**Voltage Dips and Mitigation System using Dynamic Voltage Restorer**

By

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FINAL REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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# CERTIFICATION OF APPROVAL

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Approved by,

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

May 2011

# CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MD NAJIB B MD YUSOF

# ABSTRACT

Quality of the output power delivered has become a major concern for heavy duty industry for present era. The poor power quality is due to some disturbances such as voltage sags/dips, surge, flicker, harmonics, imbalance and interruptions. It becomes more important especially with the sophisticated devices whose performance is very useful to the quality of power supply. Power quality problem in industries, factories, university, residential areas etc cause failure to the equipment and malfunction which can make the operating system stop and at the end gives a big impact to the plant production. These issues become worse if there is no mitigation system to counter back the problem. A voltage dip is loss of rms voltage which is a major power quality problem. In specific term of duration and retained voltage, it can also be representing as the lowest rms remaining voltage at the lowest point during the dips at the industry. So, it is the responsibility of the user and customers to identify the root cause of the problem and create a mitigation system to overcome the problem. To overcome this abnormal problem custom power devices are connected closer to the end of the load. One of the devices is the Dynamic Voltage Restorer (DVR) which is the most efficient custom power device used in power distribution networks. This paper presents modeling, simulation, and analysis of a Dynamic Voltage Restorer (DVR) using PSCAD (Power System Computer Aided Design) software. The main component of a DVR is voltage source converter (VSI) which is operated by pulse width modulation (PWM) technique and a PI controller. There are many different type of fault has been created and shown reliable result after mitigate using DVR.

# ACKNOWLEDGEMENT

I would like to thank Universiti Teknologi PETRONAS for giving me to use their resources and work in such excellent environment.

First and foremost I take this golden opportunity to express my gratitude to my guide Assoc Prof Dr K.S Rama Rao and Mr Bahr Eldin for their guidance during my project work. This project would not be success without their help and the valuable time that they given to me even though they are quite busy with their work.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| Var | - | Volt- Amperes Reactive |
| PSCAD | - | Power System Computer Aided Design |
| PI | - | Proportional Integral |
| EMTDC | - | Electromagnetic Transient Direct Current Software |
| UPS | - | Uninterrupted Power Supply |
| P.U | - | per unit |
| DVR | - | Dynamic Voltage Restorer |
| PWM | - | Pulse Width Modulation |
| D-Statcom | - | Distribution Static Compensator |
| PLC | - | Programmable Logic Controller |
| VSI | - | Voltage Source Inverter |
| FACTs | - | Flexible ac Technology |
| CSI | - | Current Source Inverter |
| SVC | - | Static Var Compensator |
| Hz | - | Hertz |
| IEC | - | International Electro technical Commission |
| IGBT | - | Insulated Gate Bipolar Transistor |
| IEEE | - | Institute of Electrical and Electronics Engineers |
| KV | - | kilovolt |
| MW | - | Megawatt |
| ms | - | mili second |
| GTO | - | Gate Turn-off thyristors |

# CHAPTER 1
# INTRODUCTION

## 1.1 Background of study

Nowadays, most of industries, universities, and utilities use modern equipment based on the electronic devices such as PLC (Programmable Logic Controller), laptop, washing machine, printers etc. These devices are very sensitive to the disturbances and become less efficient to the power quality problems such as voltage sags, swells, flicker and harmonic.

With increasing usage of power electronics in industrial oil and gas plants, manufacturing plants etc the issue of power quality has contributed significant adverse effects on the plant performance. The proliferation of non-linear loads (i.e. computers, variable speed drives, cranes, elevators, furnaces, motors, discharging lighting, UPS (Uninterrupted Power Supply) etc ) in industries have produced substantial voltage disturbance in Electrical Distribution System. Voltage dips can be considered as one of the major disturbances.

Voltage dips can create unexpected and unwanted operating problems with all types of equipments, ranging from nuisance tripping, miss-operation and failure of electrical plant equipment (i.e. transformers, conductors, motor, generators etc.) Plant's electrical substations experience voltage dips due to the distribution circuit from operation of multiple large electric equipment at the plant facilities.

There are many ways to overcome the problem of voltage dips. One of the electronic equipment that can be used to regulate the voltage is by using Dynamic Voltage Restorer (DVR) which can provide the reliable solution to overcome the issue of distribution power quality. The DVR mainly use for very sensitive load that effect the efficiency of the output voltage.

## 1.2 Problem statement

Voltage dips can cause additional voltage stress to the electronic components, electrical machines, cables, transformers, switchgears, circuit breakers, bus bars, light sources etc also voltage dips cause reduction in equipment life span for example in electric machines. At terminals of induction motor it causes changes in torque and slip and consequently affects the production process. In worst case it may lead to vibration, reducing mechanical strength and shortening the motor service life. These uncorrected problems make process control being harder. Process variations slow production rates, decrease product quality, increase energy consumption and the worst thing make the plant upset. By exposing plant transformers and motors to voltage dips may shorten their lives and increase the chances of catastrophic failure.

## 1.3 Objective

a. To study problems and scenarios related to the voltage dips in power quality systems.
b. To learn about Dynamic Voltage Restorer (DVR) system that can reduce the voltage dips problem.
c. To develop a simulation model of a distribution network incorporating the DVR.

## 1.4 Scope of Study

a. Power System Computer Aided Design (PSCAD) V4 software is used for modeling and simulations in the project. By creating large load running in a weak power network system to create voltage dips and model the mitigation system DVR to reduce voltage dips.
b. Understanding the Power System Computer Aided Design (PSCAD) software.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1 Power quality problems

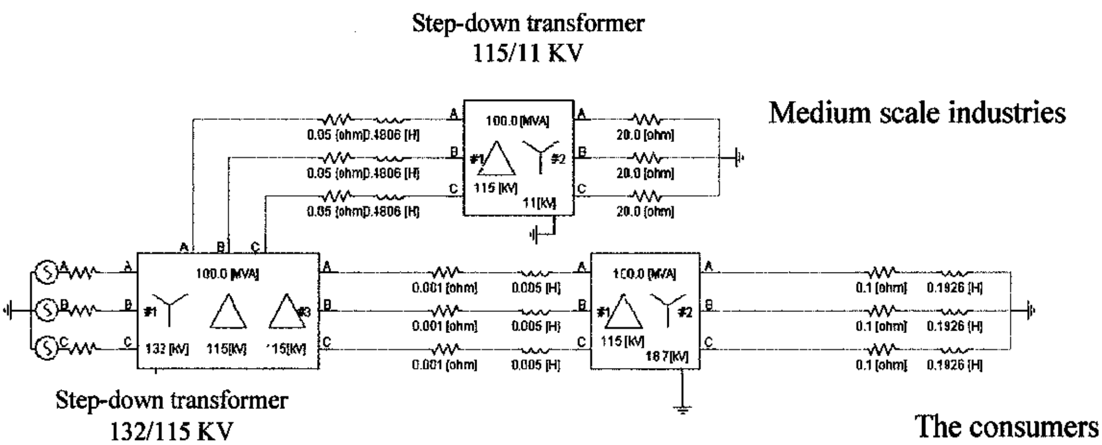



**Figure 1:** Single line diagram of power distribution system

In ideal case, power distribution system should provide a better performance without any interrupted voltage to the customer activities. However, because of the nonlinear loads it will affect the quality of power supplies. So due to this problem a smooth voltage waveform cannot be achieved thus it will end up with the power quality problem. Power Quality problem can be classified in much definition such as voltage dips (sags), swells, flicker, harmonic distortion, transient and interruption.

## 2.2 Classification of Voltage dips

Voltage dip is change of rms voltage in short interruption at load bus. A voltage dip means that the required energy is not being delivered to the load and this can have serious consequences depending on the load that involved. When heavy load are started, such as electric machine, the high starting current may drop the voltage at certain level for a short term. The magnitude of the voltage usually is below than the 10% nominal supply voltage [16]. The classification of rms voltage variations is shown in Figure 2 as plot of voltage against duration of disturbances. Figure 3 (a) and (b) is shown the voltage dip waveform.

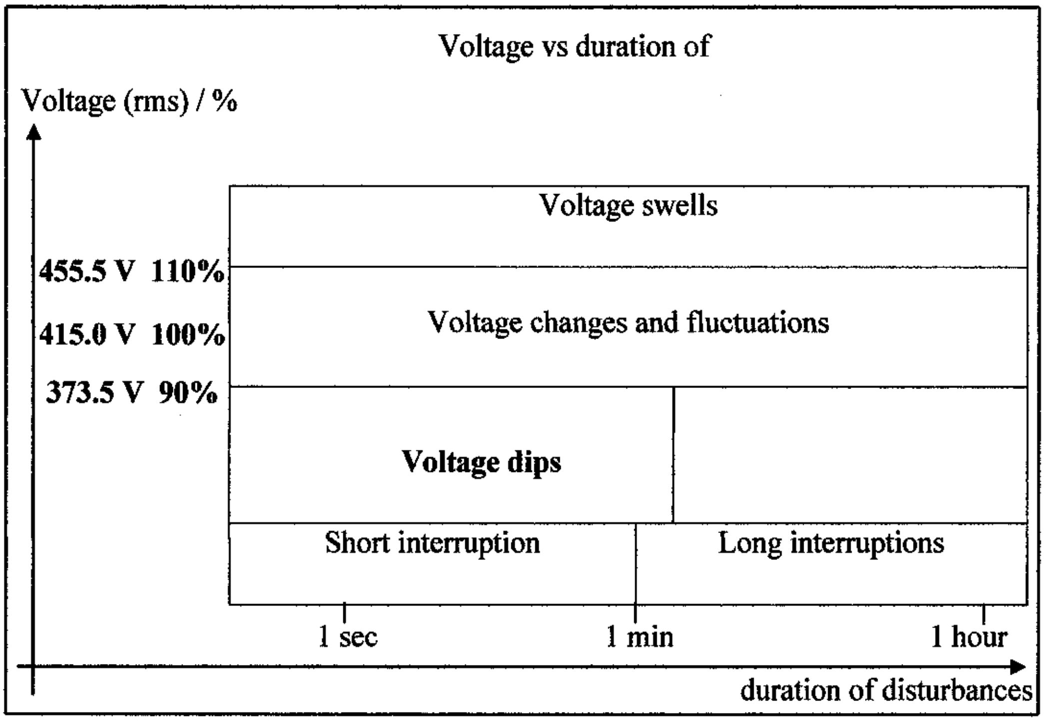
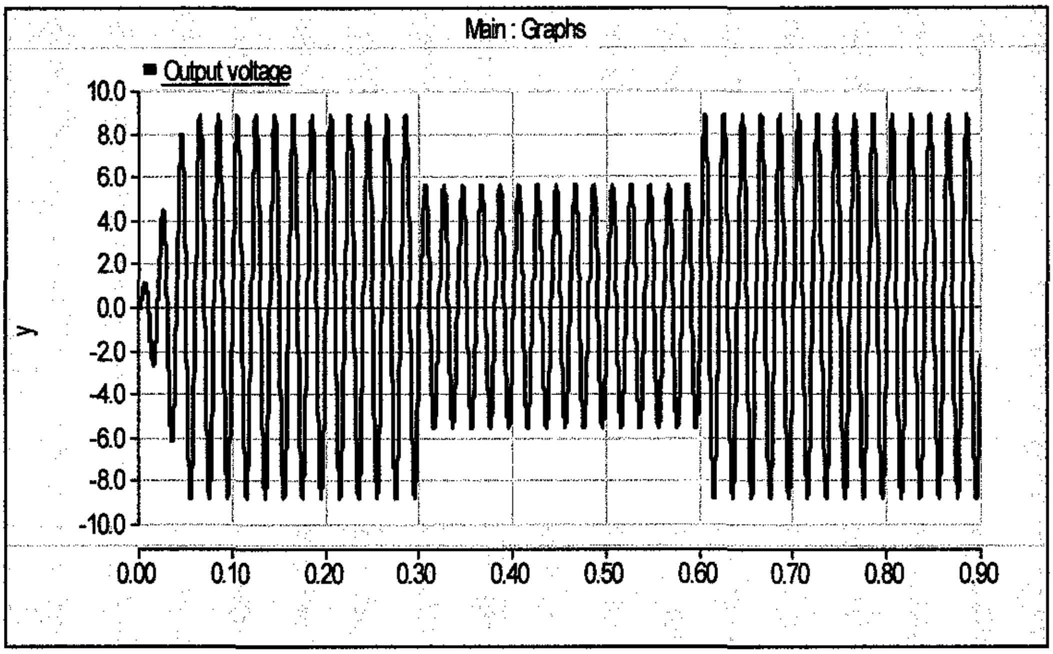
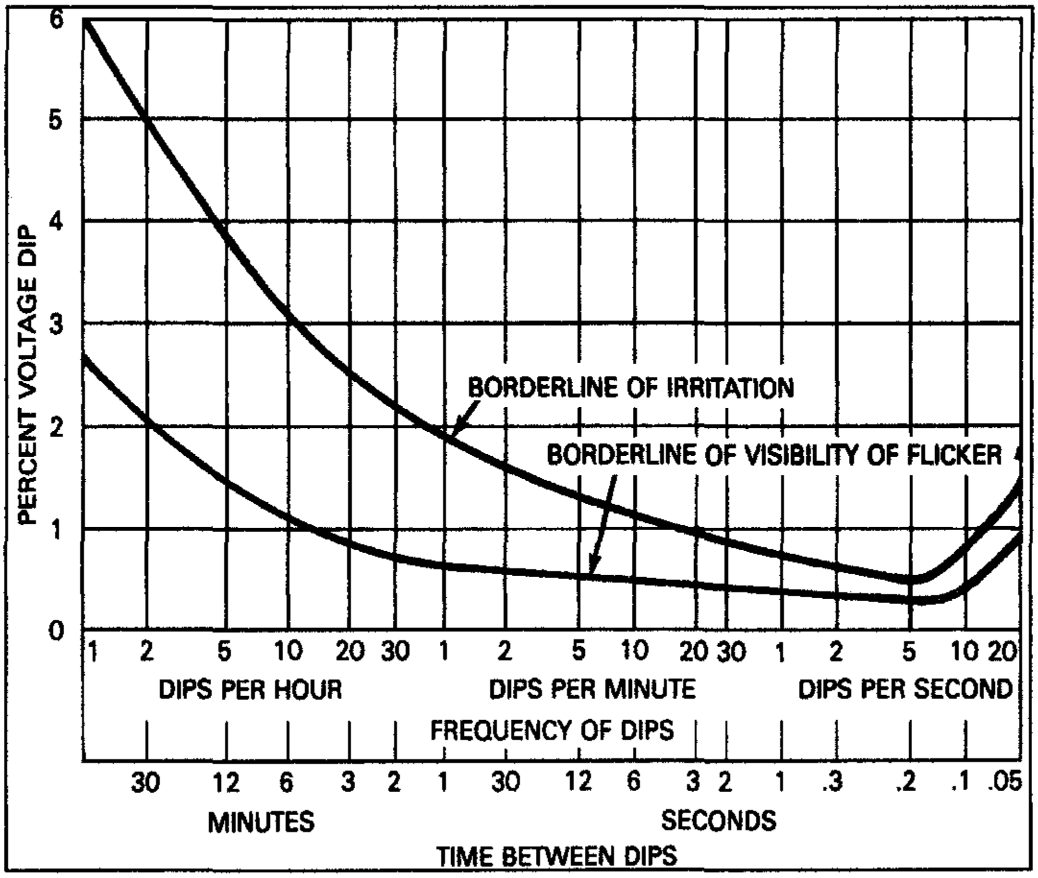



