled as shown in Fig. 4.4.

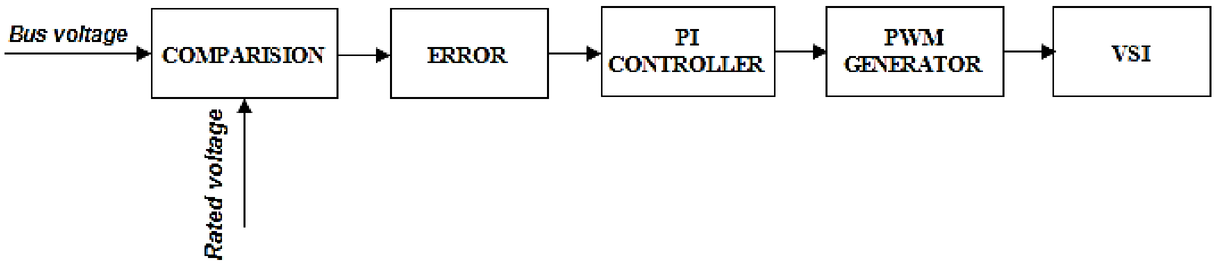

Fig. 4.4: Block Diagram of the Control Circuit of D-STATCOM

The power system bus voltage is contrasted with the rated voltage and the resultant signal obtained called error signal is passed through proportional integrator (PI controller). The controller generates signal which is given to pulse width modulation generator. The pulse width modulation generator fires the required firing pulse for voltage source inverter to correct voltage imbalance.

4.6 MULTI-PULSE INVERTER FOR DSTATCOM

With the advancement of technology, application of power electronics based devices for efficient power conversion is increasing. These devices are compact, cheap and have lesser power losses with high efficiency. However, power electronics devices suffer from certain disadvantages like harmonics. Simple and efficient technique for harmonic mitigation is provided by multi-pulse inverter. Multi-pulse converters are diode or thyristor based converters that provide more than six-pulse of AC/DC per cycle. It is the combination of number of six-pulse inverters either connected in series or parallel. The phase shift transformer is the important component of multi-pulse inverter. Each inverter is fed by a phase shifted secondary windings from the phase shift transformer. Each secondary winding is connected to one inverter. As the number of inverters increases, number of steps in primary current waveform also increases. The multi-pulse inverters with diodes as their switching elements are called uncontrolled inverters whereas the inverters with thyristor are called controlled inverters. For harmonic elimination, uncontrolled inverters are preferred due to the reason that they do not require any controller for diodes but output voltage cannot be controlled for such converters. On the other hand, controlled converters require a control system for switching purposes. Multi-pulse converters are based on the concept of harmonic cancellation. In this technique, harmonics produced by one inverter are cancelled by harmonics generated by another inverter. Various advantages of multi-pulse inverters are summarised below-

- Ripple content in DC output voltage can be reduced significantly.
- Reduction in line current harmonics.
- Good dynamic response.
- Reduction in size of filtering elements.
- Multi-pulse converters are suitable for high power ratings.
- Multi-pulse inverter are simple robust and more efficient.

4.7 APPLICATIONS OF DSTATCOM

- Reduction in harmonics
- Power factor correction
- Reactive power compensation
- Voltage stabilization in power grid
- Increase in transmission capacity
- Unbalance compensation
- Limiting voltage swell as a result of capacitor switching
- Increase in maximum load ability of the system
- Reducing voltage fluctuations from 2.5% to 0.2% causing decrease in voltage flicker substantially.

CHAPTER-5

MATLAB SIMULATION AND RESULT ANALYSIS

5.1 DESIGN OF THE TEST SYSTEM

To investigate the phenomena of voltage flicker, a two bus system is considered. In real time applications, load operation of electric arc furnace is the main source of voltage flicker into the power system as shown in Fig.5.1. In MATLAB/SIMULINK [92], a programmable voltage source block is used to inject voltage flicker into the system externally at the common coupling point. Amplitude modulation of alternating voltage from programmable voltage source is the cause flicker or fluctuations. “The disturbance in the form of voltage flicker is transferred to other loads in the power system via PCC, so the voltage flicker appears in the output load voltage [93]”. Digital flickermeter block is used to analyse the contaminated voltage. Input to the flickermeter is the voltage distorted by fluctuations and the output is instantaneous flicker level (I_{FL}).

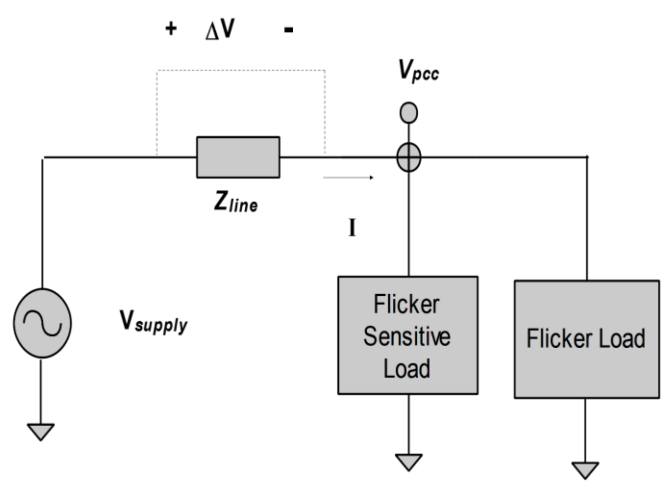

Fig. 5.1: Single Line Diagram of Load Causing Flicker

To eliminate the effect of voltage flicker in the output load voltage, DSTATCOM is connected between the utility and load at the PCC. To accomplish the investigation of the stated procedure, a two bus system is probed. The test system used is 69 kV, 3-phase, Π- section power line connected to a 3-phase step down transformer supplying a 3-phase parallel RL load. This configuration block diagram is illustrated in Fig 5.2. Voltage oscillations are the consequence of programmable voltage source.

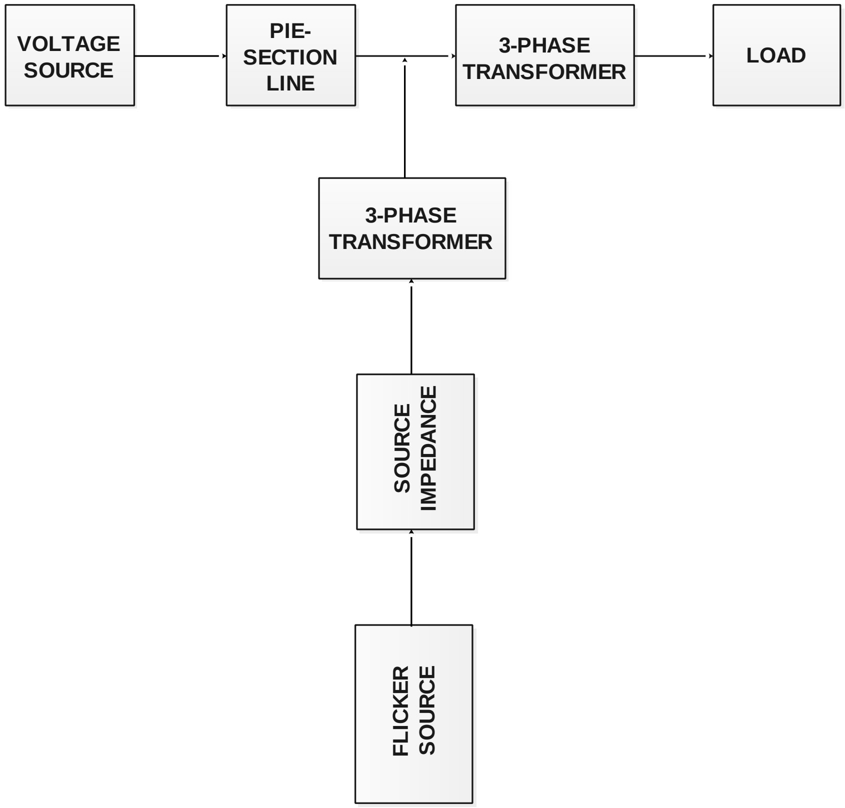

Fig. 5.2: Block Diagram of the Studied Test System

Parameter of the studied test system are:

- Generator- 3-phase, 69 kV, 50 Hz
- Transmission line- 3-phase, Π-section and 100 km length

  Zero-sequence impedance with R = 0.3864 Ohm/km, L=4.12 mH/km and C=751nF

  Positive-sequence impedance with R = 0.01273 Ohm/km, L=0.93 mH/km and C=12nF

- Load- 3-phase, parallel RL load of 30MVA
- Programmable voltage source (Flicker source)

  Amplitude modulation = 0.3 p.u.

