View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by UTHM Institutional Repository

POWER QUALITY ANALYSIS AND MITIGATION

UDECHUKWU CHUKWUEMEKA CHARLES

A project report submitted in partial
fulfillment of the requirement for the award of the
Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

MAY 2011

ABSTRACT

Due to increasing complexity in the power system, voltage sags and swells are now becoming one of the most significant power quality problems. Voltage sag is a short reduction voltage from nominal voltage, occurs in a short time, voltage swell is an increase in the r.m.s voltage from its nominal voltage; they are bound to have a greater impact on the industrial customers. If the voltage sags exceed two to three cycles, then manufacturing systems making use of sensitive electronic equipments are likely to be affected leading to major problems. It ultimately leads to wastage of resources (both material and human) as well as financial losses. The increasing competition in the market and the declining profits has made it pertinent for the industries to realize the significance of high-power quality. This is possible only by ensuring that uninterrupted flow of power is maintained at proper voltage levels. Electric utilities are looking for solutions to ensure high quality power supply to their customers, a lot of solutions have been developed, but this project tends look at the solving the problems by using custom power devices such as Dynamic Voltage Restorer (DVR) and Distribution Static compensator (D-STATCOM). The Dynamic Voltage Restorer appears to be an especially good solution in the current scenario. This work describes the techniques of correcting the supply voltage sag and voltage swell in a distributed system. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the distribution static compensator and the dynamic voltage restorer are most effective devices, both of them based on the VSC principle. A DVR injects a voltage in series with the system voltage and a D-STATCOM injects a current into the system to correct the voltage sag, swell and interruption. Comprehensive results are presented to assess the performance of each device as a potential custom power solution.

ABSTRAK

Dengan meningkatnya kesukaran pada system tenaga, voltan lendut dan voltan kembang telah menjadi satu masalah yang sangat penting dalam sistem kualiti kuasa. Voltan lendut ialah pengurangan kecil pada voltan nominal, berlaku pada kadar masa yang singkat. Voltan kembang adalah peningkatan pada voltan punca min kuasa dua (pmkd) daripada voltan nominalnya; masalah ini mengikat dan mengakibatkan satu kesan yang lebih besar kepada pelanggan-pelanggan industri. Jika voltan lendut melebihi dua hingga tiga kitaran, kemudian sistem-sistem pembuatan menggunakan peralatan-peralatan elektronik sensitive berkemungkinan akan terjejas dan membawa kepada masalah lebih besar. Kesudahannya akan membawa kepada pembaziran sumber-sumber (bahan dan manusia) serta kerugian kewangan. Peningkatan persaingan dalam pasaran dan kerugian telah membuatnya menjadi penting supaya pihak-pihak industri menyedari kepentingan kuasa kualiti yang tinggi. Ini hanya berkemungkinan dengan memastikan bahawa aliran kuasa yang tidak terganggu dipelihara pada aras-aras voltan yang sesuai. Pembekal-pembekal elektrik sedang mencari penyelesaian untuk memastikan bekalan tenaga yang berkualiti tinggi disalurkan kepada pelanggan. Terdapat beberapa cara penyelesaian telah dibangunkan, tetapi projek ini lebih cenderung kepada penyelesaian masalah dengan menggunakan alat-alat kuasa yang biasa digunakan seperti *Dynamic Voltage Restorer (DVR)* dan *Distribution Static Compensator (D-STATCOM)*. *Dynamic Voltage Restorer* menjadi satu penyelesaian yang bagus dalam senario semasa. Projek ini melibatkan teknik-teknik membetulkan bekalan voltan lendut dan voltan kembang dalam sistem pengagihan. Pada masa ini, pelbagai alat-alat kawalan fleksibal yang mengeksploitasi komponen-komponen elektronik tenaga baru yang boleh didapati adalah timbul bagi aplikasi-aplikasi tenaga biasa. Disamping itu, pengagihan kompensator statik dan pemulih voltan dinamik ialah alat-alat yang

paling berkesan dan berdasarkan prinsip *VSC*. DVR menyalurkan voltan sesiri dengan sistem voltan dan D-STATCOM menyalurkan arus kepada sistem untuk membetulkan voltan lendut, voltan kembang dan gangguan. Hasil yang komprehensif ditunjukkan bagi menilai kecekapan setiap komponen sebagai penyelesaian kuasa biasa yang berpotensi.

CONTENTS

CHAPTER 4 RESULTS AND DATA ANALYSIS

CHAPTER 5 CONCLUSION AND RECOMMENDATION

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A	-	Ampere
AC	-	Alternating Current
D.O.L	-	Direct-On-Line
EMTDC	-	Electromagnetic Transient Programme with DC Analysis
Hp/hp	-	Horsepower
IM	-	Induction Motor
PSCAD	-	Power System Computer Aided Design
Pu	-	per unit
RMS	-	Root Mean Square
kV	-	kilovolt
V	-	Volts

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Project Background

Both electric utilities and end users of electrical power are becoming increasingly concerned about the quality of electric power. The term *power quality* has become one of the most prolific buzzword in the power industry[18] . The issue in electricity power sector delivery is not confined to only energy efficiency and environment but more importantly on quality and continuity of supply or power quality and supply quality. Electrical Power quality is the degree of any deviation from the nominal values of the voltage magnitude and frequency. Power quality may also be defined as the degree to which both the utilization and delivery of electric power affects the performance of electrical equipment[2] . From a customer perspective, a power quality problem is defined as any power problem manifested in voltage, current, or frequency deviations that result in power failure or disoperation of customer of equipment. Power quality is certainly a major concern in the present era; it becomes especially important with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply.[4].

Modern industrial processes are based a large amount of electronic devices such as programmable logic controllers and adjustable speed drives. The electronic devices are very sensitive to disturbances and thus industrial loads become less tolerant to power quality problems such as voltage dips, voltage swells, harmonics, flickers, interruptions, and notches.