**Figure 2:** Classification of Voltage Variations




(a)




(b)

**Figure 3:** Sample voltage dips waveform

## 2.3 The causes

Voltage dip is sudden reduction between 10 % - 90 % from nominal voltage supply [16]. It happened because high current, short circuit, heavy loads and earth faults in the grid or electric equipment. When voltage drops down below than 90 %, the time taken for a voltage dip to occur is from millisecond up to 1 minute [3]. If number of motors start at the same time or the same repeatedly start and stop, the frequency of voltage changes may produce dips in electrical equipment that is perceived by human eyes. The voltage dips also may cause by distribution or transmission network fault, cable fault during the construction, lighting strike that trip the breaker and the higher rise building without proper grounding [4]. Other causes due to voltage dips are:

- Storm activity – lightning, wind.
- Object coming in contact with power line and tripping breaker – tree branches, animals etc.
- Utility fault.
- Construction activity.
- Accidents – motor vehicle, other.
- Equipment failure.
- Overloading.
- Poor grounding.
- Non-linear loads.

## 2.4 The effect

Voltage dip is due to high starting current that may cause the electric equipment rms voltage drop. Due to time taken by voltage dip it may affect the process of transaction of data and the communication system such as email and box mail system. Moreover it may cause spurious tripping of relays and electronic equipment. In addition, induction motor that operates at maximum torque may also damage the bearings etc. Severe voltage dips may not allow other loads to be started due to reduction in the supply voltage. Also major effects can occurs such as motor may not maintained the required speed even for a good variable speed drive, motor contactors drop out with around 65% of the nominal voltage and also many variable speed drives trip out when a voltage dip is more than 15%.[4].

## 2.5 IEEE Standard

IEEE 446-1995, "IEEE recommended practice for emergency and standby power system for industrial and commercial application range of sensibility loads".

The standard discusses about the effect of voltage sags on sensitive equipment such as motor starting, etc. It shows principles and examples on how systems shall be designed to avoid voltage sags and other power quality problems when backup system operates.

IEEE 493-1990, "Recommended practice for design of reliable and commercial power system"

The standard proposes different technique to predict voltage sag characteristic, magnitude, duration and frequency. There are few important things of interest for voltage sags. The differences can be summarized as follows:

- Calculating voltage sag magnitude by calculating voltage drop at critical load which includes the network impedance, fault impedance and location of fault.
- By studying protection equipment and fault clearing time it is possible to estimate the duration of voltage sag.
- Further it has been found that the voltage dips/sag with magnitude 70 % of the nominal value is more common than complete outages [5]. Sags/ dips and surges can be identified by the voltage magnitude and the time duration it can sustain. IEEE 519-1992, IEEE 1159-1995 as shown in Table 1[6].

**Table 1:** IEEE definitions for the voltage sags and swells

| Disturbance | Voltage | Duration |
|---|---|---|
| Voltage Sag | 0.1- 0.9 p.u | 0.5- 30 cycle |
| Voltage Swell | 1.1-1.8 p.u | 0.5- 30 cycle |

## 2.6 Custom Power Devices

Nowadays, a lot of devices have been developed to mitigate voltage dips such as Uninterrupted Power Supply (UPS), Distribution Static Compensator (D-Statcom) and Dynamic Voltage Restorer (DVR). Among these devices UPS is well known and most of the industries use UPS configuration for Power Distribution System application. Previously DVR and D-Statcom are less popular devices that being used even though they are highly efficient and in term of cost more effective. Because of the rapid development of power electronic industry and low cost devices, DVR becomes most popular among the industries.

DVR is used to eliminate two different types of abnormality that affect power quality. There are two types of load situation which are linear loads and non-linear loads. To describe that the load is linear is when the entire dependent and independent variables changes linear with each other. Resistor is the best example to describe as a linear device. For non-linear devices the entire dependent and independent variables does not change with each other. Capacitors and inductors are the best examples to describe as non-linear devices.

Among the custom power devices, UPS and DVR can be considered as the devices that can boost up the voltage waveform of the power distribution line. The comparison between UPS and DVR is shown in Table 2.

**Table 2: Comparison between UPS and DVR**

| UPS( Uninterrupted Power Supply) | DVR (Dynamic Voltage Restorer) |
|---|---|
| Supplying the full voltage to the load whether there is no distortion or not. | Voltage will inject during the voltage dips occur. |
| High power rating | Low power rating |
| Low efficiency | High efficiency |
| High cost | Low cost |

## 2.7 Dynamic Voltage Restorer

### 2.7.1 Introduction

Many power quality problems such sags, swells, harmonics etc, voltage dips are the most severe disturbances. In order to overcome the problem the concept of custom power devices has been introduced recently. One of the devices is *Dynamic Voltage Restorer* which consists of power circuit and control circuit. The DVR provides three phase independent controlled voltage source. It controls the voltage vectors which have magnitude and angle. These voltages are injected into the ac distribution system at the reference voltage. DVR is the most efficient and an effective device that has been used for power system network. DVR is a series connection to the powers system network that injects voltage into the system that regulates the load side voltage. Normally it is connected into a power system network between the supply and the critical load at a common point of coupling. Other than voltage dips, DVR also can be used for other application such as harmonic compensation, transient in voltage and current and etc. Figure 4 and 5 show the location of DVR and basic operation of DVR respectively.

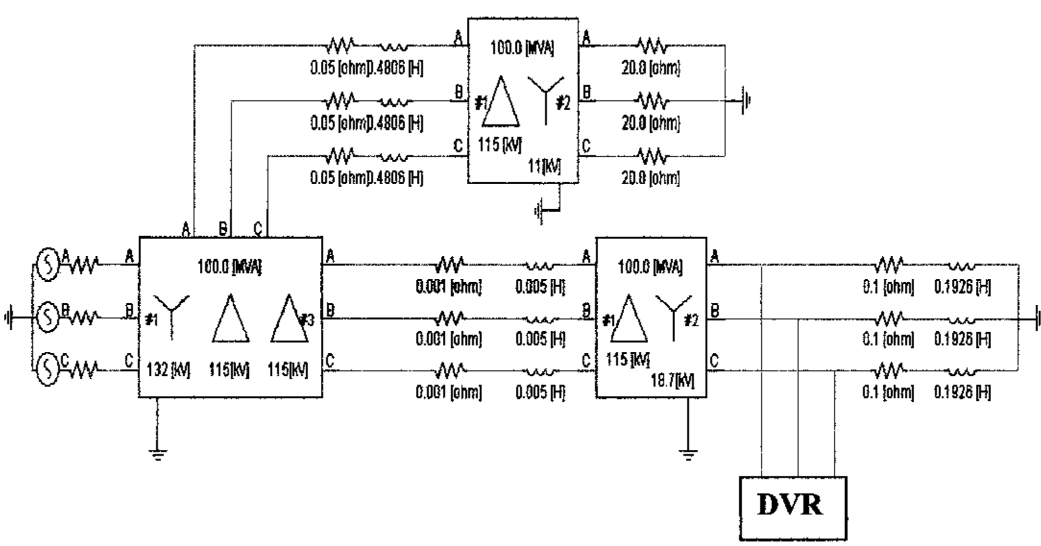



**Figure 4: Location of DVR**

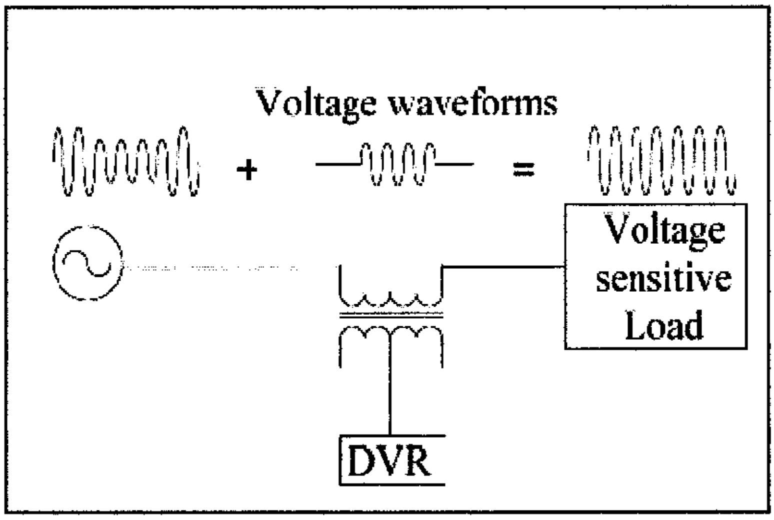



**Figure 5: Basic operation of DVR**

## 2.8 Basic structure of DVR

Figure 6 shows general configuration of the DVR which consists of:

i. Booster Transformer
ii. A harmonic filter
iii. Storage device
iv. A voltage source converter
v. DC charging circuit

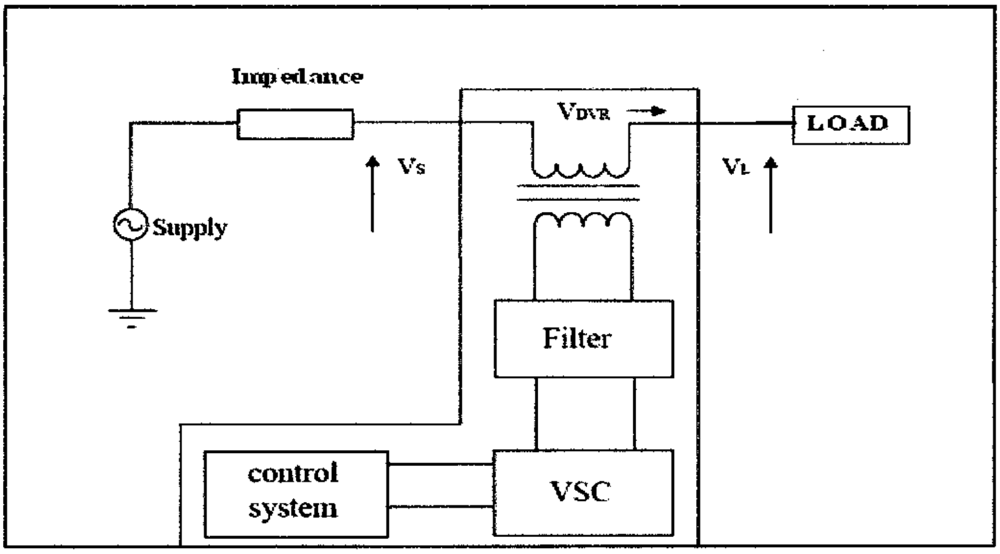



**Figure 6: Schematic of Dynamic Voltage Restorer**

### 2.8.1 Energy Storage Unit

The energy storage unit is responsible to store DC voltage. It can use a super capacitor or bank of batteries that being to storage energy. Its supply real power to the system that is required when DVR is used for compensation.