In order to analyse the influence of DSTATCOM as an effective mitigation device for voltage flicker, the compensation is adopted using six-pulse voltage source converter DSTATCOM. However to achieve minimal distortion, multi-pulse inverter along with the magnetic interface which is provided by a phase shifting transformer is used. Fig. 5.3 (a) and 5.3 (b) shows the output voltage of the system when external flicker source is added to the system. The contaminated voltage is analysed by the aid of digital flicker block set to obtain instantaneous flicker level as shown in Fig. 5.4 (c), giving the inspection of the studied wave.

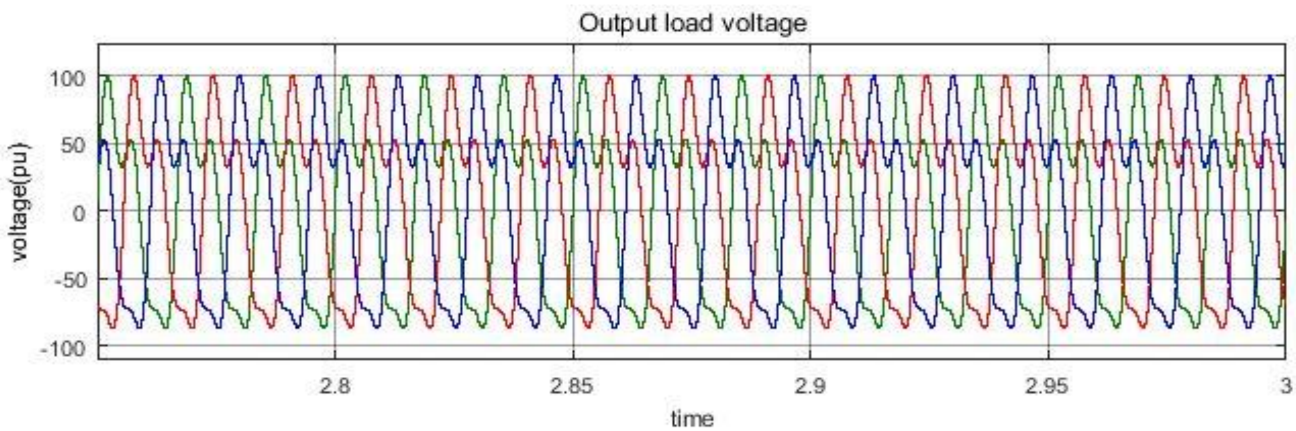

Fig. 5.3 (a): Output Voltage Waveform of Test System

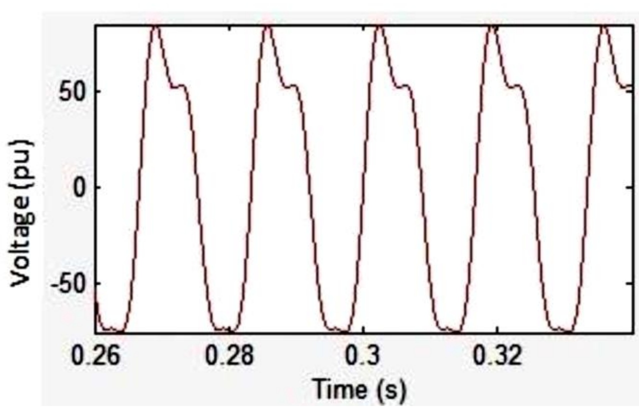

Fig. 5.3 (b): Uncompensated Output Voltage Waveform

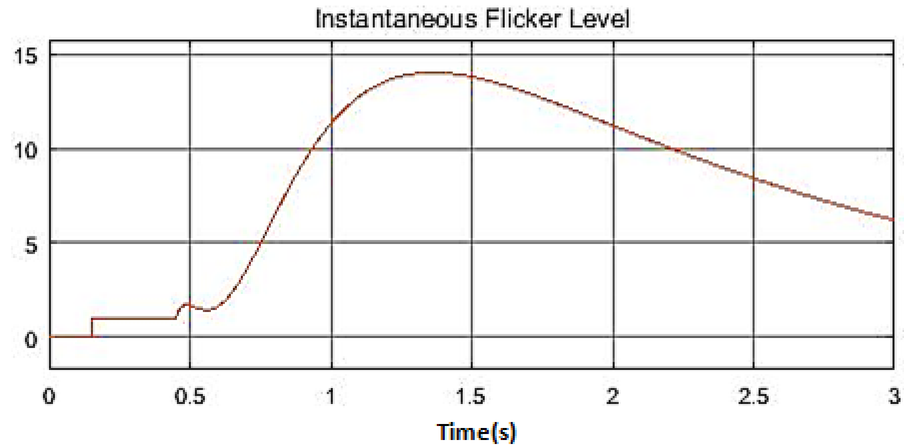

Fig. 5.3 (c): Instantaneous Flicker Level of an Uncompensated System

5.2 DESIGN OF SIX-PULSE VOLTAGE SOURCE INVERTER BASED DSTATCOM

Voltage source inverter aims at generating AC output from DC input. The voltage source inverter is the prime functioning part of any FACT device including DSTATCOM. A six-pulse voltage source inverter is also called 3-phase inverter. It consists of six asymmetric power electronics based switching devices like GTO or IGBT with diodes connected in anti-parallel forming a six-pulse graetz bridge [91] as shown in Fig. 5.4. The firing signals are controlled to ensure that each transistor conducts for 180° while feeding the resistive load. The inverter is basically designed from three single phase inverters, each inverter providing the voltage shifted by a phase angle of ±120° with respect to the other two inverters.

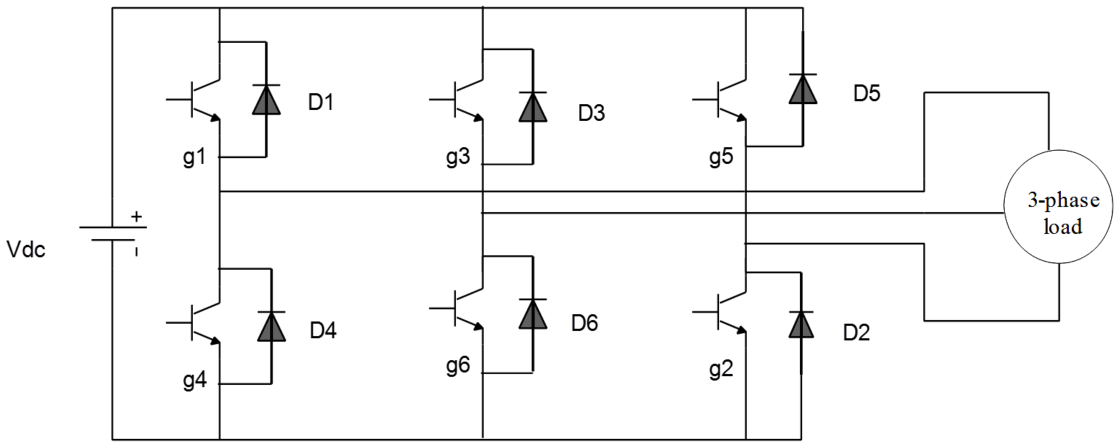

Fig. 5.4: Six-pulse Voltage Source Inverter

The controller for the DSTATCOM is designed based on the "concept of instantaneous reactive power" theory. The 3-phase flicker voltage is transformed to synchronous reference frame using abc to dq0 transformation. To implement this concept, phase lock looped (PLL) block is used. The input to this block is 3-phase AC system's load voltage. The output of PLL, sinωt and cosωt act as an input for abc to dq0 transformation, initiating the development of three instantaneous space vectors Vd on the direct or real axis, Vq on the quadrature or imaginary axis and $V_{0.}$ The equations for this transformation are expressed in MATLAB/SIMULINK software as-