Below is a table showing some common power quality problems and their effects:

Problems	Effects
Over voltage	Overstress insulation
Under voltage	Excessive motor current
Unbalance	Motor heating
Neutral-ground voltage	Digital device malfunction
Interruption	Complete shut down
Sag	Variable speed drive & computer trip-out
Swell	Overstress insulation
Fluctuations	Light flicker

Table 1.0: Some effects of power quality problems for the voltage events.

Among them, two power quality problems have been identified to be of major concern to the customers are voltage sags and swells, but this project will be focusing on voltage sags/swells, as well as interruptions.

Voltage dips are considered one of the most severe disturbances to the industrial equipment. A paper machine can be affected by disturbances of 10% voltage drop lasting for 100ms. A voltage dip of 75% (of the nominal voltage) with duration shorter than 100ms can result in material loss in the range of thousands of US dollars for the semiconductors industry. Swells and over voltages can cause over heating tripping or even destruction of industrial equipment such as motor drives.[7]

1.2 Objectives

The aim of this project is to study the various types of power quality problems and their effects on both the utility and customer's side of the system, with more emphasis on these two namely: voltage sag and voltage swells, and how they can be mitigated with the use of the DVR (Dynamic Voltage Restorer) and the D-STATCOM (Distribution Static Compensator),which are also called custom power devices,and its effectiveness in mitigating the named power quality problems given above.

The objectives of this project are:

i. To investigate that the mitigation techniques are suitable for voltage sags,swells and interruptions in the event of a fault in a distribution system.
ii. To observe the effect on the characteristic of voltage sag, swell and interruption for the techniques.
iii. To suggest on the suitability of the techniques used for the mitigation process.

1.3 Background of study

Power quality is certainly a major concern in the present era; it becomes especially important with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Modern industrial processes are based a large amount of electronic devices such as programmable logic controllers and adjustable speed drives. The electronic devices are very sensitive to disturbances and thus industrial loads become less tolerant to power quality problems such as voltage dips, voltage swells, and harmonics. Voltage dips are considered one of the most severe disturbances to the industrial equipment. Swells and over voltages can cause over heating tripping or even destruction of industrial equipment such as motor drives. Electronic equipments are very sensitive loads against harmonics because their control depends on either the peak value or the zero crossing of the supplied voltage, which are all influenced by the harmonic distortion. This project analyzes the key issues in the power quality problems. As one of the prominent power quality problems, the origin, consequences and mitigation techniques of voltage sag/swells and interruptions problem will be discussed in detail. The study describes the techniques of correcting the problems in a distribution system by a strong power electronics based devices called Dynamic Voltage Restorer (DVR) and the Distribution Static Compensator (D-STATCOM). Voltage from both devices is connected into the system to correct the problems.The performance of the DVR and the D-STATCOM is studied for the power quality problems to be viewed.

1.4 Problem Statements

With the increased use of sophisticated electronics, high efficiency variable speed drive, and power electronic controller, power quality has become an increasing concern to utilities and customers. Voltage sags is the most common type of power quality disturbance in the distribution system. It can be caused by fault in the electrical network or by the starting of a large induction motor. Although the electric utilities have made a substantial amount of investment to improve the reliability of the network, they cannot control the external factor that causes the fault, such as lightning or accumulation of salt at a transmission tower located near to sea.

Meanwhile during short circuits, bus voltages throughout the supply network are depressed, severities of which are dependent of the distance from each bus to point where the short circuit occurs. After clearance of the fault by the protective system the voltages return to their new steady state values. Part of the circuit that is cleared will suffer supply disruption or blackout. Thus in general a short circuit will cause voltage sags/swells throughout the system and may cause blackout to a small portion of the network.

1.5 Scope of Study

The scope of study tends to look at the following,

I. Investigate the mentioned power quality problems,

II. How they can be mitigated with the custom power device introduced.

III. More details about the mitigation device would also be given,in terms of their composition and design; and also how they will be configured in an electrical system.

CHAPTER 2

LITERATURE REVIEW

2.1 Power Quality

Power quality is simply the interaction of electrical power with electrical equipment. If electrical equipment operates correctly and reliably without being damaged or stressed, we would say that the electrical power is of good quality. On the other hand, if the electrical equipment malfunctions, is unreliable, or is damaged during normal usage, we would suspect that the power quality is poor[2]. There are two approaches to the mitigation of power quality problems. The solution to the power quality can be done from customer side or from utility side . First approach is called load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts the power system disturbances. A flexible and versatile solution to voltage quality problems is offered by active power filters. Currently they are based on PWM converters and connect to low and medium voltage distribution system in shunt or in series. Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters , with a dc bus having a reactive element such as a capacitor[8].

One of the most common power quality problems today is voltage dips. A voltage dip is a short time (10 ms to 1 minute) event during which a reduction in r.m.s voltage magnitude occurs. It is often set only by two parameters, depth/magnitude and duration. The voltage dip magnitude is ranged from 10% to 90% of nominal voltage (which corresponds to 90% to 10% remaining voltage) and with a duration from half a cycle to 1 min. In a three-phase system a voltage dip is by nature a three-phase phenomenon, which affects both the phase-to-ground and phase-to-phase voltages. A voltage dip is caused by a fault in the utility system, a fault within the customer's facility or a large increase of the load current, like starting a motor or transformer energizing. Typical faults are single-phase or multiple-phase short circuits, which leads to high currents. The high current results in a voltage drop over the network impedance. At the fault location the voltage in the faulted phases drops close to zero, whereas in the non-faulted phases it remains more or less unchanged [1, 2].