### 2.8.2 DC charging

The DC charging circuit has two tasks:

- To charge back the energy that has been used after the voltage dips compensation.
- To maintain the dc voltage at the nominal dc voltage.

### 2.8.3 PWM Voltage Source Inverter (VSI)

With the cost being the driving factor, general purpose PWM-VSI devices with low kilowatt ratings (fractional to several tens of kilowatts) are generally designed with minimum component count and complexity. In ac motor drive applications, a single/three phase diode bridge circuit rectifies the AC input voltage and a dc link capacitor filters the rectified voltage forming a stiff dc voltage source. The PWM-VSI converts the dc voltage to three-phase ac voltages with controllable magnitude and frequency via a PWM method. Below about hundred volts MOSFETs and at higher voltages IGBT power semiconductor switching devices are utilized in the VSI, and the switching frequency can be as high as many tens of kilohertz. The power circuit may also contain a dc link capacitor pre-charging circuit, a small EMI filter, and transient voltage suppression devices [14].

With the ac utility line power quality regulations becoming more stringent, at power ratings higher than several tens of kilowatts the input rectifier device performance becomes important. An inductor (dc reactor) is inserted in series with the rectifier in order to reduce the harmonic content on both the ac line and the dc link capacitor. In higher power non-regenerative applications 12-pulse rectifiers together with input transformers with star primary and star-delta secondary windings are frequently utilized to reduce the input current harmonic distortion. In the megawatt power range, the PWM-VSI may be formed from parallel inverters, inverters with parallel devices, or more complex inverter device structures such as the three levels VSI.[15]

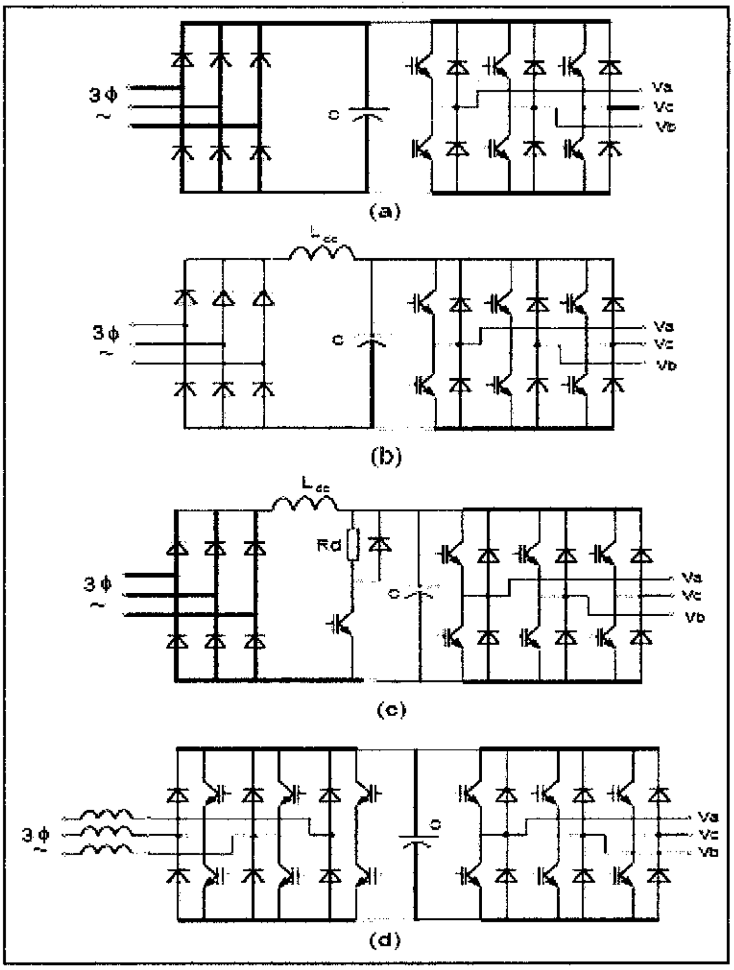



**Figure 7**: The power converter structure of various PWM-VSI drives

In ac motor drive applications, shown in Figure 7 (a) a single/three-phase diode bridge circuit rectifies the ac input voltage and a dc link capacitor filters the rectified voltage forming a stiff dc voltage source.

As shown in Figure 7 (b) an inductor (dc reactor) is inserted in series with the rectifier in order to reduce the harmonic content on both the ac line and the dc link capacitor. Alternatively, a three phase reactor may be inserted in series with the ac line to suppress the harmonics. Also a dynamic brake formed by a resistor and a gate turn-off switch 20 is connected across the dc bus capacitor in order to limit the dc bus voltage under transients and during regeneration (Figure 7(c)). In regenerative applications with emphasis on energy efficiency back-to-back connected thyristor bridges or more commonly a PWM-VSI can be utilized (Figure7 (d)).

However, with the PWM-VSI a relatively large and therefore expensive three phase reactor is required. Therefore, this solution is the most expensive approach. Up to near a megawatt the switching device choice remains to be IGBT due to its cost and performance advantages.

The power semiconductor devices can be IGBT's, GTO's or some of the recently developed high voltage IGBT's and other new devices. Due to the switching losses and the thermal issues associated with them, the switching frequency of the PWM-VSI decreases from tens of kilohertz at lower tens of kilowatts level to less than a kilohertz at the megawatt level. At increasing power levels, typically snubber circuits are added to reduce the commutation losses and the peak stresses on the devices [15].

### 2.8.4 PWM Current Source Inverter (CSI)

An inverter of the current source type makes it possible to convert the energy supplied by a dc source into the mains without using an auxiliary dc to dc converter. The current source inverter's efficiency depends on the input dc voltage of the inverter, so the rating of the dc source voltage influences the overall efficiency of the system.

Figure 8 shows the simplified circuit of the CSI. The limited literature on the CSI for Var compensation concentrates on the steady-state characteristic analysis and main circuit design. These references employ a PWM switching pattern for the CSI which is pre-calculated for harmonic elimination, where the modulation index is fixed and the CSI is controlled by its firing angle [12]. The advantages and disadvantages of voltage source inverter and current source inverter is shown in Table 3 and 4.

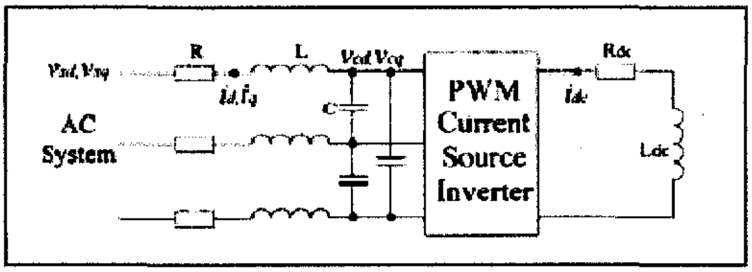



**Figure 8**: Simplified Circuit diagram of CSI

**Table 3**: Advantage and Disadvantage of Voltage Source Inverter

| Advantages | Disadvantages |
|---|---|
| Simple and robust | High switching frequency |
| Easy to control in the feed-forward voltage or feedback current mode | Large switching losses. |
| Wide ranges of frequency, magnitude of fundamental output voltage are attainable. | Conducted and radiated electromagnetic interference. |
| PWM allows direct control of magnitude and phase of output space vector. | Hazardous over-voltage in long cables. |
| | Accelerated deterioration of insulation in bearings and supplied motors. |

**Table 4**: Advantage and Disadvantage of Current Source Inverter

| Advantages | Disadvantages |
|---|---|
| Can transfer power in both direction | Inductance slows down response to current magnitude control commands, can cause overvoltage if current path is broken. |
| In square-wave mode is more efficient than a PWM VSI | The output current is a square-wave waveform. |
| Power circuit is simpler and more robust than the VSI | High level of low-order harmonics. |
| Lack of free-wheeling diodes, large dc-link inductance, current control in the rectifier results in inherent protection from over-currents. | When supplying a motor, can cause voltage spikes in the stator leakage inductance. |
| | PWM CSIs are large and costly, and they lost their efficiency advantage over VSI. |

### 2.8.5 Passive filter

To eliminate the unwanted harmonic waveforms that are generate from VSI process the filters can be placed on the high voltage side or on low voltage side of the injection/booster transformer, thus higher order harmonics are eliminated from passing through the voltage transformer. But there can be a phase shift and voltage drop in the inverted output. This can be reduced by placing the filter on the load side. But in the case of the higher order harmonic current passing through to the secondary side of the transformer, a higher rating of the transformer is necessary. Figure 9 shows the different filter placement in the system.

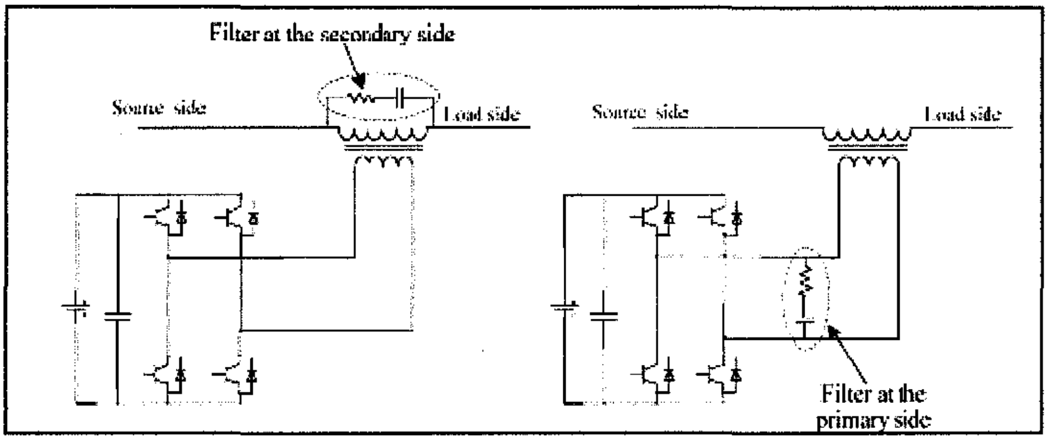


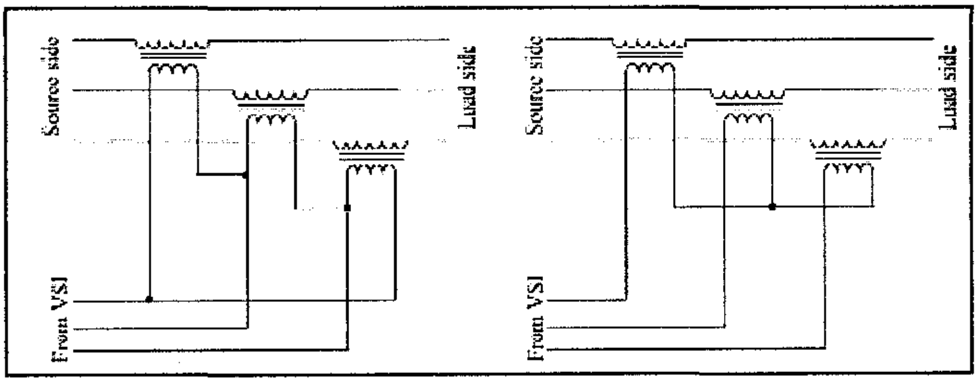

**Figure 9:** Different filter placement

### 2.8.6 Voltage Injection Transformers

The booster transformer is specially designed to limit the coupling noise and also to limit the transient energy from the primary and secondary side. Its main tasks are:

- The DVR is connected to the power system network to H-V windings and transforms and injects is specified voltage from supply source.
- It is also to isolate the load form the system.

The high voltage of the injection transformer is connected in series with powers system network while the low voltage side is connected to the DVR power circuit. The three-single phase transformers and the three-phase DVR can be connected either star or delta open as shown in figure 10[10].




**Delta/open configuration** **Star/open configuration**

**Figure 10:** Connection methods for the primary side of the injection transformer

The transformer winding ratio depends on the voltage required by the secondary of the transformer. Normally the supply voltage must be equal to DVR needed at the full voltage dips compensation. The higher the ratio of transformer winding the higher current will flow at primary side which will affect the performance of the electronic devices.

The winding configuration of the transformer depends on the power system. If the transformer uses delta/star ( $\Delta$ - Y ) connection with the grounded neutral, during the fault, earth fault happens on the high voltage side, no zero sequence current flows to the secondary and only positive and negative sequence components will flow. So the DVR can only compensate with the positive and negative sequence components and for the open configuration it will be used to compensate the positive and negative sequence. Similarly for other winding configuration such as delta/ delta connection of the transformer, during the fault, earth fault occur, the positive, negative and zero sequence components flow through the secondary side [8].

## 2.9 DVR operating system

The basic function of DVR is to control the voltage, $V_{DVR}$ generated by the voltage source converter to the booster transformer. If there is a different voltage that is caused by power system network, the DVR will compensate by injecting to the distribution line from voltage source converter through the injection/booster transformer.

The DVR has three modes of operation which are: protection mode, standby mode and injection/ booster mode.

### 2.9.1 Protection mode

If the load current exceeds the limit of the winding transformer current, the DVR is isolated from the system by using bypass switches whereby S2 and S3 will open and S1 will close to supply another path to the current to flow as shown in Figure 11.