$$Vd = \frac{2}{3}\left[Va\sin(\omega t) + Vb\sin\left(\omega t - \frac{2\pi}{3}\right) + Vc\sin\left(\omega t + \frac{2\pi}{3}\right)\right] \tag{5.1}$$

$$Vq = \frac{2}{3}\left[Va\cos(\omega t) + Vb\cos\left(\omega t - \frac{2\pi}{3}\right) + Vc\cos\left(\omega t + \frac{2\pi}{3}\right)\right] \tag{5.2}$$

$$V_O = \frac{1}{3}[Va + Vb + Vc] \tag{5.3}$$

Where, ω = rotation speed of rotating frame in rad/s.

The output is split into three components via demux block. To reduce voltage flicker, reactive power component is to be controlled. So the controlling system requires only Vq to control DSTATCOM. The Vq is fed to the sum block, which requires another input of constant value zero, indicating the Vq per unit reference value. The output of sum block acts as an error signal for propotional integrator. Output of PI controller is the firing angle which is fed to the pulse generator. Pulses from pulse generator are sent to voltage source converter to trigger the switching devices like GTO or IGBT of DSTATCOM to produce required voltage magnitude. The output of six-pulse inverter is shown in Fig. 5.5 (a). The compensated output load voltage and instantaneous flicker level respectively by six-pulse voltage source converter based DSTATCOM are shown in Fig. 5.5(b) and Fig. 5.5(c), respectively.

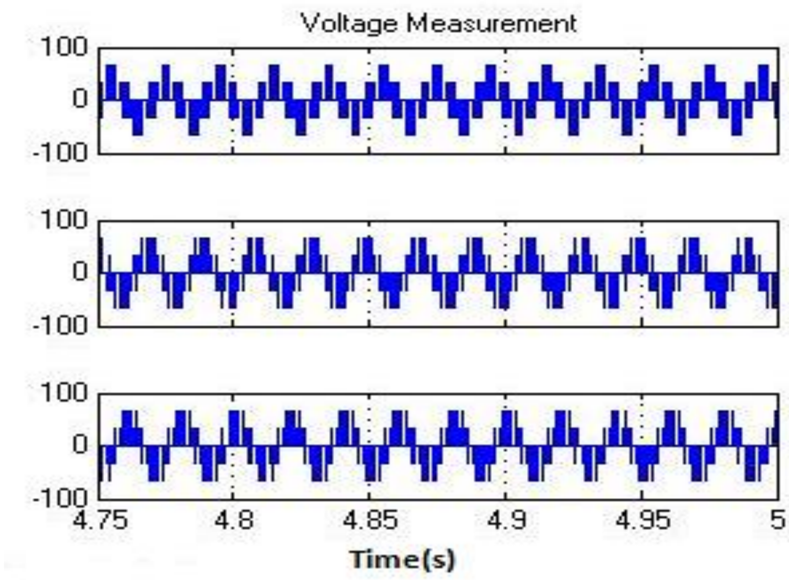

Fig. 5.5 (a): Output waveform of Six-pulse Voltage source Inverter

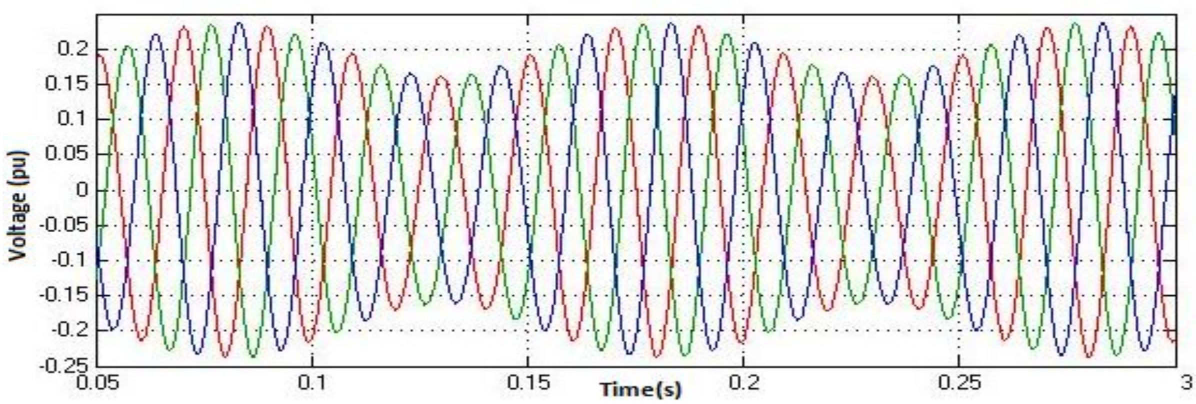

Fig. 5.5 (b): Compensated Output Voltage by Six-Pulse Voltage Source Converter DSTATCOM

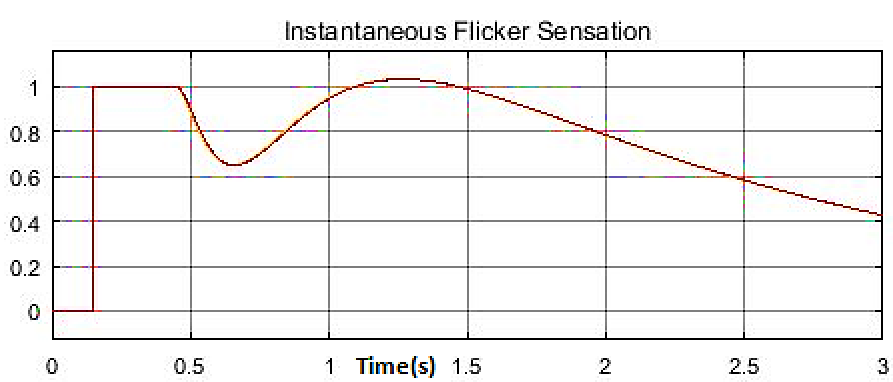

Fig. 5.5 (c): Instantaneous Flicker Sensation Levels with Six-pulse Voltage Source Inverter DSTATCOM

5.3 DESIGN OF TEN-PULSE AND FORTY-PULSE VOLTAGE SOURCE INVERTER BASED DSTATCOM

As mentioned in the previous section, six-pulse configured VSI is the building block of a basic DSTATCOM. However for high power applications, it exhibits high harmonics thus, in high power applications 3-phase or six-pulse voltage source inverter fed DSTATCOM is not desirable for appropriate performance. Therefore for high power application multi-pulse inverter (more than six-pulse) is opted for. Multi-pulsing is a very effective technique of reducing harmonics. The principle behind this technique is "to displace power electronic based switching devices of identical modules, so that harmonics produced from switching of different modules can cancel each other."

In the mentioned thesis work, ten-pulse inverter which is the non-integral multiple of six has been used for the purpose. The basic configuration of a ten-pulse voltage source inverter is illustrated in Fig. 5.6 (a).