Voltage dips are one of the most occurring power quality problems. Off course, for an industry an outage is worse, than a voltage dip, but voltage dips occur more often and cause severe problems and economical losses. Utilities often focus on disturbances from end-user equipment as the main power quality problems. This is correct for many disturbances, flicker, harmonics, etc., but voltage dips mainly have their origin in the higher voltage levels. Faults due to lightning, is one of the most common causes to voltage dips on overhead lines. If the economical losses due to voltage dips are significant, mitigation actions can be profitable for the customer and even in some cases for the utility. Since there is no standard solution which will work for every site, each mitigation action must be carefully planned and evaluated. There are different ways to mitigate voltage dips, swell and interruptions in transmission and distribution systems. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications [3, 4]. Among these, the distribution static compensator and the dynamic voltage restorer are most effective devices, both of them based on the VSC principle. A new PWM-based control scheme has been implemented to control the electronic valves in the two-level VSC used in the D-STATCOM and DVR [5, 6].

2.2 Voltage Dips (Sags)

A voltage dip is a sudden reduction in the r.m.s voltage between 0.1 and 0.9 pu at a point in the electrical system,and lasting for 0.5 cycle to several seconds. Dips with durations of less than a cycle are regarded as transients. Figure 2.1 shows a waveform depicting a voltage sag.

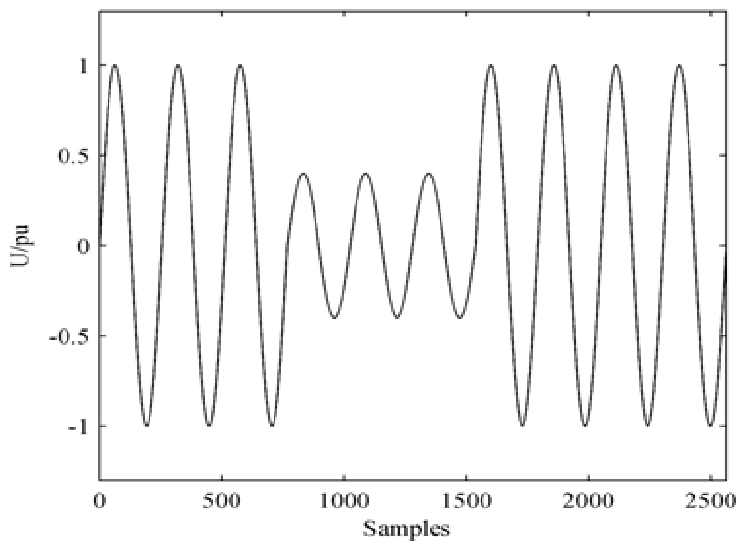

Figure 2.1: Voltage dip (sag) waveform

A voltage dip may be caused by switching operations associated with a temporary disconnection of supply, the flow of heavy current associated with the starting of a large electric motors or the flow of fault currents or the transfer of load from one power source to another. These events may emanate from customers' systems or from the public suply network. The main cause of momentary voltage dips is probably the ligthning strike. Each of these cases may cause a sag with a special characteristics (magnitude and duration).

The possible effects of voltage sags are:

- Extinction of discharge lamps
- Malfunctions of electrical low-voltage devices

- Computer system crash
- Tripping of contactors.

2.3 Voltage swell

The increase of voltage magnitudes between 1.1 and 1.8pu is called Swell,it sometimes accompany voltage sags.The most accepted duration of a swell is from 0.5 cycles to 1 minute. They appear on the switching off of a large load; energizing a capacitor bank ; or voltage increase of the unfaulted phases during a single line-to-ground fault. Figure 2.2 shows a waveform of voltage swell.

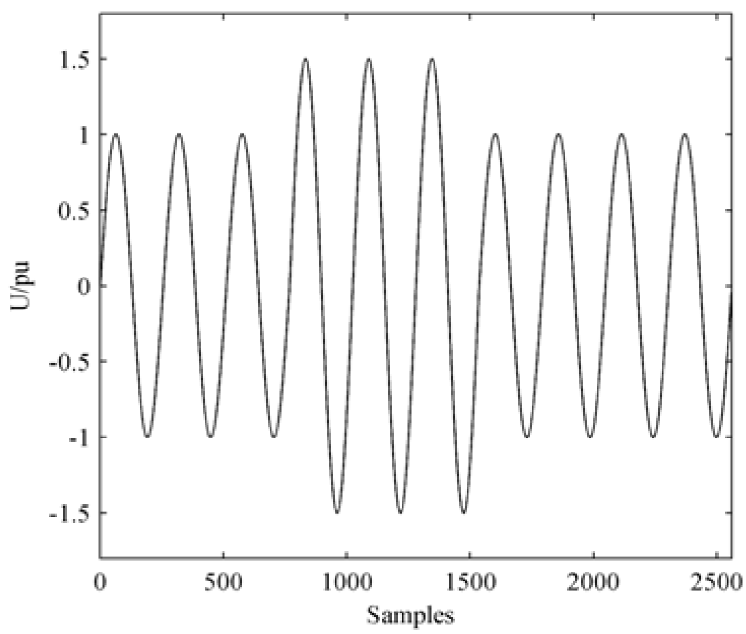

Figure 2.2: Voltage swell waveform

Swells can upset electric controls and electric motor drives, particularly common adjustable-speed drives, which can trip because of their built in protective circuitry. Swells can also put stress on delicate computer computer components and shorten their life span.

2.4 Interruptions

Interruptions occurs when the supply voltage decreases to less than 0.1 pu for a minute or less. Some causes of interruptions are equipment failures, control malfunction, and blown fuse or breaker opening due to fault on a system.

2.5 Voltage Source Converters (VSC)

A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. Voltage source converters are widely used in adjustable-speed drives, but can also be used to mitigate voltage dips. The VSC is used to either completely replace the voltage or to inject the ‘missing voltage’. The ‘missing voltage’ is the difference between the nominal voltage and the actual. The converter is normally based on some kind of energy storage, which will supply the converter with a DC voltage. The solid-state electronics in the converter is then switched to get the desired output voltage. Normally the VSC is not only used for voltage dip mitigation, but also for other power quality issues, e.g. flicker and harmonics.