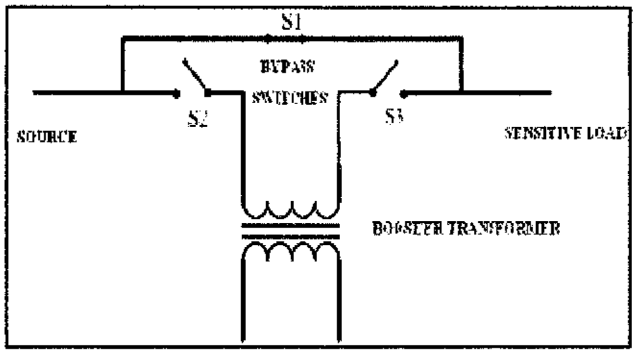



**Figure 11:** Protection Mode

### 2.9.2 Standby Mode ($V_{DVR} = 0$)

In the standby mode the injection/booster transformer low winding will not inject voltage to the system. In this case the voltage source converter is not switched on and the full load current will pass through the primary as shown in Figure 12.

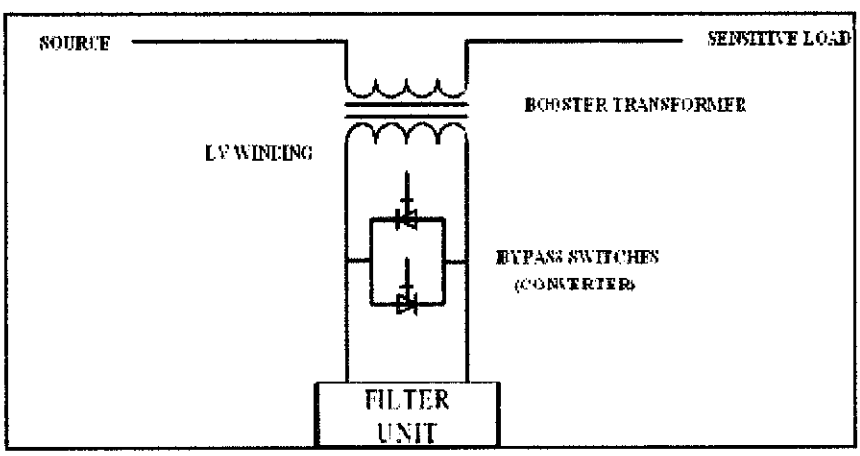



**Figure 12:** Standby Mode

### 2.9.3 Injection/ Boost Mode: ($V_{DVR} > 0$)

In this case, the DVR injects a voltage trough the booster transformer due to the disturbances on the power system network

# CHAPTER 3
# METHODOLOGY

## 3.1 Procedure Identification

The project is carried out according to the flow chart as shown in Figure 13. It is started with study of the voltage dips and the mitigation system using dynamic voltage restorer. Then data is collected on DVR part by gathering the information from internet resources, technical papers and also books. During this phase, voltage dip fundamental also must be studied in order to achieve expected result at the end of the research. Current technology also needs to be taken into account so that a clear understanding on the operation of DVR can be obtained.

In addition, the control system also needs to be studied to get better understanding on DVR and its application. Preparing weak power system network with load need also to be studied in order to apply and enhance the knowledge of this type of power quality problem. Next, simulate the weak power network system and analyze the voltage dip in order to get voltage dip graph. In this stage, collecting data of varies type of fault is needed.

After all the data have been taken, the next phase is designing the structure of DVR and mitigates the poor voltage using DVR. After that, the controller part needs to apply to the system so that the voltage can be control automatically. After doing all the simulation and achieve the data for every parameter needed, analysis the result will conducted.

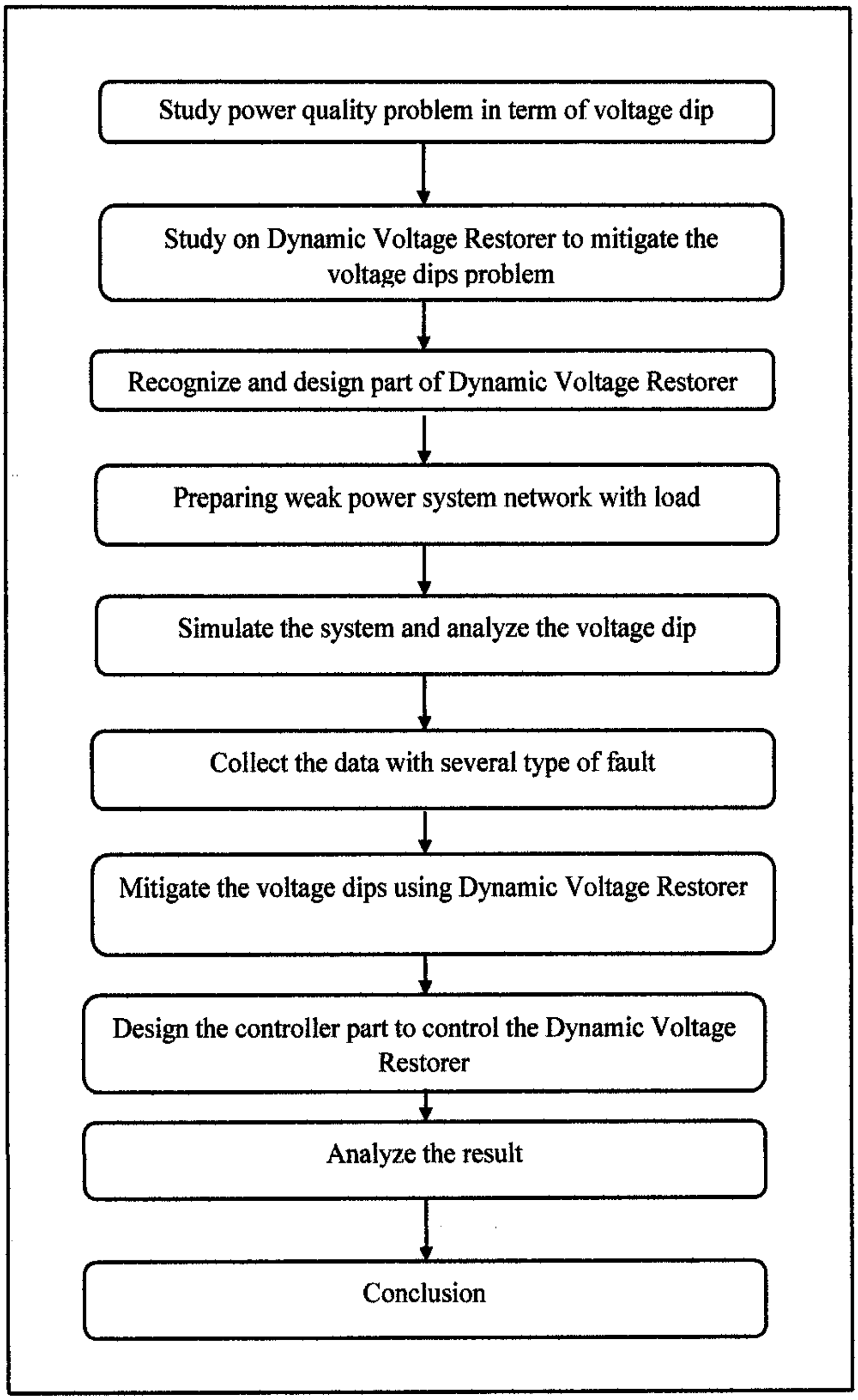



**Figure 13**: Flow diagram of project work

## 3.2 Modeling

Figure 14 is shown the single line diagram with load.

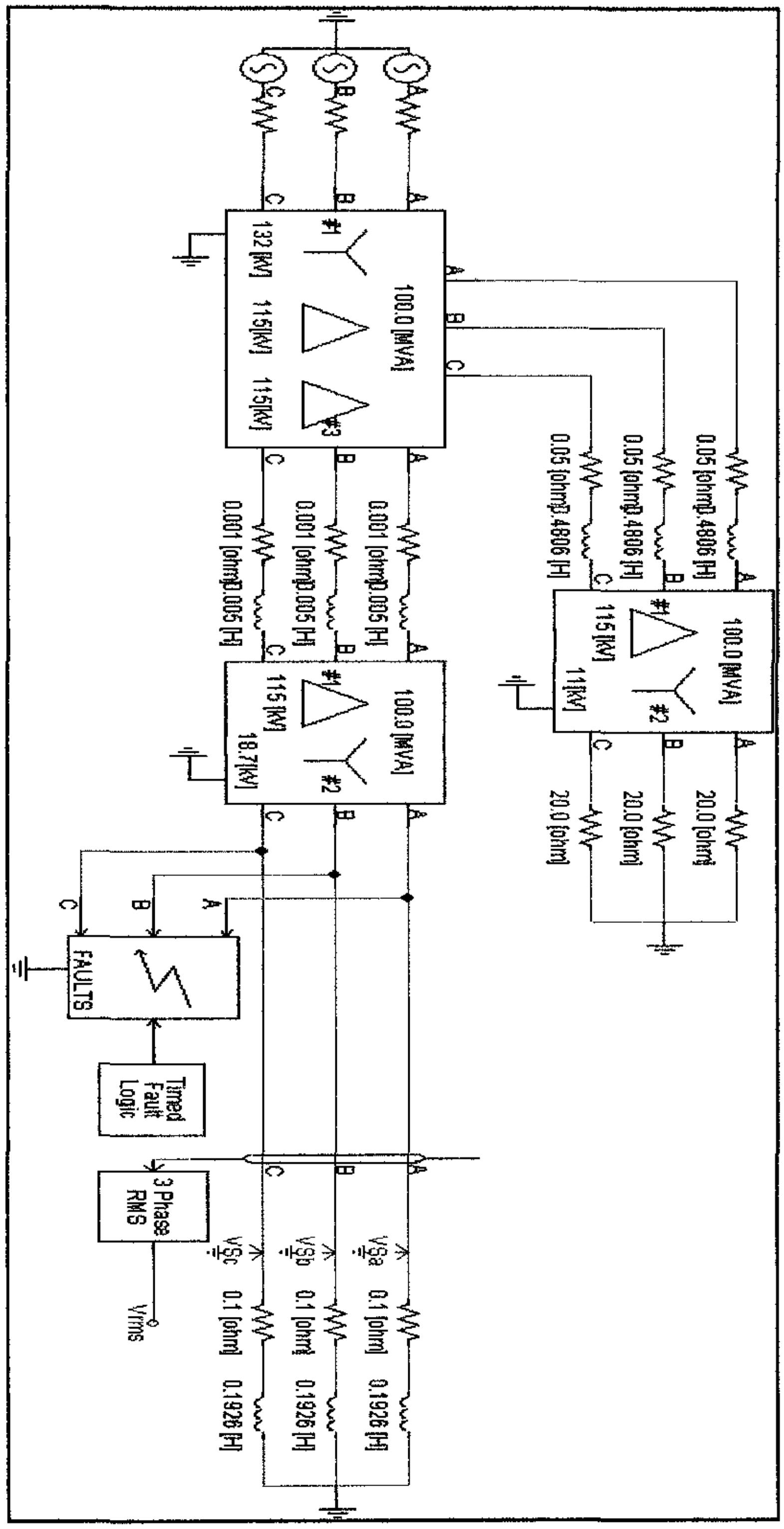



**Figure 14:** Single line diagram

Single line diagram shown in Figure 14 of the system is composed by a 132kV, 50 Hz generation system, feeding two transmission lines through a 3-winding transformer connected in star/delta/delta,132/115/115 kV. Such transmission line feed two distribution networks through two transformers in delta/star, 115/ 18.7 kV and 115/11kV. The DVR is simulated to be in operation only when the fault occurs. The duration of fault considered to be is 300 ms. The Figure 15 show the timed fault configuration and Figure 16 (a), (b) and (c) show the transformer voltage configuration.