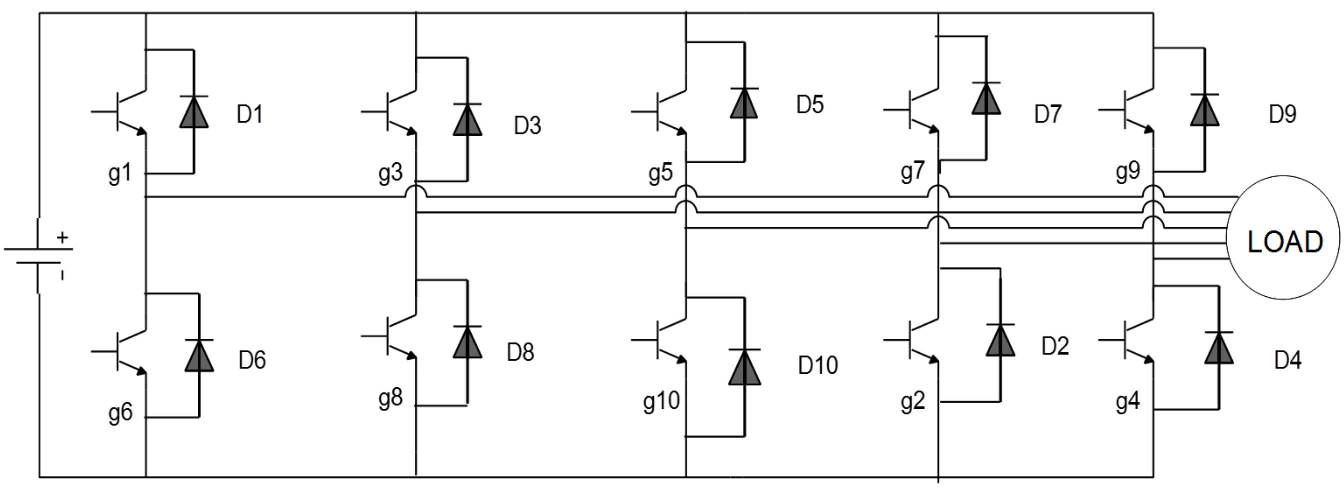

Fig. 5.6 (a): Circuit for Ten-pulse Voltage Source Inverter

A forty-pulse voltage source inverter is also designed for the operation of DSTATCOM. A forty-pulse inverter employs phase shifting transformer and four ten-pulse inverters. A uniform phase shift is applied to each inverter to achieve proper wave. A single leg of voltage source inverter consists of two IGBT or GTO semi-conducting switches (G1 and G6, G3 and G8, G5 and G10, G7 and G2 or G9 and G4). Two switches in the same arm cannot be switched simultaneously as it would lead to short circuit across the DC link supply. The ten pulse inverter is the basic converter unit from which forty-pulse inverter is derived as shown in Fig. 5.6 (b).

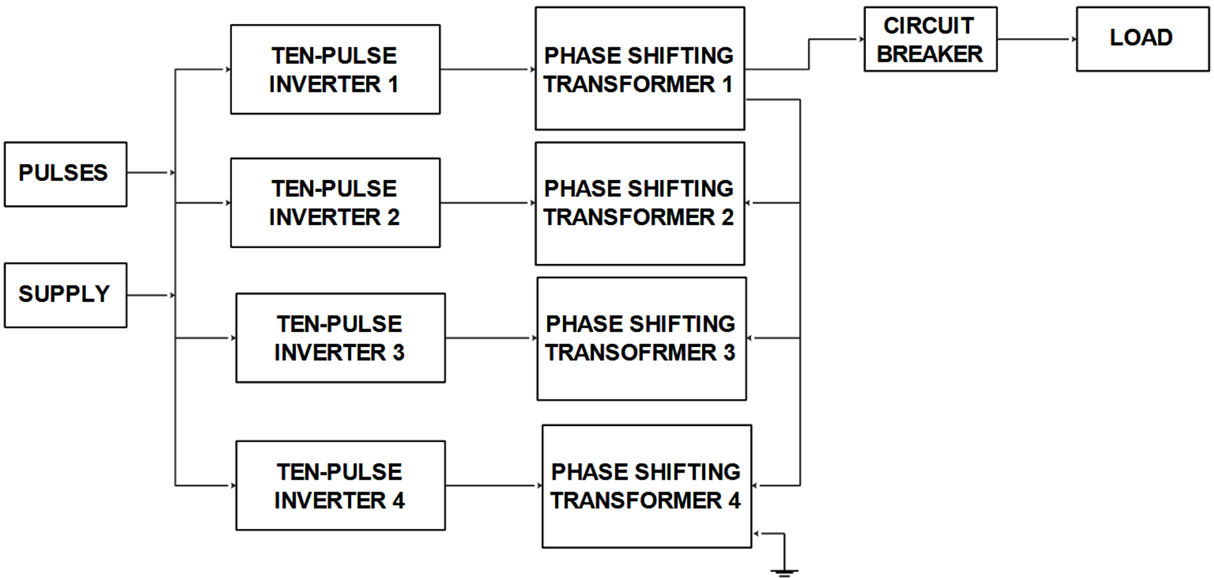

Fig. 5.6 (b): Block Diagram of Forty-pulse Inverter

Voltage source inverter is modelled in MATLAB/SIMULINK. SPWM is used to generate pulses for switches like IGBT or GTO. The output of ten-pulse and forty-pulse inverter is shown are Fig. 5.7 (a) and Fig. 5.7 (b), respectively.