2.6 Dynamic Voltage Restorer (DVR)

A DVR, Dynamic Voltage Restorer is a distribution voltage DC-to-AC solid-state switching converter that injects three single phase AC output voltages in series with the distribution feeder, and in synchronism with the voltages of the distribution system. By injecting voltages of controllable amplitude, phase angle, and frequency (harmonic) into the distribution feeder in instantaneous real time via a series-injection transformer, the DVR can restore the quality of voltage at its load side terminals when the quality of the source side terminal voltage is significantly out of specification for sensitive load equipment.It is designed to mitigate voltage sags and swells on lines feeding sensitive equipment.

A viable alternative to uninterruptible power systems (UPS) and other utilization solutions to the voltage sag problem, the DVR is specially designed for large loads of the order of 2 MVA to 10 MVA served at distribution voltage. A DVR typically requires less than one-third the nominal power rating of the UPS . DVR can also be used to mitigate troublesome harmonic voltages on the distribution network.

DVR comprises of three main parts:

1. Inverter
2. DC energy storage
3. Control system

The basic configuration of a DVR is shown in Figure 2.3 below;

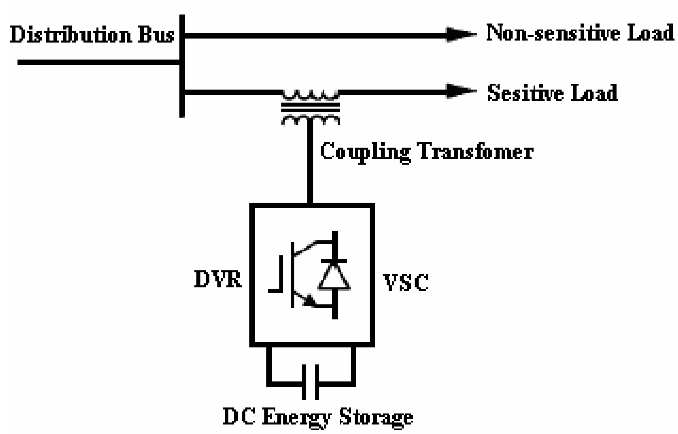

Figure 2.3: Basic configuration of a DVR

2.7 Distribution Static Compensator (D-STATCOM)

A D-STATCOM (Distribution Static Compensator), which is schematically depicted in Figure, consists of a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power.

The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes:

1. Voltage regulation and compensation of reactive power;
2. Correction of power factor; and
3. Elimination of current harmonics.

Here, such device is employed to provide continuous voltage regulation using an indirectly controlled converter. The basic configuration of the D-STATCOM is shown in the diagram below,Figure 2.4;

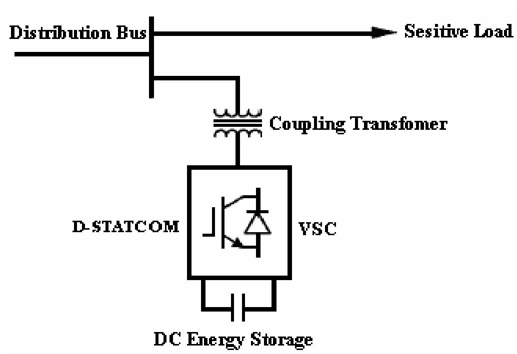

Figure 2.4: Configuration of a D-STATCOM

2.8 Previous Research

Byung-Moon Han, Bo-Hyung Cho, Seung-Ki Sul and Jae-Eon Kim (2006) developed a configuration for the Unified Power Quality Conditioner,which has a DC/DC converter with super-capacitors for energy storage. The proposed UPQC cancompensate the reactive power, harmonic current, voltage sag and swell, voltage imbalance, and voltage interruption. . The proposed UPQC has ultimate capability to improve the power quality at the point of installation on power distribution systems and industrial power systems.

Active power filters can perform one or more of the functions required to compensate power systems and improving power quality. Their performance also depends on the power rating and the speed of response. Many mitigation techniques have been proposed and implemented to maintain the voltage and current within recommended levels.

The UPQC is utilized for simultaneous compensation of the load current and the voltage disturbance at the sourceside. Normally the UPQC has two voltage-source inverters of three-phase four-wire or three-phase three-wire configuration. One inverter, called the series inverter is connected through transformers between the source and the common connection point. The other inverter, called the shunt inverter is connected in parallel through the transformers. The series inverter operates as a voltage source, while the shunt inverter operates as a current source.

The UPQC has compensation capabilities for the harmonic current, the reactive power compensation, the voltage disturbances, and the power flow control. However, it has no compensation capability for voltage interruption because no energy is stored. This paper proposes a new configuration for the UPQC that has the super-capacitors for energy storage connected to the dc link through the DC/DC converter. The proposed UPQC can compensate the voltage interruption in the source side to make the shunt inverter operate as an uninterruptible power supply. Therefore, the shunt inverter operates as a voltage source in interruption mode as well as a current source in normal mode.

The proposed UPQC has the ultimate capability of improving the power quality at the point of installation on power distribution systems or industrial power systems,voltage swell/sags,interruptions, harmonics and voltage imbalance,but it has a complicated structure and control,also it looks expensive to design.

CHAPTER 3

METHODOLOGY

3.1 Overview of Project Methodology

This project intends to investigate mitigation technique that is suitable for the voltage sags /swells source with different type of loads/systems, with the occurance of a fault. The simulation will be carried out using PSCAD/EMTDC software. The mitigation techniques that will be studied are the dynamic voltage restorer (DVR) and distribution static compensator (D-STATCOM).