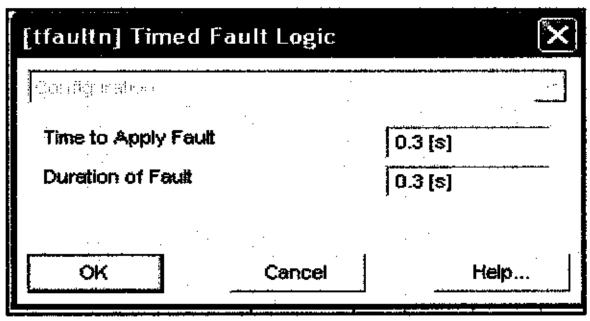
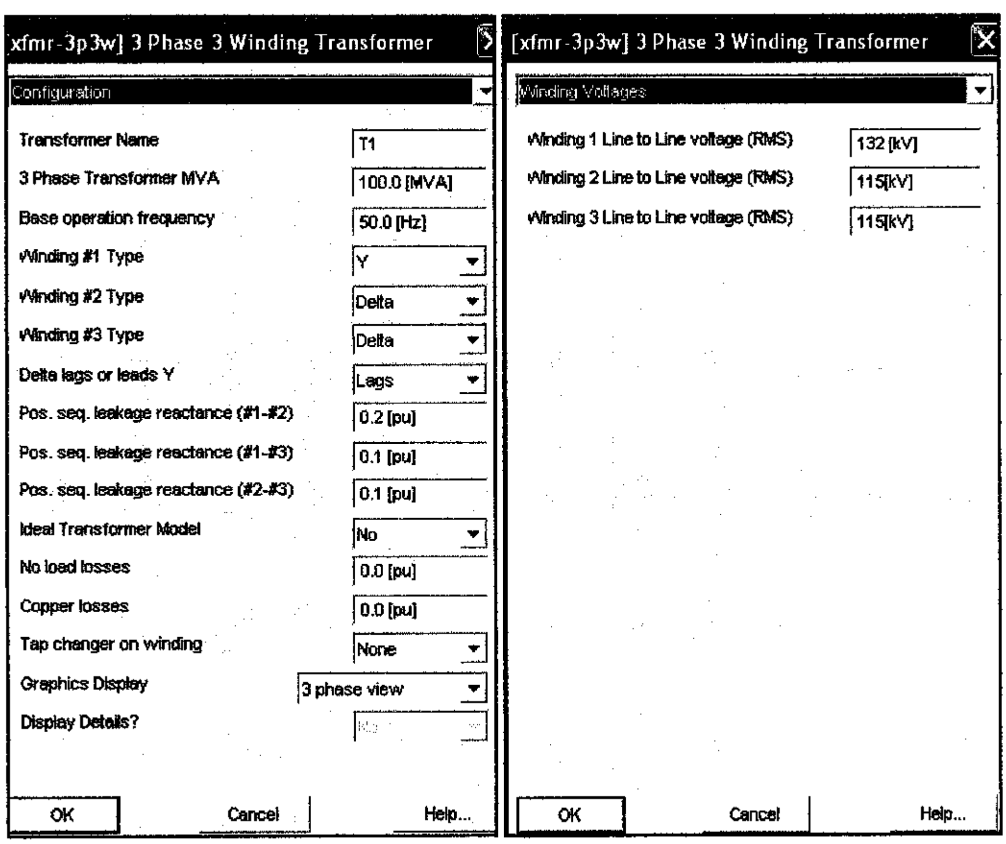
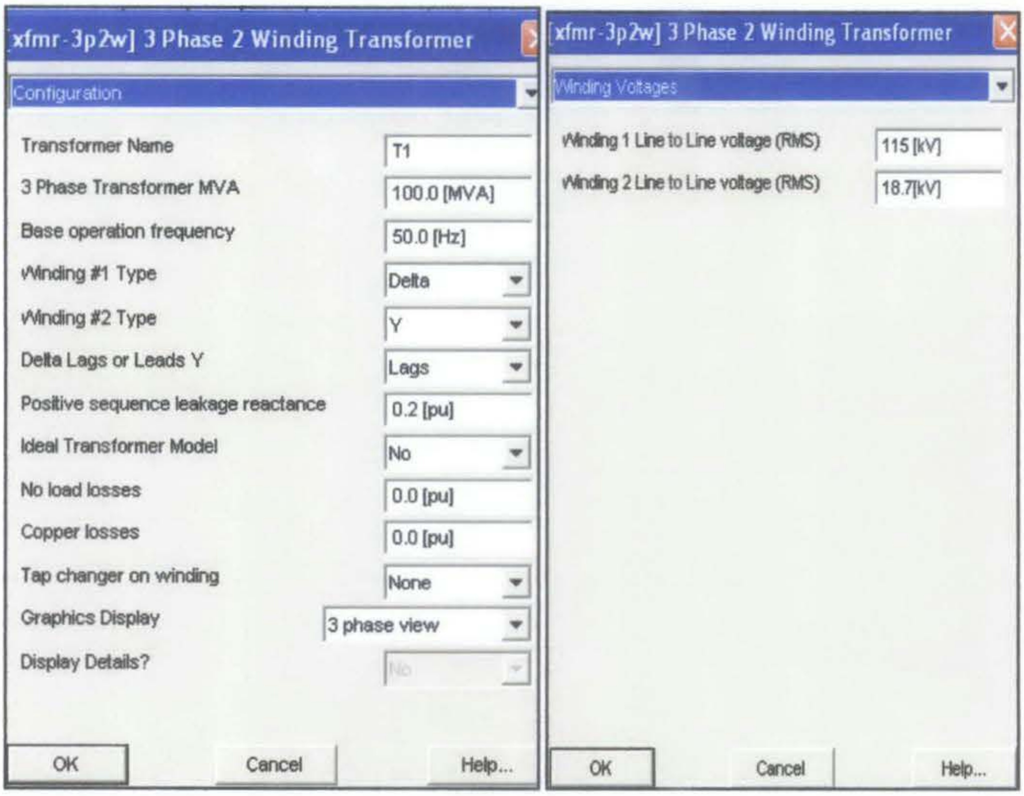



**Figure 15:** Timed fault configuration




**(a)**

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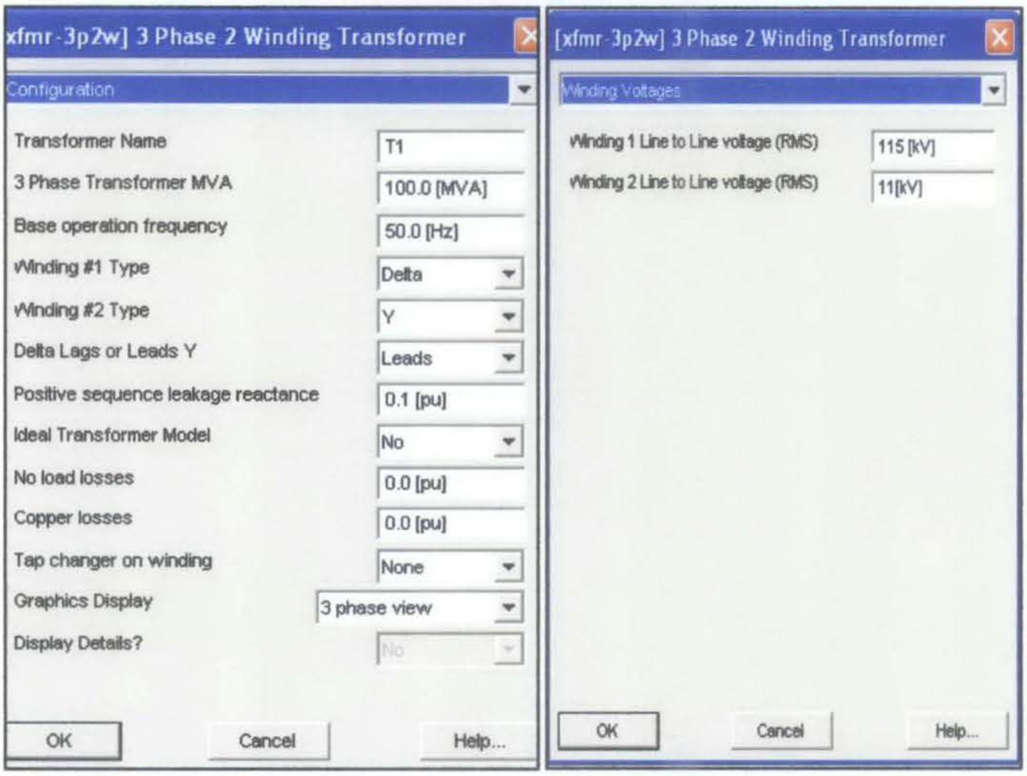



(c)

**Figure 16:** Configuration data of the voltage transformer

### 3.3 Equation related to DVR

Referring to Figure 17, for normal operation (no fault) current will flow through the balanced load A and B. Both 2 load is balance load. When there is fault occur for example at load A, a high current will flow into the feeder A. So based on the Kirchhoff's Law current will flow into feeder B. A voltage drop occurs at feeder B.

For example:

Load A impedance = $Z_{load\,A}$

Load B impedance = $Z_{load\,B}$

Feeder A reactance = $X_1$

Feeder B reactance = $X_2$

Current flow from power supply = $I$

Current flow from feeder A = $I_1$

Current flow from feeder B = $I_2$

Therefore, $I = I_1 + I_2$

In normal condition (without any fault)

$$I = \frac{V_2}{X_2 + Z_{LOAD\,B}} + \frac{V_2}{X_1 + Z_{LOAD\,A}} \qquad (1)$$

When fault occurs at feeder A, because of the short circuit occur, the high current will flowing through feeder B as well as through the source. At this moment voltage at feeder B will decease due to the voltage drop across source reactance $X_s$. So from this condition voltage at feeder B will decrease from nominal voltage.

During fault, the source current,

$$I = \frac{V_2}{X_2 + Z_{LOAD\,B}} + \frac{V_2}{X_1} \qquad (2)$$

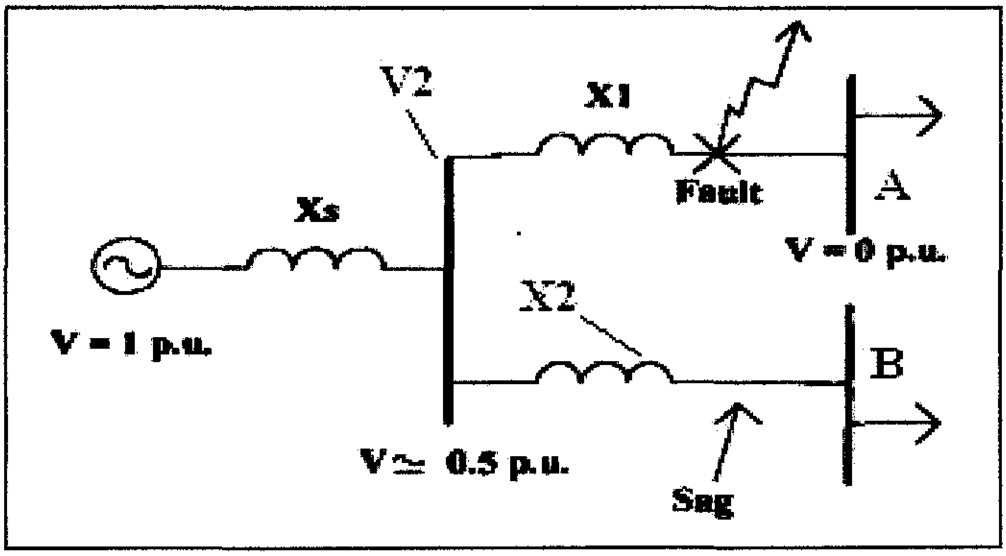



**Figure 17:** Calculation for voltage sag (dip).

### 3.3.1 Mathematical model for voltage injection by DVR system.

Consider the schematic diagram shown in Figure 18. The impedance represented $Z_{th}$ where the real part of the impedance $R_{th}$ and the imaginary part in reactance$X_{th}$.

$$Z_{th} = R_{th} + jX_{th} \tag{1}$$

$$V_{dvr} + V_{th} = V_L + Z_{th}I_L \tag{2}$$

Where

$V_L$ = *The desired voltage magnitude*

$Z_{th}$ = *Load impedance*

$I_L$ = *Load current*

$V_{th}$ = *System voltage during the fault*

Thus, when the voltage drop occurs at feeder B, DVR will inject a voltage through the transformer so that the magnitude of the voltage is same as the load voltage.

$$V_{DVR} = V_L + Z_{th}I_L - V_{th} \tag{3}$$

The load current $I_L$ is given by,

$$I_L = \frac{P_L + jQ_L}{V_L} \tag{4}$$

Where

$P_L = Real\,power$

$Q_L = Reactive\,power$

When $V_L$ is a voltage reference,

$$V_{DVR} < V_{DVR} < \alpha = V_L < 0 + Z_{th} I_L < (\beta - \theta) - V_{th} < \partial \tag{5}$$

$\alpha, \beta$ *and* $\partial$ *are angles of* $V_{DVR}$ *and* $\theta$ *is load angle.*

$$\theta = \tan^{-1}\left(\frac{Q_L}{P_L}\right) \tag{6}$$

The complex power injection of the DVR can be describe as

$$S_{VDR} = V_{DVR} I_{DVR} \tag{7}$$

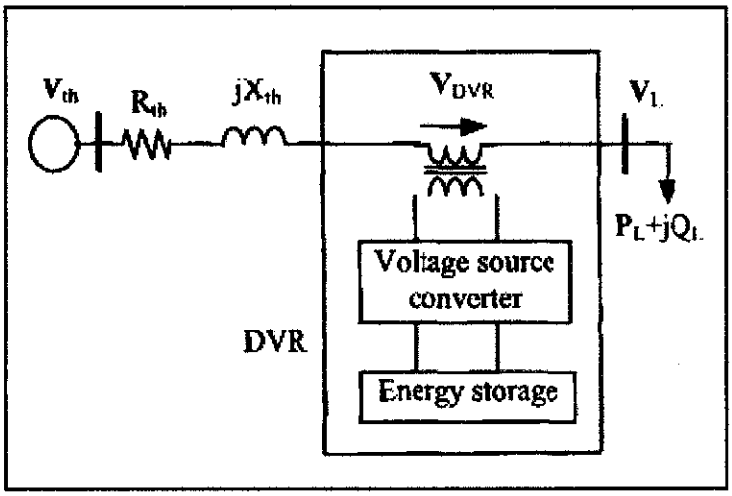



**Figure 18:** Calculation for DVR injection transformer

## 3.4 Tools and Equipment Required

The simulation and analysis uses the Power System Computer Aided Design software.