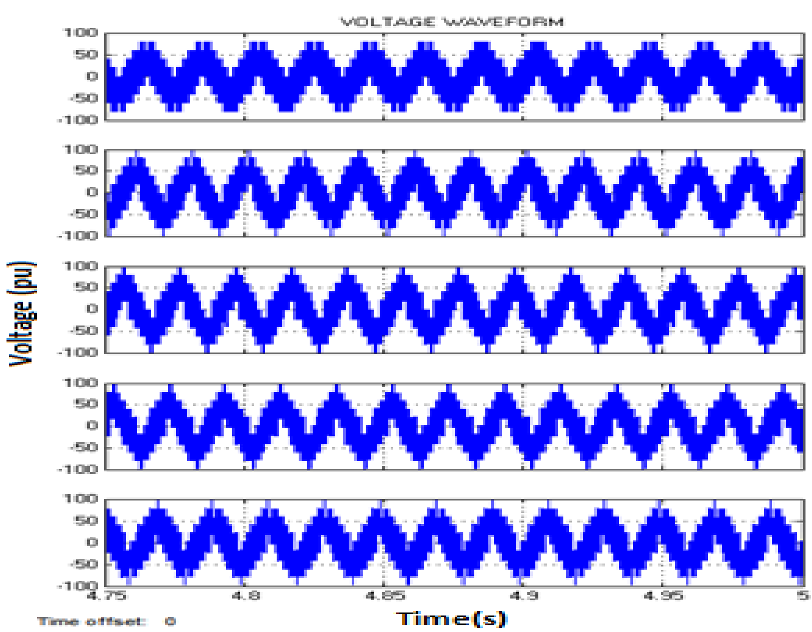

Fig. 5.7 (a): Output Waveform of Ten-pulse Voltage Source Inverter

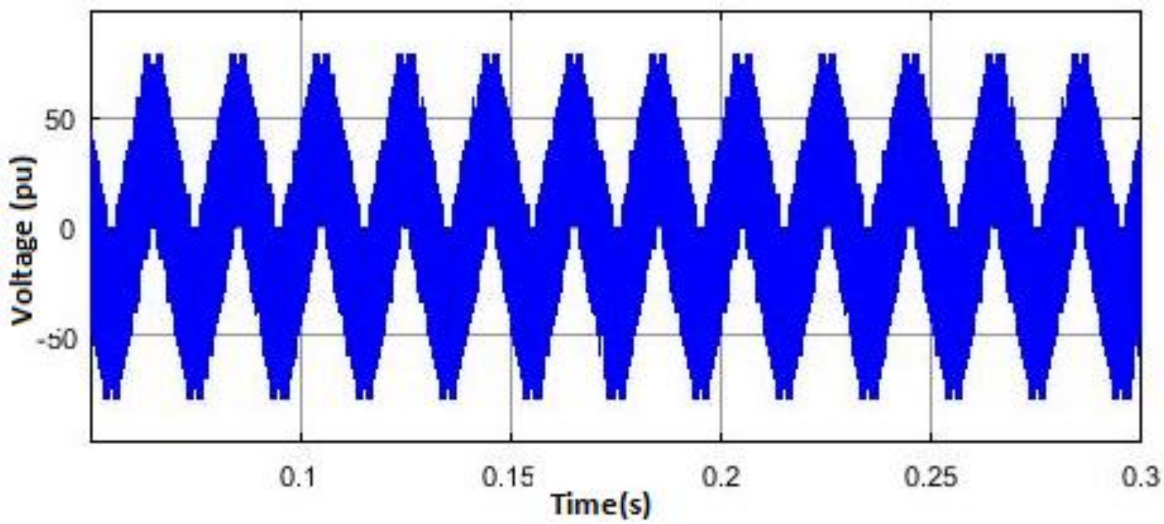

Fig. 5.7 (b): Output Waveform of Forty-pulse Voltage Source Inverter

The voltage flicker mitigation is achieved using ten-pulse and forty-pulse voltage source converter. The output voltage for the system and the output of the digital flicker meter is shown in Fig. 5.8 (a) to Fig. 5.8 (d).

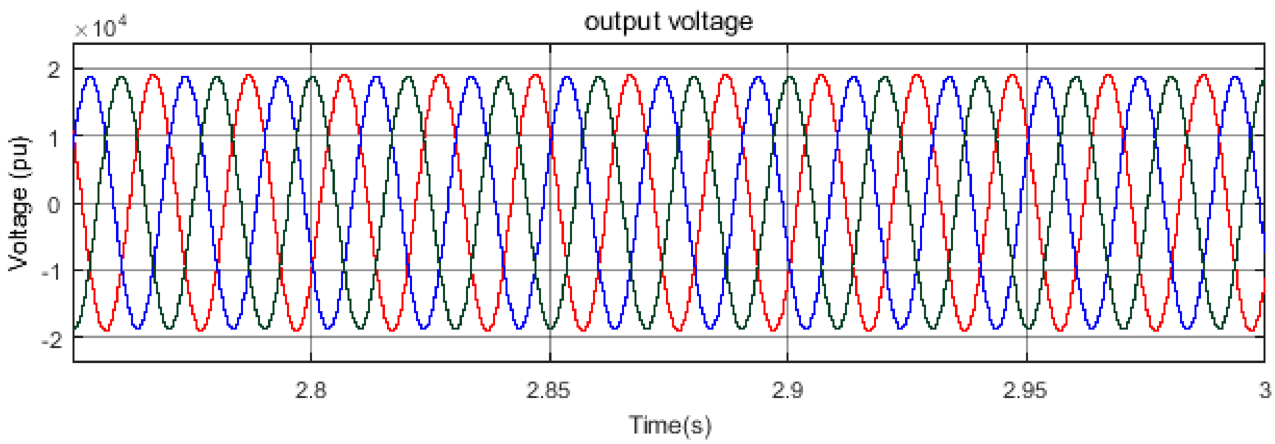

Fig. 5.8 (a): Compensated Output Voltage by Ten-Pulse Voltage Source Converter Based DSTATCOM

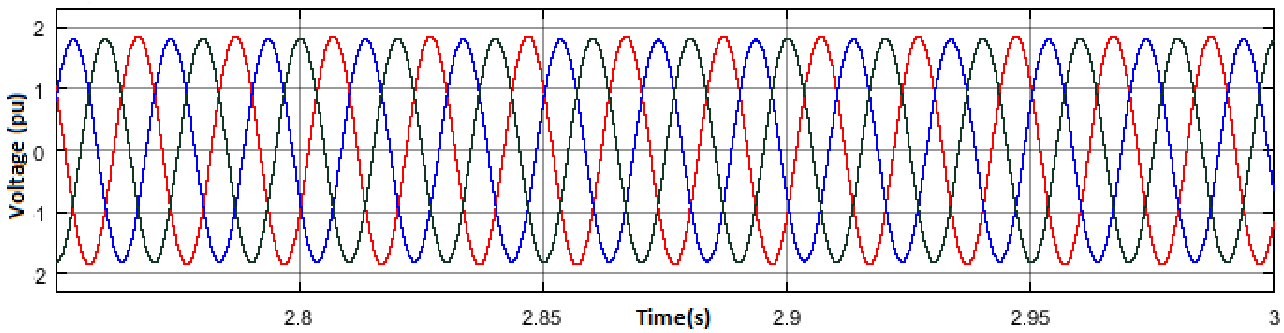

Fig. 5.8 (b): Compensated Output Voltage by Forty-Pulse Voltage Source Converter Based DSTATCOM

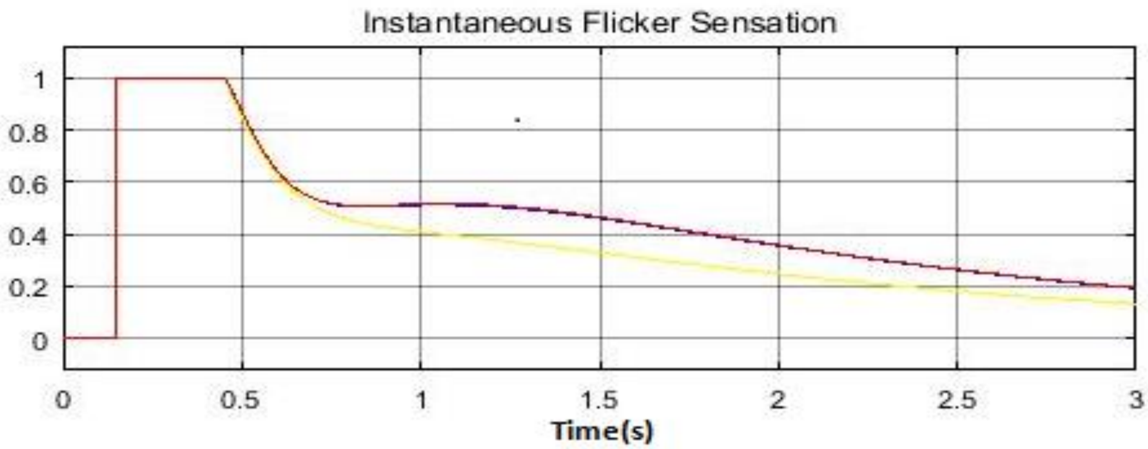

Fig. 5.8 (c): Instantaneous Flicker Sensation Levels with Ten-pulse Voltage Source Inverter DSTATCOM