3.2 Sinusoidal PWM-Based Control

In order to mitigate the simulated voltage sags/swells in the test system of each mitigation technique, also to mitigate voltage sags/swells in practical application, a sinusoidal PWM-based control scheme is implemented, with reference to the D-STATCOM. The control scheme for the DVR follows the same principle. The aim of the control scheme is to maintain a constant voltage magnitude at the point where sensitive load is connected, under the system disturbance. The control system only measures the rms voltage at load point, for example, no reactive power measurements is required. The VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. Since custom power is a relatively low-power application, PWM methods offer a more flexible option than the fundamental frequency switching (FFS) methods favored in FACTS applications. Besides, high switching frequencies can be used to improve the efficiency of the converter, without incurring significant switching losses. Figure 3.1 shows the D-STATCOM controller scheme implemented in PSCAD/EMTDC. The D-STATCOM control system exerts voltage angle control as follows: an error signal is obtained by comparing the reference voltage with the rms voltage measured at the load point. The PI controller processes the error signal and generates the required angle δ to drive the error to zero, for example, the load rms voltage is brought back to the reference voltage. In the PWM generators, the sinusoidal signal, $V_{control}$, is phase modulated by means of the angle δ or delta as nominated in the Figure 3.1. The modulated signal, $V_{control}$, is compared against a triangular signal (carrier) in order to generate the switching signals of the VSC valves.

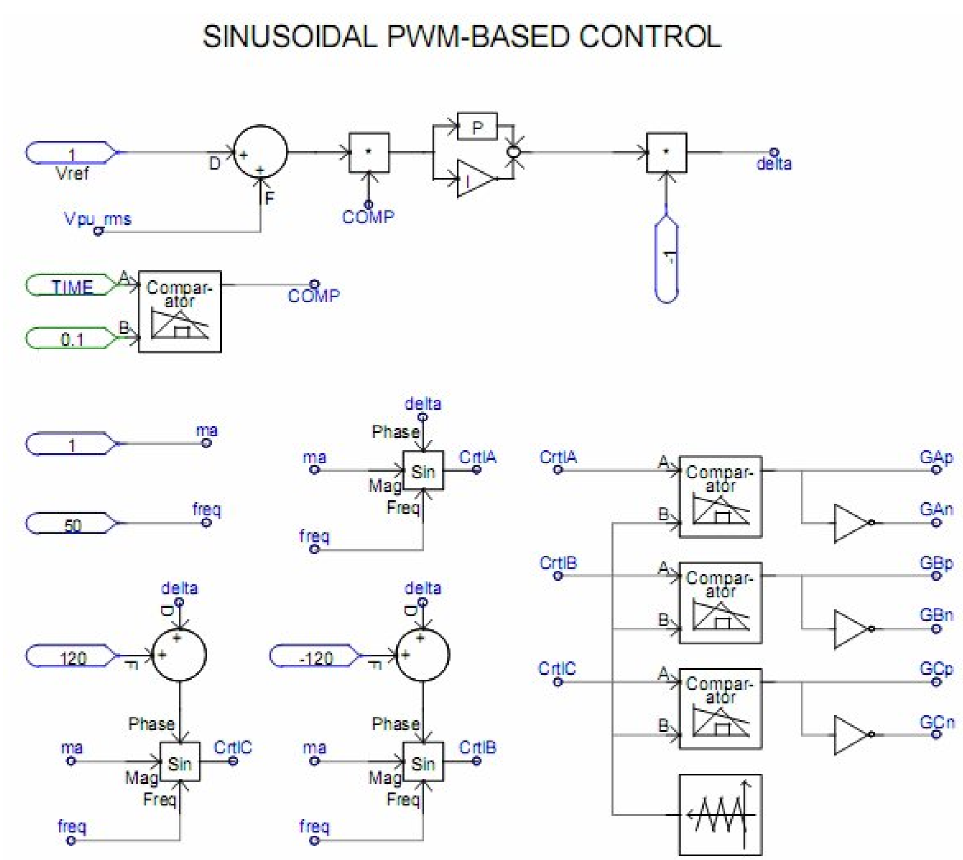

Figure 3.1: Control scheme for the test system implemented in PSCAD/EMTDC to carry out the DVR and D-STATCOM simulations.

The main parameters of the sinusoidal PWM scheme are the amplitude modulation index, m_a, of signal $v_{control}$, and the frequency modulation index, m_f, of the triangular signal. The $v_{control}$ in the Figure 3.1 are nominated as CtrlA, CtrlB and CtrlC. The amplitude index m_a is kept fixed at 1 pu, in order to obtain the highest fundamental voltage component at the controller output [13, 18]. The switching frequency m_f is set at 450 Hz, $m_f = 9$. It should be noted that, an assumption of balanced network and operating conditions are made. The modulating angle δ or delta is applied to the PWM generators in phase A, whereas the angles for phase B and C are shifted by 240° or -120° and 120° respectively. It can be seen in Figure 3.1 that the control implementation is kept very simple by using only voltage measurements as feedback variable in the control scheme. The speed of response and robustness of the control scheme are clearly shown in the test results.

3.3 Test System

In this project, various test systems were used to carry out the aforementioned mitigation techniques, implemented using the PSCAD/EMTDC software. The test system comprises of Test System A, to carry out simulations for the DVR, which comprises of a 13 kilovolts, 50 Hertz transmission system, feeding into a 3- phase, 3 winding transformer at the primary side, which is stepped up to 115 kilovolts. The secondary side supplies the primary side of 3- phase, 2 winding transformer, which supplies 11 kilovolts to the load.

For the D-STATCOM simulation, a Test System B, comprising of a 230 kilovolt, 50 Hertz transmission system, represented in Thevenin equivalent, feeding into the primary side of a 2-winding transformer. The load is connected to the 11 kilovolt secondary side of the transformer. Another 3-winding transformer will be used to replace the 2-winding transformer to accommodate the implantation of the two-level D-STATCOM and it will be connected in the tertiary winding of the transformer to provide instantaneous voltage support at the load point. The transformer employs a leakage reactance of 10% or 0.1 per unit with a unity turns ratio and no booster capabilities exist.