### 3.4.1 Power System Computer Aided Design (PSCAD)

In this project PSCAD/EMTDC software as shown in Figure 19 is used to model, simulate and analyze voltage dips and mitigation using DVR. The student version is used to familiarize with the software. This student edition is limited but provides examples and tutorial is important to understand the software functionality. To have more knowledge about this software, liaise with Simulation Research and Support Engineer, Manitoba HVDC Research Center, Canada or access to the website PSCAD such as www.pscad.com

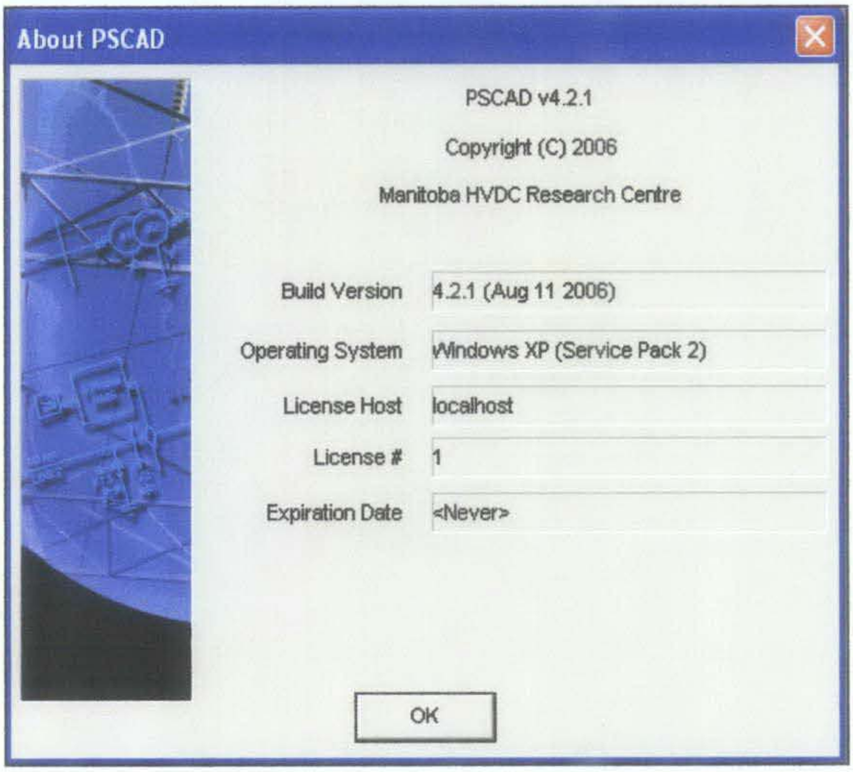



**Figure 19:** PSCAD Software Version 4.2.1

### 3.4.2 What is PSCAD?

PSCAD (Power System computer aided design) is software used to perform the modeling analysis of such controller for a wide range of operating conditions. PSCAD also enables the user to construct the circuit schematically, run simulation, analyze the result and imaging the data in completely integrated in graphical environment. Online plotting function, control meters are also included so that the user can alter the system parameters during a simulation run and view the result directly. PSCAD comes completely with a library of pre-programmed and tested models, ranging from simple passive elements and control functions. It is easy to the user to do any type of modeling such as FACTS devices, transmission line, breakers, transformers etc. If a particular model does not exist, PSCAD provides the flexibility of simple custom model either by assembling those graphically using existing models or by utilizing an intuitively designed from Design Editor.

The following are some common models found in system studied using PSCAD:

I. Resistors, inductors, capacitors
II. Mutually coupled windings, such as transformers.
III. Frequency dependent transmission lines and cables(including the most accurate time domain line model)
IV. Current and voltage source.
V. Switches and breakers.
VI. Protection and relaying
VII. Diodes, thyristors and GTO's
VIII. Analog and digital control functions
IX. AC and DC machines, exciters, governors, stabilizers and inertial model
X. Meters and measuring functions.
XI. Generic DC and AC controls
XII. HVDC,SVC and other FACTS controllers
XIII. Wind source, turbines and governor.

### 3.5 DVR structure

The power circuit of DVR consists of Energy Storage (DC supply), PWM (Pulse Width Modulation) inverter and injection transformer and is shown in Figure 20. Figure 21 is shown the setting mode for breaker operation.

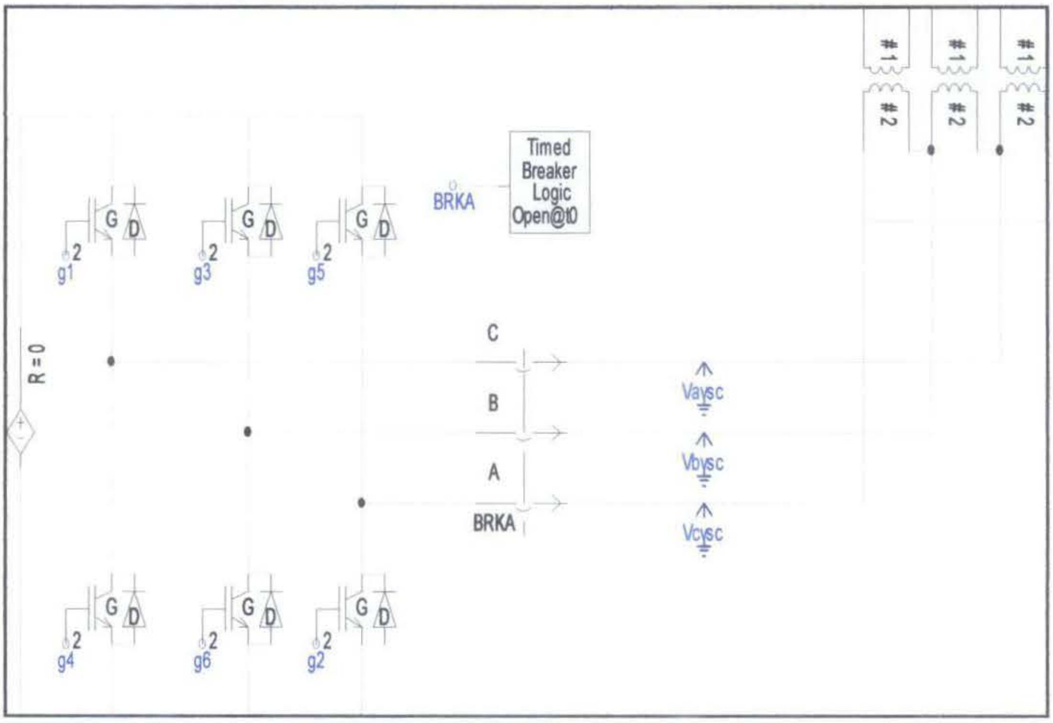



**Figure 20:** DVR structure

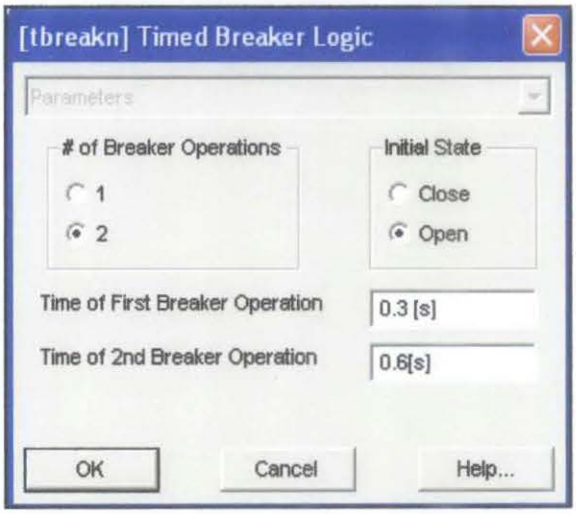


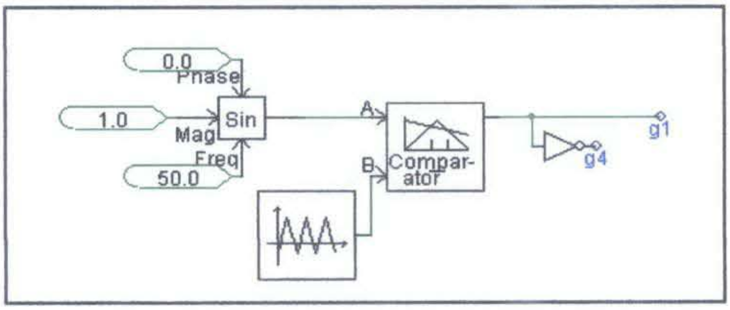

**Figure 21:** Setting mode for breaker operation

### 3.6 Energy Storage

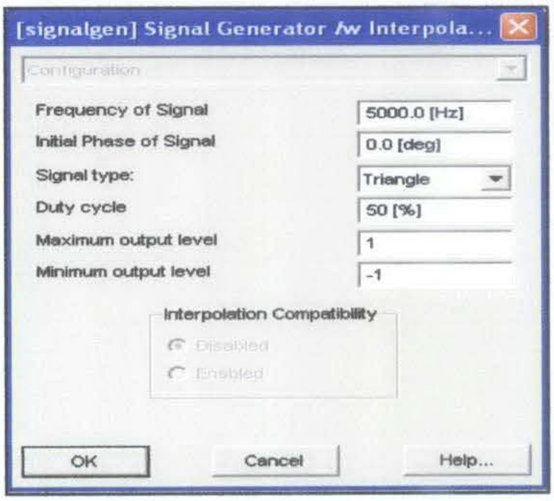
The dc (direct current) voltage is used to provide the real power during the voltage dips compensation.

### 3.7 Pulse Width Modulation (PWM)

Pulse Width Modulation is one of the techniques of controlling the voltage within dc-dc converter. With this technique the converter output voltage involves a pulse modulated wave and the voltage is controlled by varying the duration of the output voltage pulses. The control voltage will be achieved by comparing the triangular waveform with a switching frequency. The reference control voltage output obtained from the sinusoidal wave is compared with a high frequency triangular wave of 5000 Hz with 50 % duty cycle. The high value of the switching frequency is required for voltage dips compensation. Figure 22 to 24 represents the generation of SPWM (Sinusoidal Pulse Width Modulation) signal for the VSI (Voltage Source Inverter).




(a)

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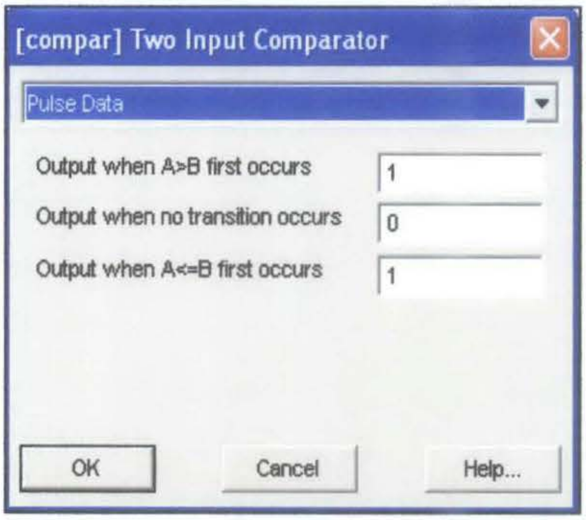



(c)

**Figure 22:** PWM generation

a) The comparator generate an output equal to 1 when the magnitude of the triangular waveform higher than sine wave/ control waveform.

b) The comparator generates an output equal to 0 when the magnitude of the triangular waveform lowers or equal than sine wave/ control waveform.