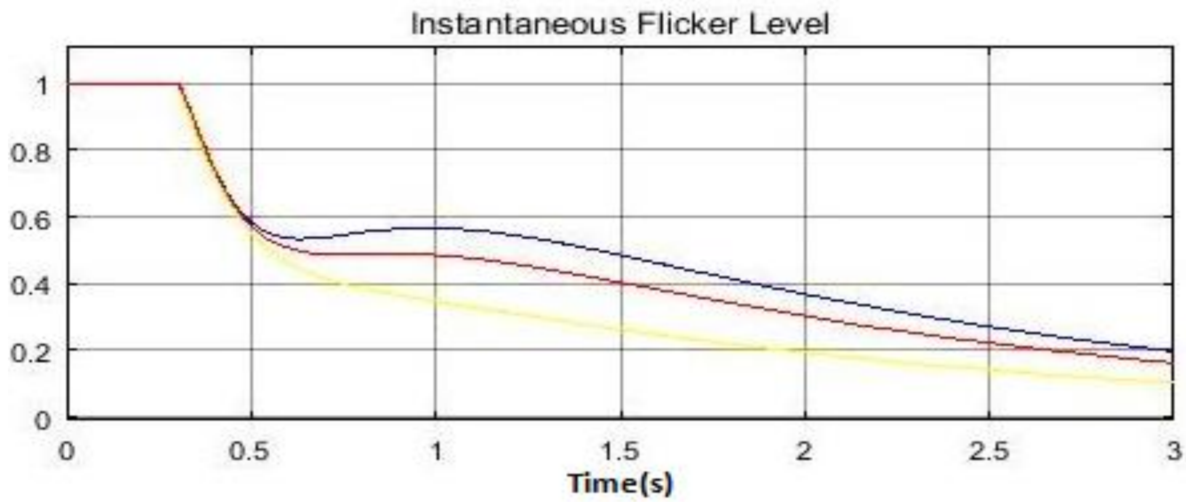

Fig. 5.8 (d): Instantaneous Flicker Sensation Levels with Forty-pulse Voltage Source Inverter DSTATCOM

5.4 RESULT ANALYSIS

The performance based comparison of the system for different conditions in context to instantaneous flicker level as obtained from the simulation waveforms is illustrated in Table 5.1 with the corresponding graphical analysis as shown in Fig. 5.9.

Table 5.1: Instantaneous Flicker Sensation Values for Different System Conditions

Time (s)	Instantaneous Flicker Level			
	Uncompensated System	*6-pulse VSC based DSTATCOM*	*10-pulse VSC based DSTATCOM*	*40-pulse VSC based DSTATCOM*
0.05	0	0	0	1
0.55	1.448	0.7542	0.7245	0.4992
1.05	12.12	1.114	0.4013	0.3371
1.55	13.62	1.064	0.3195	0.2551
2.05	10.91	0.8246	0.2386	0.1875
2.55	8.152	0.6099	0.1748	0.1368
3	6.178	0.46	0.1314	0.1027

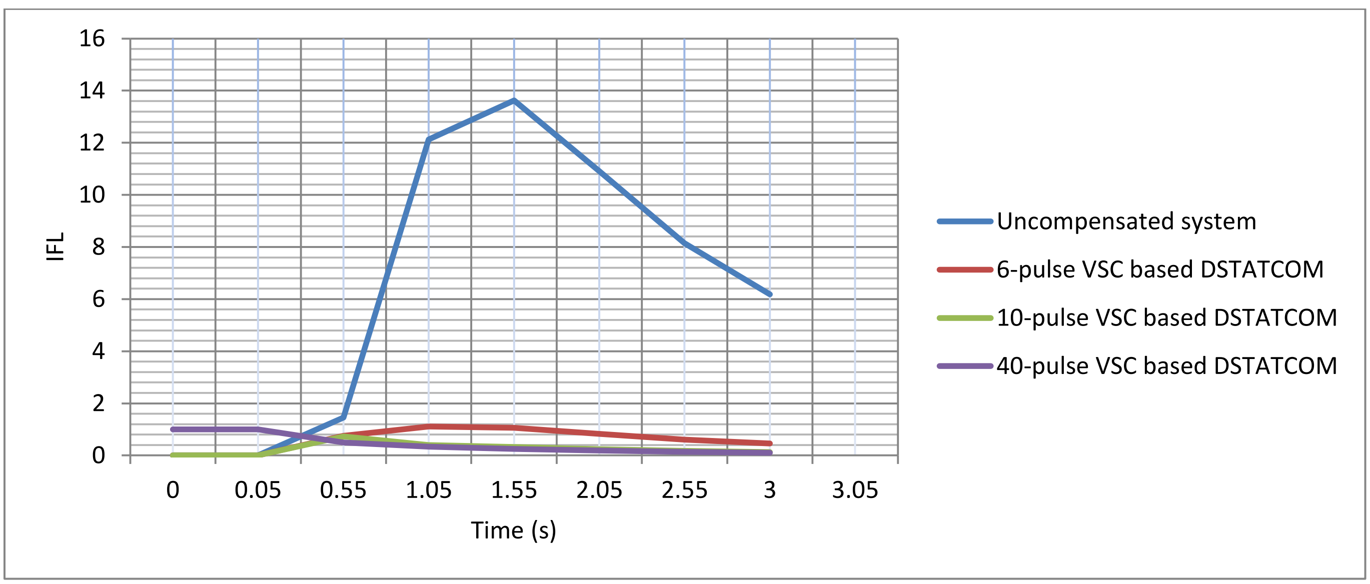

Fig. 5.9: Graphical Representation of Instantaneous Flicker Sensation

Harmonic spectrum analysis is also carried out to determine the THD levels present in the output load voltages for the uncompensated system and the system compensated using six-pulse, ten-pulse and forty pulse Voltage source inverter based DSTATCOM establishing the efficiency of forty-pulse VSI. The harmonic analysis is shown in Fig. 5.10 (a) to Fig. 5.10 (d).

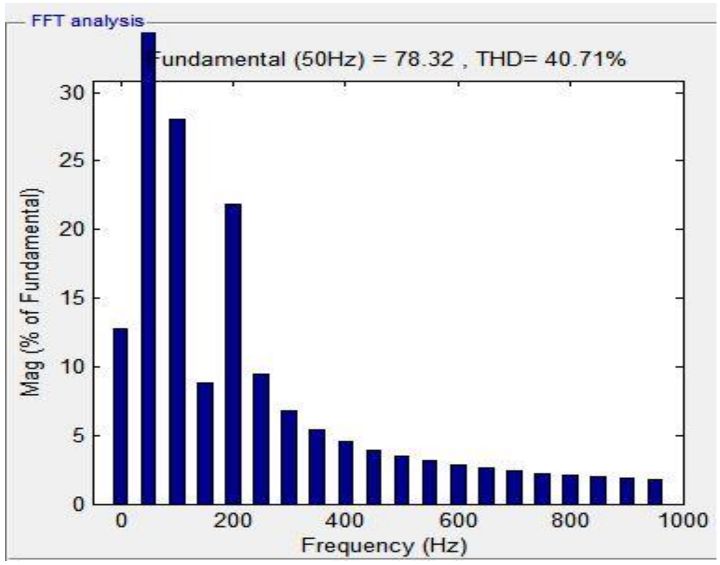

Fig. 5.10 (a): Harmonic Spectrum of Uncompensated System

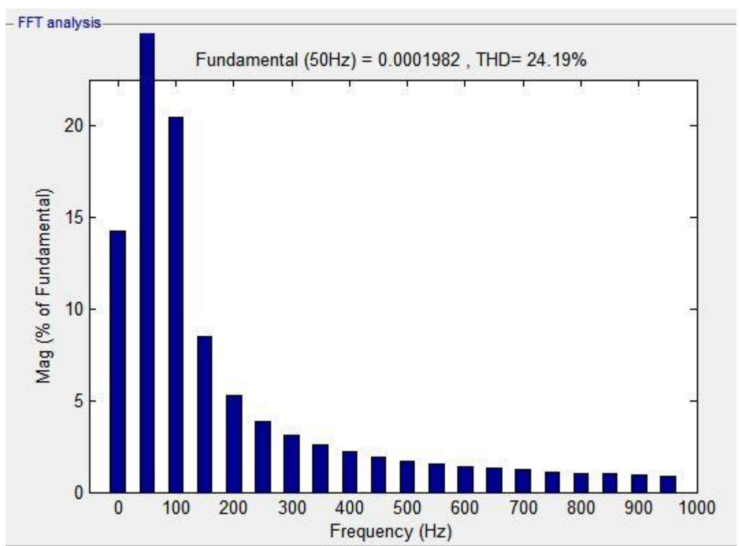

Fig. 5.10 (b): Harmonic Spectrum of System Compensated Using Six-pulse Voltage Source Inverter Based DSTATCOM