Also, in order to prove that the effectiveness is more on the mitigation devices, it was also implemented or tested on another sets of systems designed based on motor starting methods comprising of Direct- On- Line, Star-Delta and Autotransformer Starting methods which were designed with the aid of the PSCAD/EMTDC software. Also all were carried out with various faults applied to the system to generate the voltage sags/swells and interruption.

3.4 Theory on Motor Starting Circuits

During motor starting, they occurs an increase in the current level up to approximately six to ten times that of the rated current and the high starting torque is caused by this. The high starting currents often lead to unwelcome voltage surges in the supply network and the high starting torque put the mechanical elements under considerable strain. Therefore, it is imperative to determine the limiting values for the motor starting currents in relation to the rated operational currents. The permissible values vary from network to network and depend on its load-bearing capacity. With regard to mechanics, methods are required which reduce starting torque. Various starters and methods can be used to reduce currents and torque:

a) Direct-On-Line Starting
b) Star-Delta Starting
c) Auto-transformer Starting

3.4.1 Direct-On-Line (DOL) Starting

This is the most common starting method available. The components consist of only a main contactor and thermal or electronic overload relay. The disadvantage with this method is that it gives the highest possible starting current. During the starting of a motor using the Direct-On-Line Starting technique, the motor behaves like a transformer with its secondary side formed by the very low resistance rotor cage, in short circuit. There is a high induced current in the rotor which results in a current peak in the main supply, where the starting current is about 5 to 8 times higher than that rated current. In spite of its advantages (simple equipment, high starting torque, fast start, low cost), Direct-On-Line starting is only suitable when the power of the motor is low compared to that of the mains, which limits interference from inrush current, and the machine to drive, does not need to speed up gradually or has a dampiing device to limit the shock of starting. The starting torque can be high without affecting machine operation or the load that is driven. Figure 3.2 shos the Direct-On-Line circuit connection, where the stator is connected directly to the mains supply.

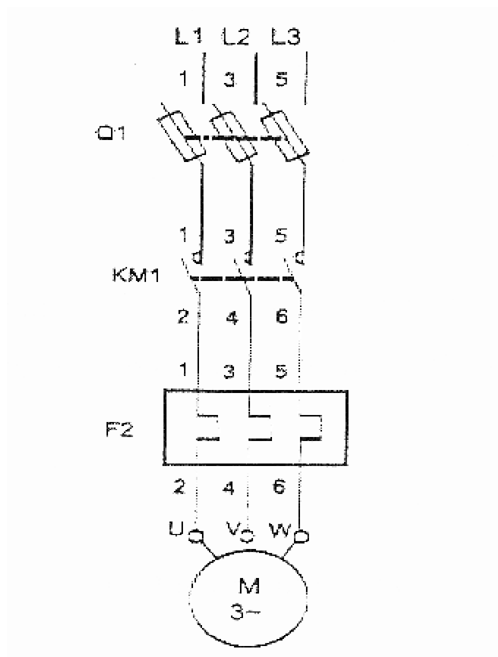

Figure 3.2: Direct-On-Line Circuit Connection

3.4.2 Star-Delta Starting

The Star-Delta starter can only be used with a motor which is rated for connection in delta operation at the required line voltage, and has both ends each of the three windings available individually. At start, the line voltage is applied to one end of each of the windings in a star connection. Under this connection, the voltage across each winding is $1/\sqrt{3}$ of the line voltage and so the current flowing in each winding is also reduced by this amount. The resultant current flowing from the supply is reduced by a factor of 1/3 as is the torque. In some cases, this may be enough to get the motor up to full speed, but most, as this is a constant voltage starter, the transition to full voltage will occur at part speed resulting in a virtual DOL type start. To step to full voltage, the star connection is opened, effectively open circuiting the motor, and the ends of the windings are then connected to the three phase supply in a fashion to create a delta connection. This type of starter is an open transition starter and so the switch to delta is accompanied by a very high torque and current transient. In most situations, there would be less damage to the equipment and less interference to the supply if a DOL starter was used. Figure 3.3 shows the Star-Delta connection circuit.