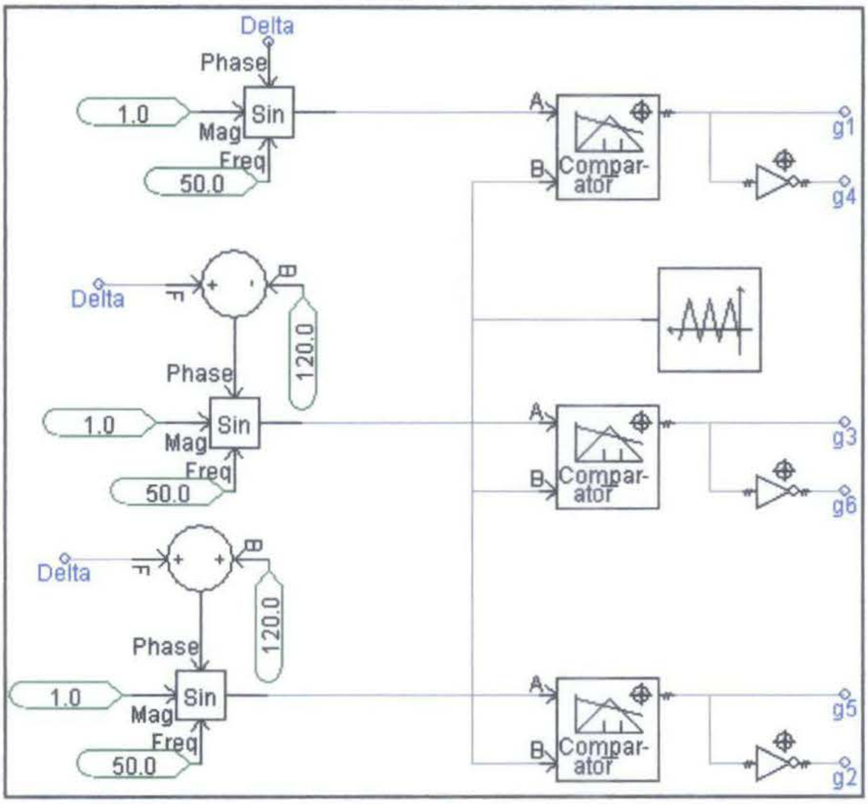



**Figure 23:** Sinusoidal Pulse Width Modulation block diagram

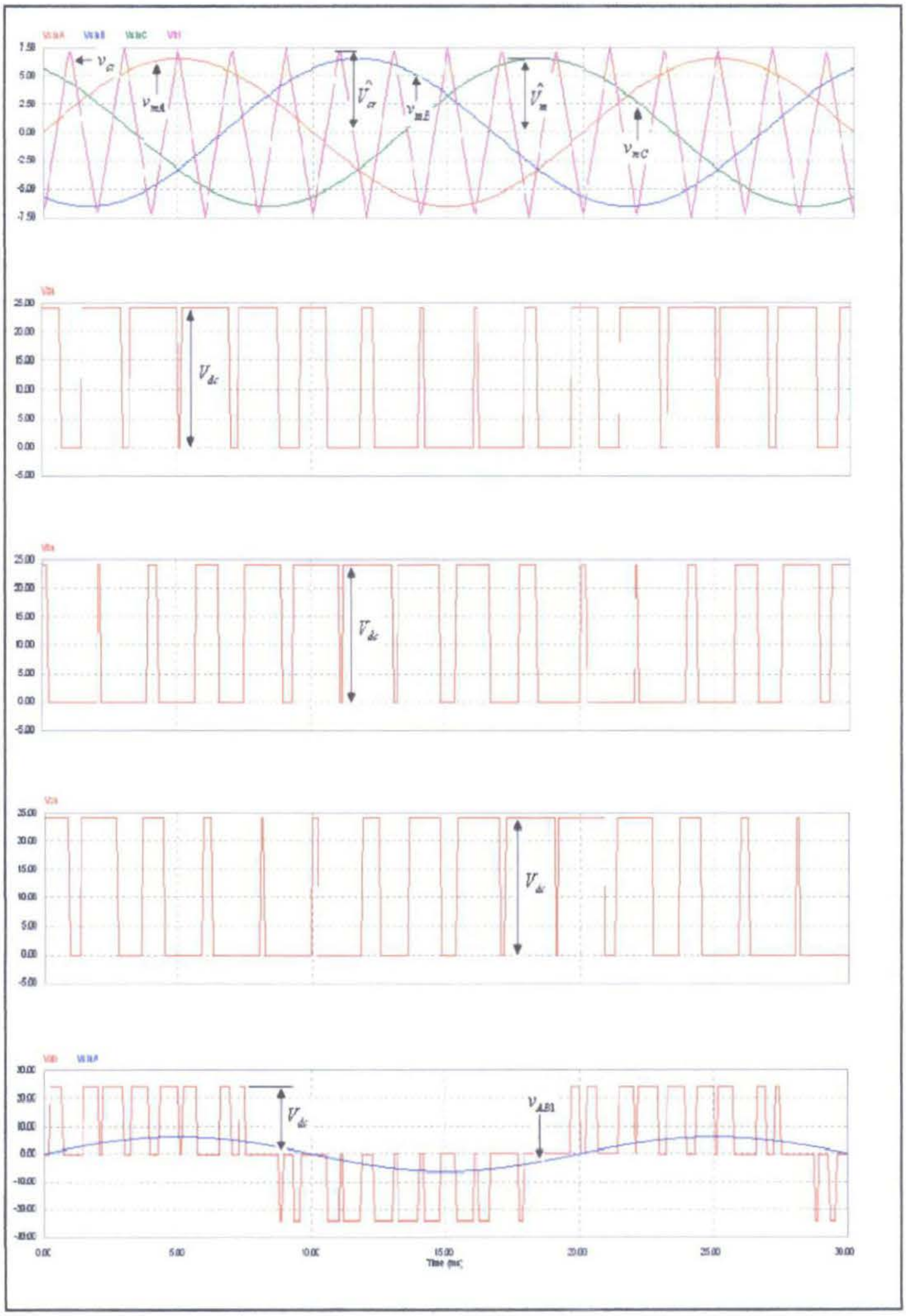


**Figure 24:** Sinusoidal Pulse Width Modulation signal

### 3.8 PI controller

For the control system part, a Proportional Integration (PI) controller was used to regulate the error between the supply voltage (measured) to the reference voltage as shown in Figure 25. The reason PI controller being chosen is because the function of the proportional itself will respond quickly toward the changes of error occurs. The integration function is used to remove the offsets of the reference of steady state with the input. Before DVR start to inject the voltage to the system, the timed consideration is allowed for the synchronization process. The synchronization process was made according to the possible system frequency deviation. The system is not much deviated from 50 Hz frequency. Hence, it will help the load voltage without phase jumps.

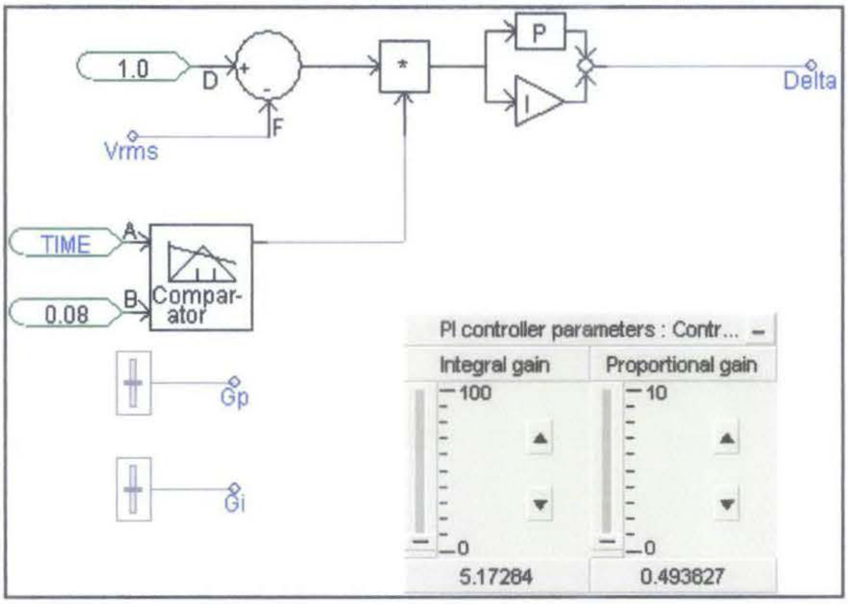
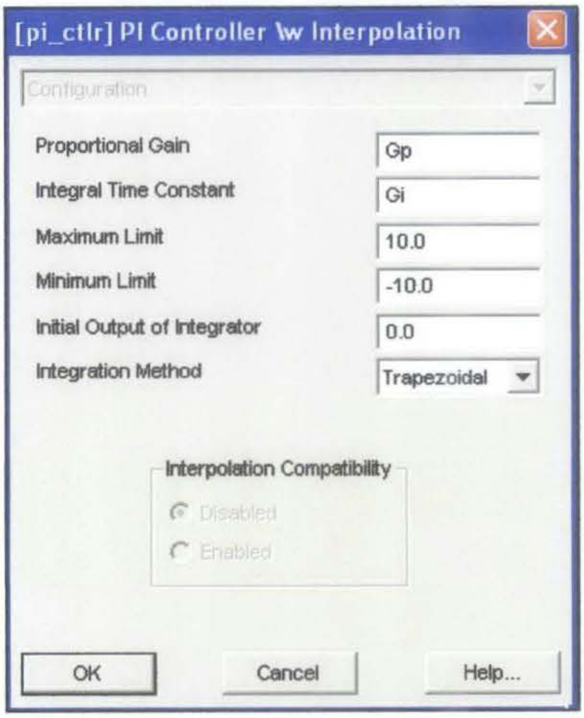


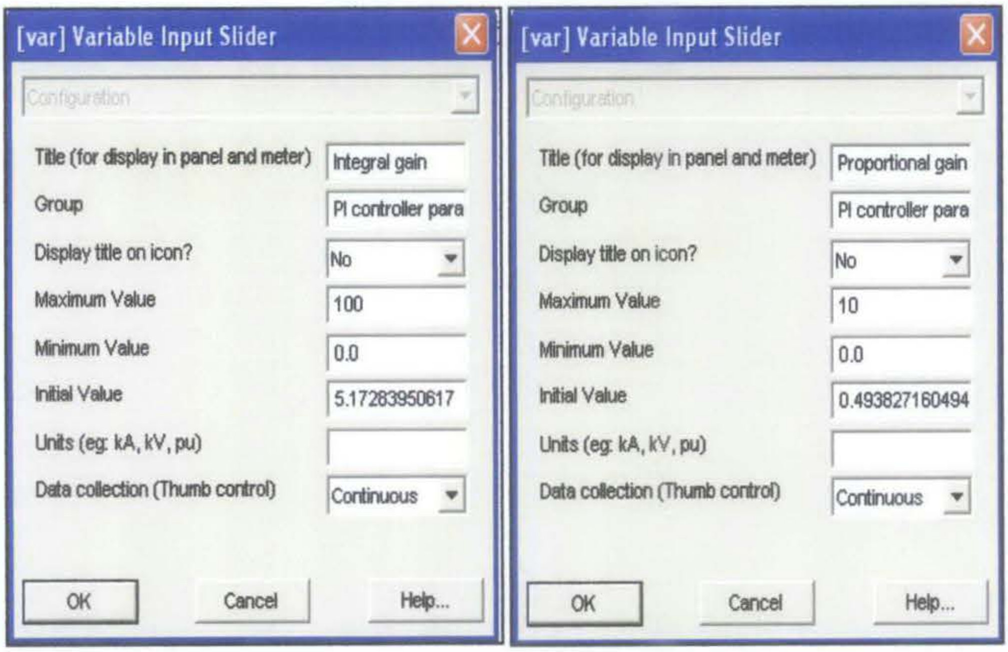

**Figure 25**: PI controller block diagram

### 3.8.1 Tuning the PI controller

Figure 26 show the interface to key in the parameter for the PI controller.



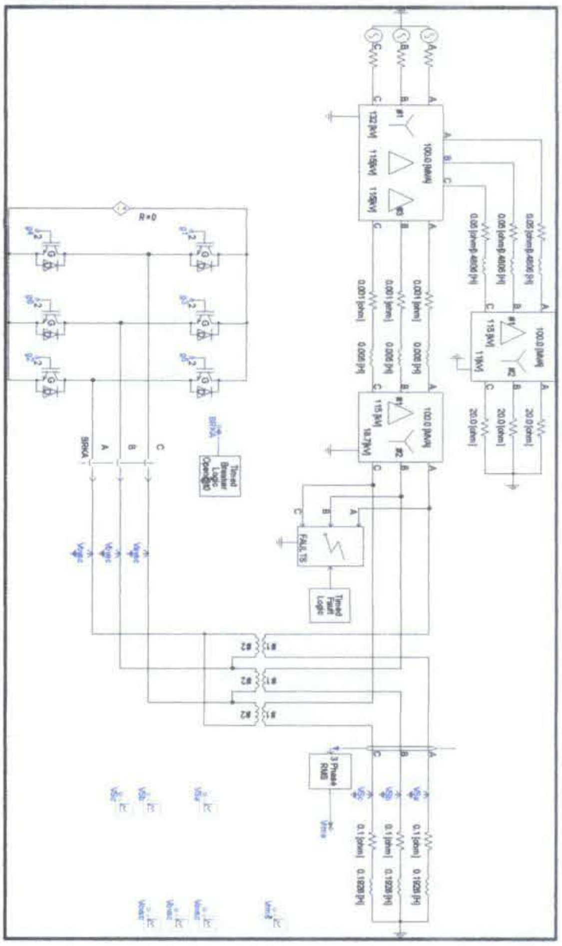

(a)



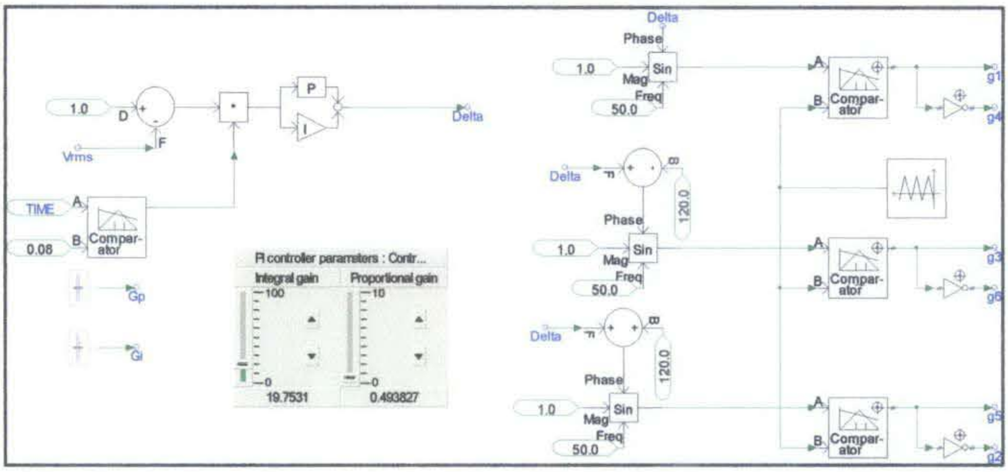

(b)

**Figure 26:** Defining the PI controller parameter

The PSCAD simulation diagram of the proposed distribution network together with the DVR and with control circuit is presented in Figure 27.