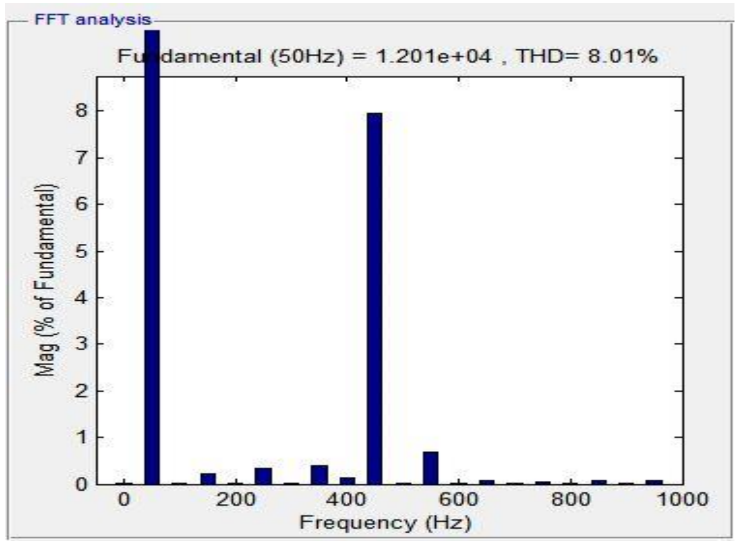

Fig. 5.10 (c): Harmonic Spectrum of System Compensated Using Ten-pulse VSI Based DSTATCOM

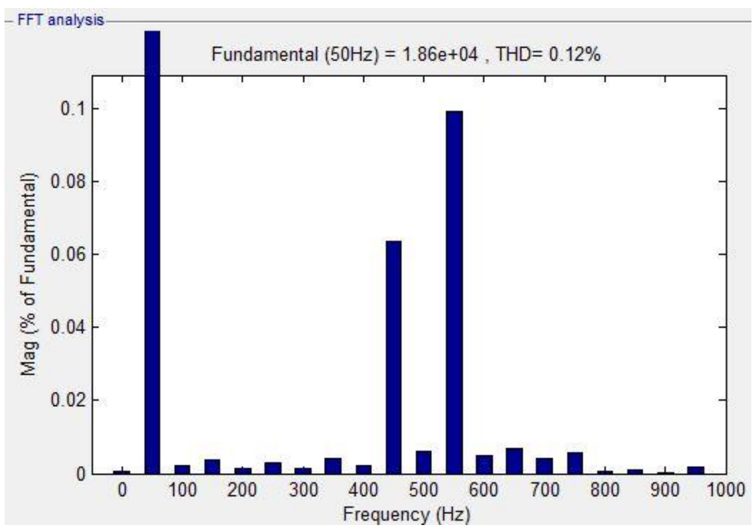

Fig. 5.10 (d): Harmonic Spectrum of System Compensated Using Forty-pulse VSI Based DSTATCOM

As mentioned earlier, the output of the digital flickermeter is instantaneous flicker level. It is fed to the evaluation block which is also called as statistical processing block. This block calculates the cumulative probability function (CPF) based on the instantaneous flicker values collected over an observation time of ten minutes as shown in Fig 5.11 (a) to Fig. 5.11 (d). For simplified analysis, instantaneous flicker level is divided into short term and long term flicker. The short term flicker index P_{ST} is calculated over a time span of ten minutes. The second index, long-term flicker severity index, P_{LT} is the average of P_{ST} values evaluated ones a period of two hours using a cubic law mentioned in equation (3.7).

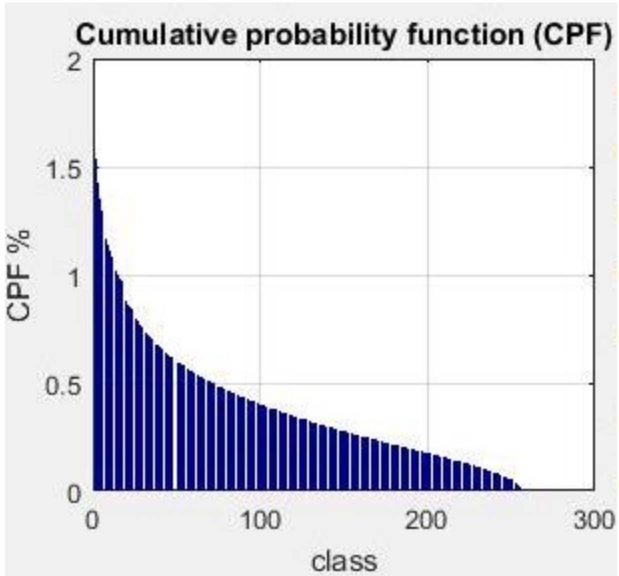

Fig. 5.11 (a): Cumulative Probability Function of Uncompensated System

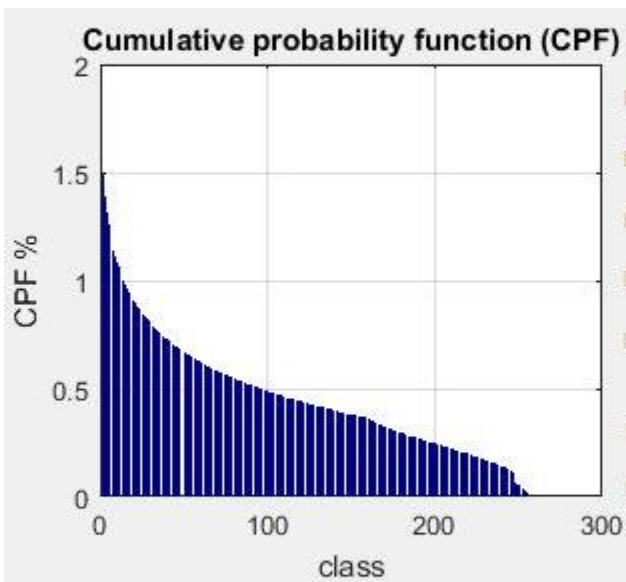

Fig. 5.11 (b): Cumulative Probability Function of System Compensated Using Six-pulse VSI Based DSTATCOM

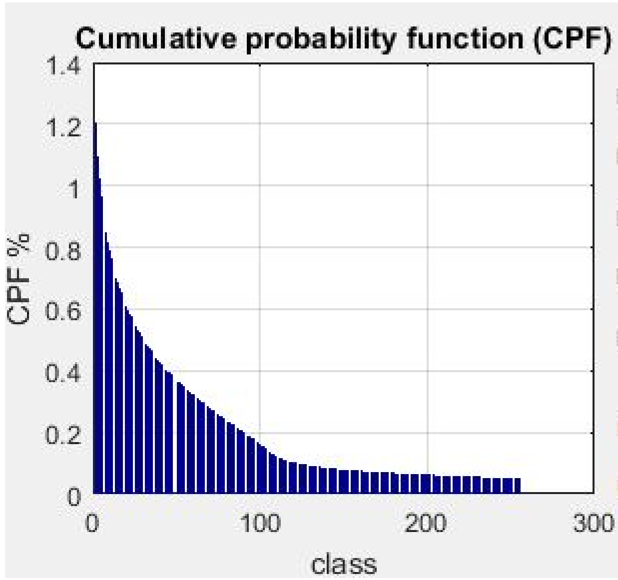

Fig. 5.11 (c): Cumulative Probability Function of System Compensated Using Ten-pulse VSI Based DSTATCOM