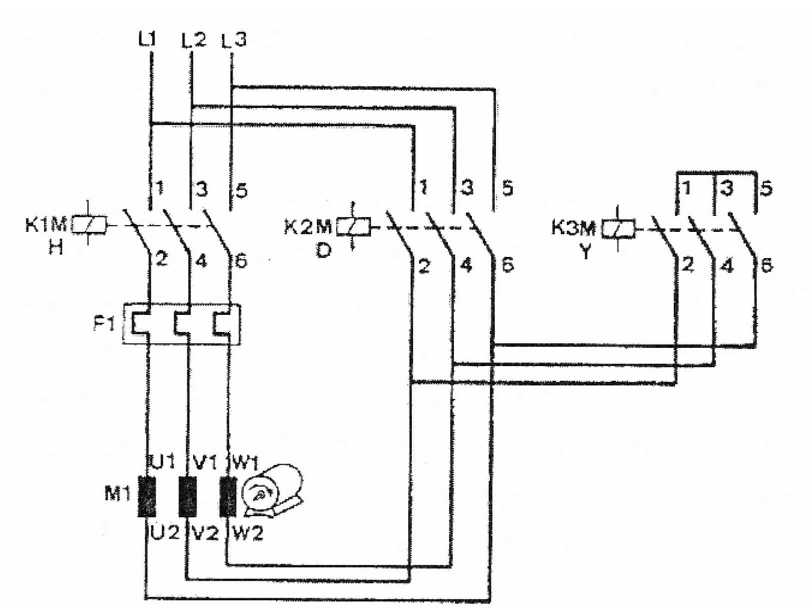

Figure 3.3: Star-Delta Connection using Contactors

3.4.3 Autotransformer Starting

An autotransformer starter uses an autotransformer to reduce the voltage applied to motor during start. This is another starting method that reduces the starting current and starting torque but contrary to Star-Delta starting where this starting method needs three wires and three terminals on the motor. Autotransformers are generally equipped with taps at each phase in order to adapt the starting parameters to the application starting requirement. During starting, the motor is connected to the autotransformer taps. With the star and autotransformer contactors closed, the motor is under reduced voltage. Consequently the torque is reduced as the square of the applied voltage. When the motor reaches the 80 to 95% of the nominal speed, the star contactor opens. Then the line contactor closes and the autotransformer contactor opens. The motor is never disconnected from the power supply during starting (closed transition) and reduces transient phenomena. Taps on the autotransformer allow for selection of the motor with 50%, 65%, or 80% of the current inrush seen during a full voltage start. The resulting starting torque will be 25%, 42%, or 64% of full voltage values, as will be the current draw on the line. Thus, the autotransformer provides the maximum torque with minimum line current. Figure 3.4 below shows the Autotransformer starting circuit.

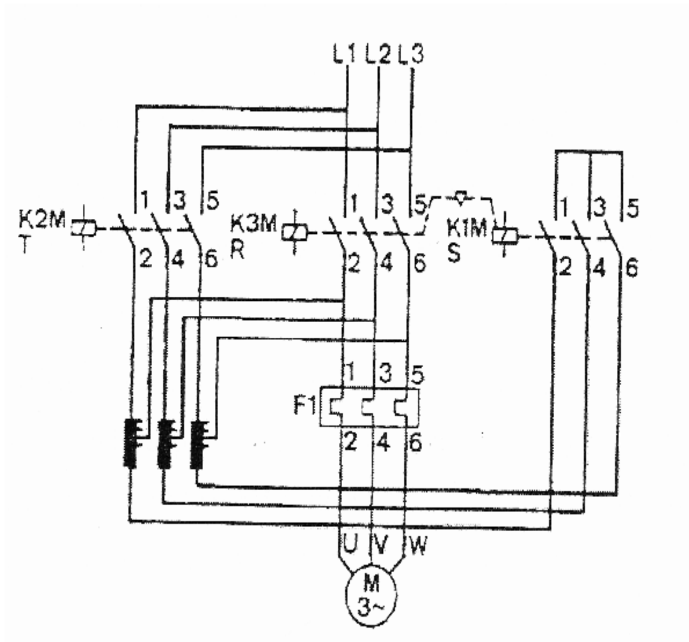

Figure 3.4: Autotransformer Connection for the Motor Starting

3.5 Dynamic Voltage Restorer

The DVR is a powerful controller that is commonly being used for voltage sags/swells mitigation at the point of connection. The DVR employs the same block as the D-STATCOM. However, in this application the coupling transformer is connected in series with the ac system, as illustrated in Figure 2.3. The VSC generates a three-phase ac output voltage which is controllable in phase and magnitude. These voltages are injected into the ac system in order to maintain the load voltage at the desired voltage reference. The main features of the DVR control scheme have been explained in section 3.2. The DVR that has been used to test the system in section 3.2 is shown in Figure 3.5. The DVR is basically the same as D-STATCOM but instead of using a capacitor, DVR employs 5 kilovolt dc storage supply. The DVR is then connected in series using transformers in delta to the lines.

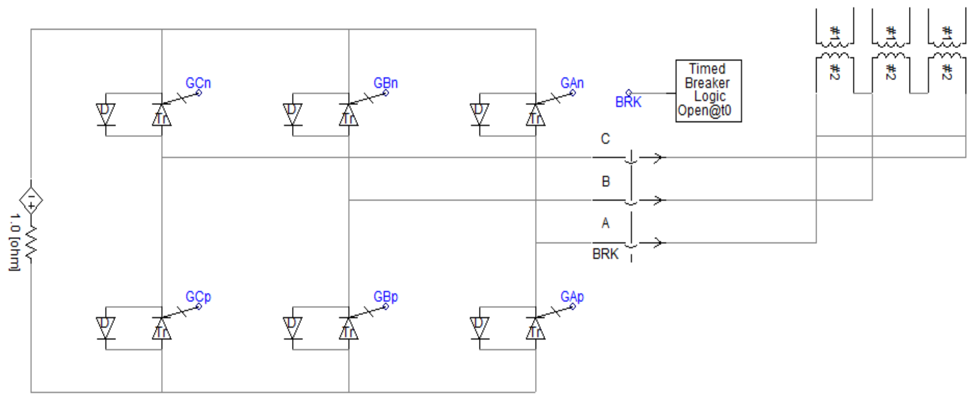

Figure 3.5: Diagram of the DVR designed using the PSCAD/EMTDC.

3.6 Distribution Static Compensator

The test system employed to carry out the simulations concerning the D-STATCOM actuation is shown in Figure 3.8 (a & b). A two-level D-STATCOM is connected to the 11 kV tertiary winding to provide instantaneous voltage support at the load point. A 750 μF capacitor on the dc side provides the D-STATCOM energy storage capabilities. The transformer of the test system has been changed to a 3-winding transformer to accommodate D-STATCOM. The purpose of including the transformer is to protect and provide isolation between the IGBT legs. This prevents the dc storage capacitor from being shorted through switches in different IGBT. Figure 3.6 shows the build of the D-STATCOM in PSCAD/EMTDC which is the two-level voltage source converter and the realization of the test systems to be employed.