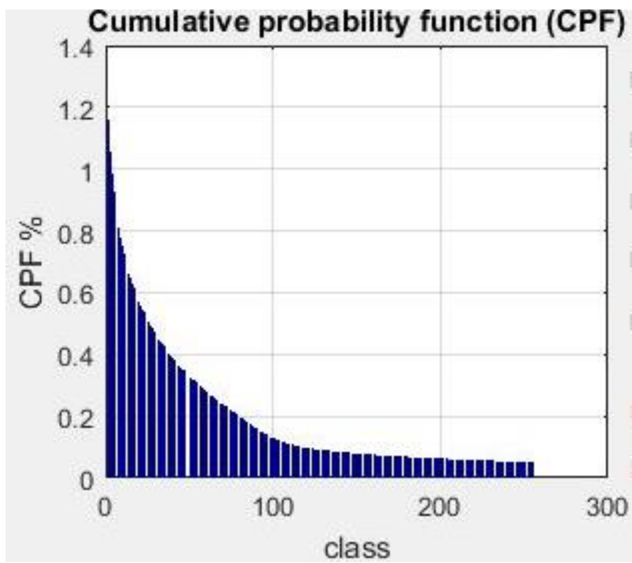

Fig. 5.11 (d): Cumulative Probability Function of System Compensated Using Forty-pulse VSI Based DSTATCOM

The short term flicker is calculated over the time span of ten minutes. The results obtained are tabulated in Table 5.2. The long term flicker severity index is also calculated for the time period of 120 minutes which is illustrated in Table 5.3. Based upon the calculated results a graph is plotted to explain the efficiency of forty-pulse voltage source inverter based DSTATCOM in voltage flicker mitigation. The graph is illustrated as Fig. 5.12.

Table 5.2: Statistical Analysis of Instantaneous Flicker Level

System Type	***$P_{0.1S}$***	***P_{1S}***	***P_{3S}***	***P_{10S}***	***P_{50S}***	***P_{ST}***
Uncompensated	12.85	0.957303	0.0274061	0.0274061	0.0274061	0.682214
Six-pulse VSC based DSTATCOM	1.05595	0.0859403	0.00224729	0.00224729	0.00224729	0.196533
Ten-pulse VSC based DSTATCOM	0.475725	0.235805	0.00195312	0.00195312	0.00195312	0.130412
Forty-pulse VSC based DSTATCOM	0.460335	0.0202095	0.00204464	0.00204464	0.00204464	0.128008

Table 5.3: Long Term Flicker Severity Index

Time (min)	**Long Term Flicker Severity Index P_{LT}**			
	Uncompensated System	***6-pulse VSC based DSTATCOM***	***10-pulse VSC based DSTATCOM***	***40-pulse VSC based DSTATCOM***
10	0.682214	0.196533	0.130412	0.128008
20	0.577414	0.155989	0.103514	0.101607
30	0.504418	0.136269	0.0904333	0.0887675
40	0.458294	0.123808	0.0821690	0.0719472
50	0.425442	0.114934	0.0762835	0.0692651
60	0.400357	0.108157	0.0717897	0.0625896
70	0.380304	0.102740	0.0681981	0.0589617
80	0.363748	0.0982673	0.0652330	0.0517324
90	0.349744	0.0944841	0.0627252	0.0492130
100	0.337673	0.0912235	0.0605641	0.0423165
110	0.327114	0.0883709	0.0586737	0.0372958
120	0.317763	0.0856448	0.0569998	0.0321170

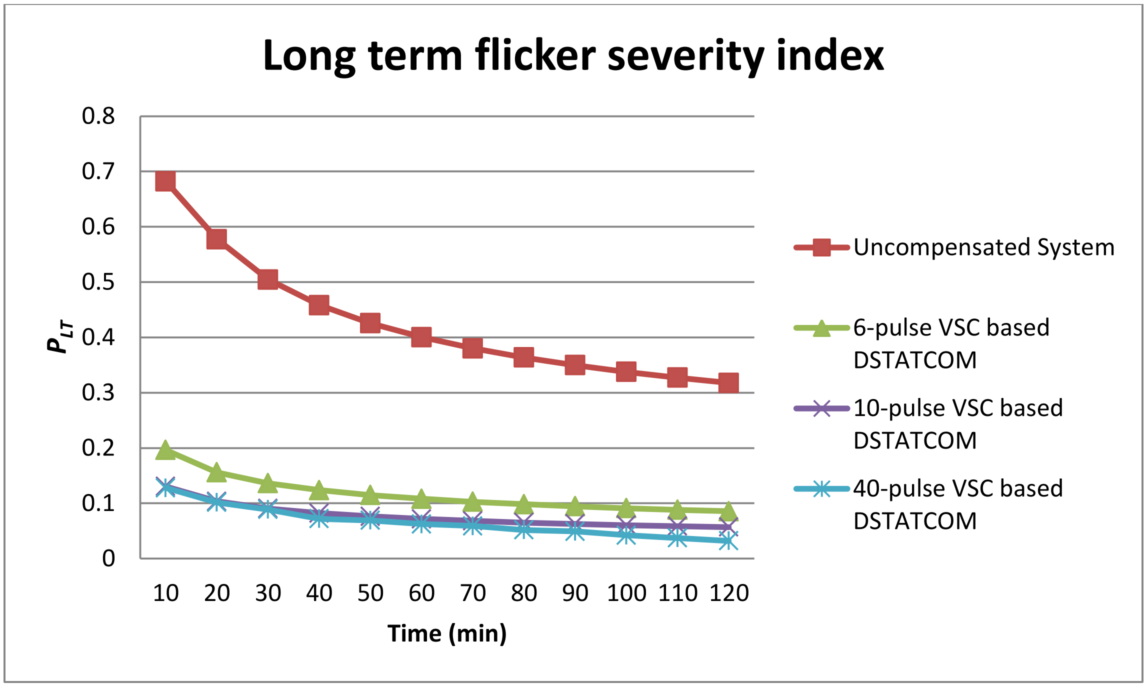

Fig. 5.12: Long Term Flicker Index Over the Time Span of 2hrs

CHAPTER-6

CONCLUSIONS AND FUTURE SCOPE

6.1 CONCLUSIONS

This report presents the MATLAB SIMULINK based simulation results of two bus system without and with DSTATCOM. The voltage flicker is analysed using digital flickermeter. Device performance in mitigating voltage flicker is studied and analysed using a six-pulse, ten-pulse and forty-pulse voltage source inverter based DSTATCOM. A comparative analysis is also carried out based on the instantaneous flicker levels, THD levels and statistical results obtained from the load voltage before and after compensation. In general, six-pulse and multiple of six-pulse voltage source inverter based DSTATCOM has been accounted in various compositions, but here an attempt has been made to realize a forty-pulse VSC based DSTATCOM which is realized using four Ten-pulse converters, for voltage flicker mitigation. No doubt the increase in pulse number results in increase in complexity and increased amount of switching but, definitely improves the system performance. From the harmonic analysis, it can be seen that THD of 40.7% is reduced to a considerable value of 0.12% which is quiet below the limit specified in IEEE-519 Standard. Also reduction in flicker magnitude can be seen from the statistical analysis. Statistical and harmonic analysis carried out preface that due to fast response and flexible control, the proposed inverter design based DSTATCOM is efficient for voltage flicker mitigation.

6.2 FUTURE SCOPE

The future scope of work carried out in this thesis is:

- To use modified SVPWM technique for generation of pulses for voltage flicker mitigation.
- To use different topologies to design forty-pulse inverter.
- Realization of intelligent fuzzy logic based DSTATCOM with hybrid controllers to eliminate voltage flicker
- Study and control of power quality issues in terms of voltage flicker elimination for deregulated power system

- As FACTS devices fail to take care of voltage surges, study can be extended to this direction also.

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