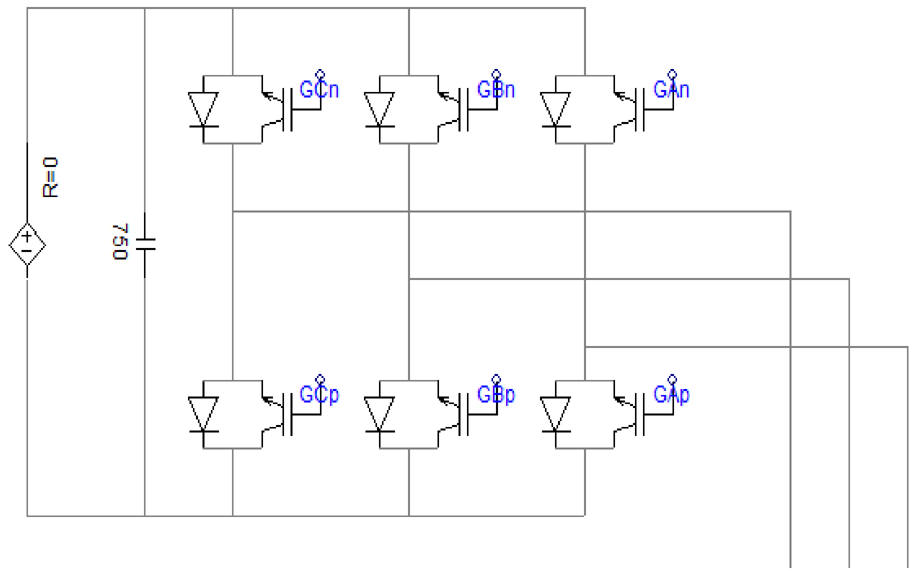

Figure 3.6: Diagram of the D-STATCOM designed using the PSCAD/EMTDC.

3.7 Test Cases

Below are the diagrams of the test to be implemented using the PSCAD/EMTDC software as stated in 3.3

3.7.1 Test System A

The designed diagram of the Test System A for the DVR simulation is shown in Figure 3.7(a). The test system is composed by a 13 kV, 50 Hz generation system, feeding two transmission lines through a 3-winding transformer connected in

REFERENCES

1. H. Hingorani,(1995). “Introducing custom power” IEEE spectrum, vol.32 no.6, p 41-48.

2. M. H. J. Bollen,(2000) “Understanding Power Quality Problems—Voltage Sags and Interruptions” Piscataway, New York: IEEE Press.

3. M.Madrigal, E.Acha,(2000), “Modelling of Custom Power Equipment Using Harmonic Domain Techniques”, IEEE.

4. Ewald F.F, Mohammad A.S.M, (2008), Power Quality in Power Systems and Electrical Machines, Burlington,USA, Elsevier Academic Press.

5. Ray Arnold, (2001), “Solutions to Power Quality Problems” power engineering journal 2001 pages: 65-73.

6. John Stones and Alan Collinsion, (2001), “Introduction to Power Quality” power engineering journal , pages: 58 -64.

7. E. Acha, V. G. Agelidis, O. Anaya-Lara, and T. J. E. Miller,(2001), ‘Electronic Control in Electrical Power Systems,” London, U.K., Butterworth-Heinemann.

8. Gregory F. Reed, Masatoshi Takeda, (1998), "Improved power quality solutions using advanced solid-state switching and static compensation technologies," Power Engineering Society , Winter Meeting, IEEE.

9. M. Wang and A. V Mamishev, “Classification of Power Quality Events Using

Optimal Time-Frequency representation," Part 2: Application, IEEE Transactions on Power Delivery, vol. 18, pp. 544-549, 2003.

10. Flores, R.A, "State of the Art in the Classification of Power Quality Events, An Overview". Harmonics and Quality of Power, 2002, 10th International Conference on Volume 1, issue, 6-9, pp. 17-20, Oct. 2002.

11. David Hart, David Uy, Damir Novosel, Steven Kunsman, Carl LaPlace and Marco Tellarini, "Improving Power Quality", ABB Review, 4/2000.

12. Adly Girgis, Bi Chang and Elham Makram, "A Digital Recursive Measurement for On Line Tracking of Power Systems Harmonics", IEEE transactions on Power Delivery, Vol. 6, No.3 July 1991.

13. V.K. Ramachandaramurthy, A. Arulampalam, C.Fitzer, C. Zhan, M. Barnes and N.Jenkins,(2002),"Supervisory control of dynamic voltage restorers "IEE Proc.-Gener.Transm. Distrib. Vol. 151, No. 4, pp. 509-516.

14. Chris Fitzer, Mike Barnes, Peter Green,(2004), " Voltage Sag Detection Technique for a Dynamic Voltage Restore'', IEEE Transactions on Power Delivery, Vol. 40,No. 1,pp. 203-212.

15. Il-Yop Chung, Dong-Jun Won, Sang-Young Park,Seung-Il Moon, Jong-Keun Park "The DC link energy control method in dynamic voltage restorersystem" Electrical Power and Energy Systems.

16. Pohjanheimo, P. and E. Lakervi,(2000). Steady state modeling of custom power components in power distribution networks. In: IEEE Power Engineering Society Winter Meeting, pp: 2949-2954.

17. S&C Electric Company, Descriptive Bulletin 654-30,(2002),Pure Wave DVR Dynamic Voltage Restorer: Protects Sensitive loads from Voltage Sags and swells, page 2 of 4.

18. Roger C. Dugan/Mark F. McGranaghan, etc,(2002),Electrical Power Systems Quality, McGraw-Hill,Professional Engineering.

19. Douglas S. Dorr,(1995) “Point of Utilization Power Quality Study Results”, IEEE Transactions on Industry Applications, Vol. 31, No. 4.

20. Bollen, M.H.J.,(2001)” Voltage sags in three-phase systems” Power Engineering Review, IEEE, Vol. 21, Issue: pp: 8 - 11, 15.

21. M.S. Looi, H.H. Goh, and B.C. Kok, ‘‘Comparison betweem Direct-On-Line, Star-Delta and Autotransformer Induction Motor Starting Methods in terms of Power Quality, ’’ in IMECS, 2009, paper ICEE_56, p.1558.

22. PSCAD Electromagnetic Transients User’s Guide, The Professional’s Tool for Power System Simulation.