(a)




(b)

**Figure 27:** Complete power system network with DVR

# CHAPTER 4

# RESULTS AND DISCUSSIONS

The simulation is carried out and the results are analyzed for different voltage dip and fault condition.

Different voltage dip conditions

(i) No fault
(ii) Single line to ground fault without DVR
(iii) Double line to ground fault without DVR
(iv) Three phase to ground fault without DVR
(v) Injection voltage with DVR
(vi) Single line to ground fault with DVR
(vii) Double line to ground fault with DVR
(viii) Three phase to ground fault with DVR

Besides that, the graph of the output voltage VSC will shows as one of the DVR part to generate 3-phase signals from dc to ac voltage. Also the injection transformer graph will shows to see the changes before and after voltage dip occurs.

PSCAD simulation diagram of the proposed PWM is presented in Figure 28. The signal (here the red, yellow and blue) is compared with the triangular waveform (green) to generate ac waveform. Figure 29 shows the ac signal. Each of the signal is 120 degree a part each others.

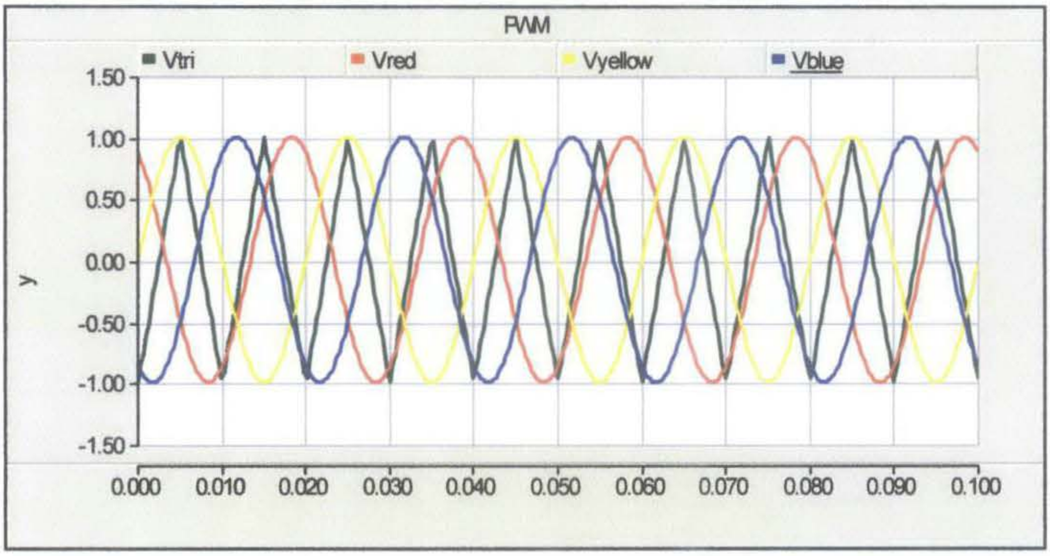



**Figure 28:** Pulse Width Modulation

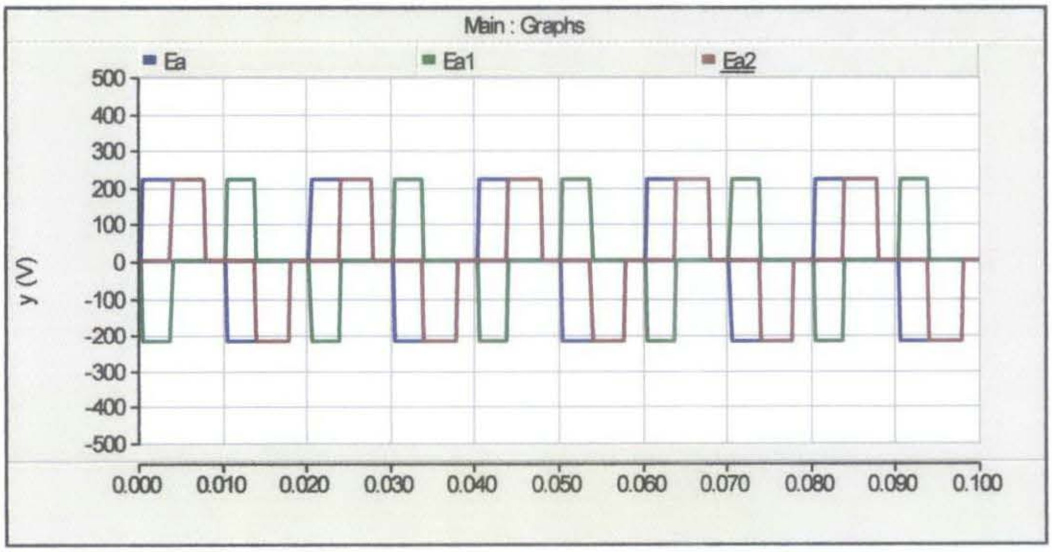



**Figure 29:** Switching signals for inverter leg

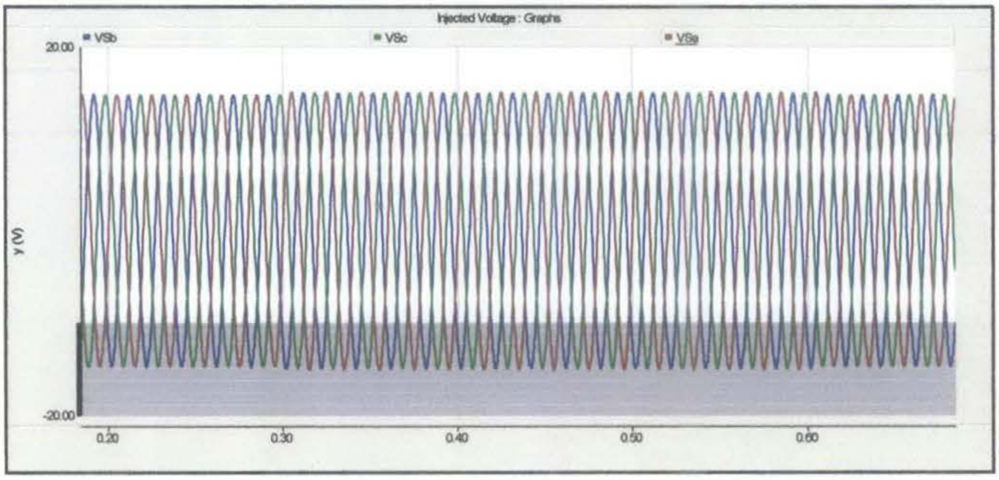
## 4.1 Result

**Case 1 : No fault**

This section shows the simulation and results when no fault occurred at the system.

Voltage dip created at t = 0 s

Figure 30 shows the injected voltage and load voltage during normal condition.



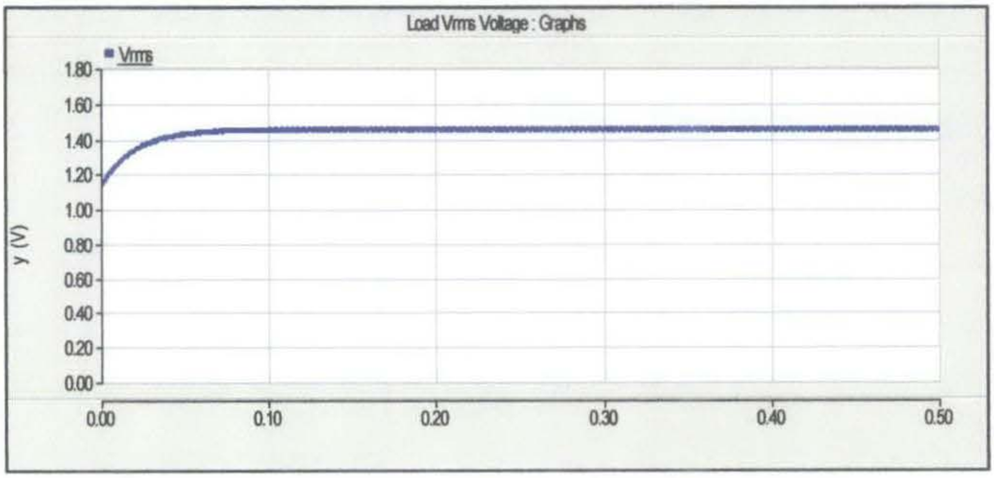




**Figure 30:** Three phase and load voltage at normal condition

**Case 2: Single phase to ground fault without DVR**

This section shows the simulation and results when single phase fault occurred at the system.

Voltage dip created at t = 0.3 - 0.6 s

Figure 31 shows the red voltage phase drop during the voltage dip. Figure 32 shows the load voltage drop during the voltage dip.

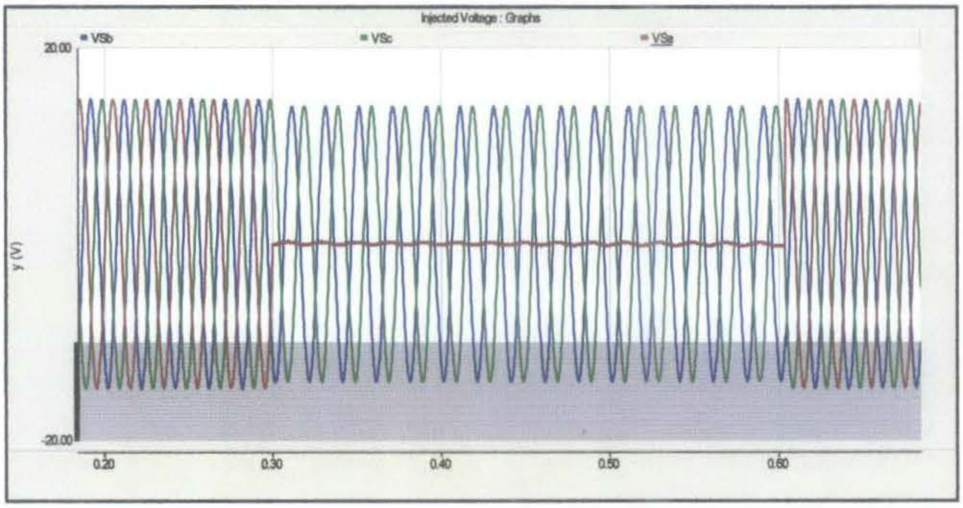



**Figure 31:** 3 phase voltages with single phase fault without DVR

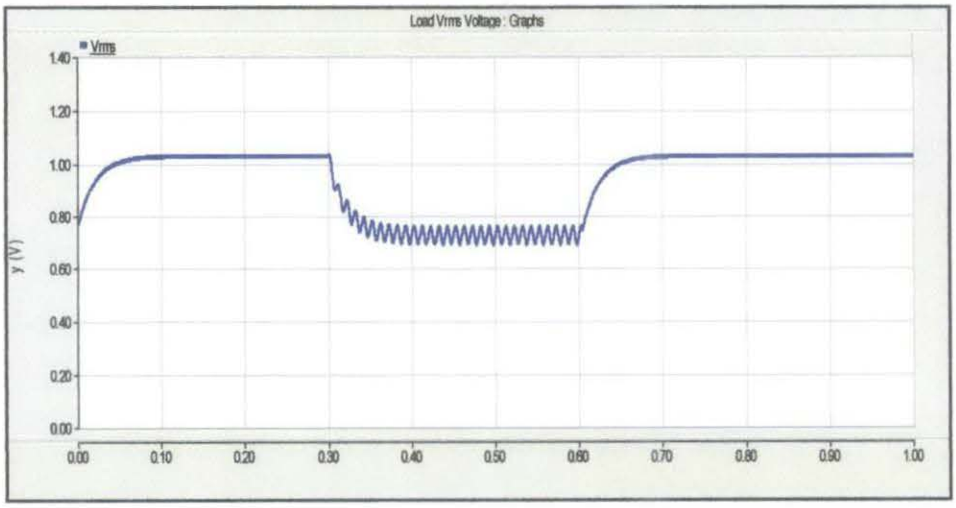



**Figure 32:** Voltage at load side without DVR

**Case 3 : Double phase to ground fault without DVR**

This section shows the simulations and results when double phase fault occurred at the system.

Voltage dip created at t = 0.3 - 0.6 s

Figure 33 shows the blue and green voltage phase drop from 9.0 p.u to 3.0 p.u during the voltage dip. Figure 34 shows the load voltage drop from 0.9 p.u to 0.6 p.u during the voltage dip.

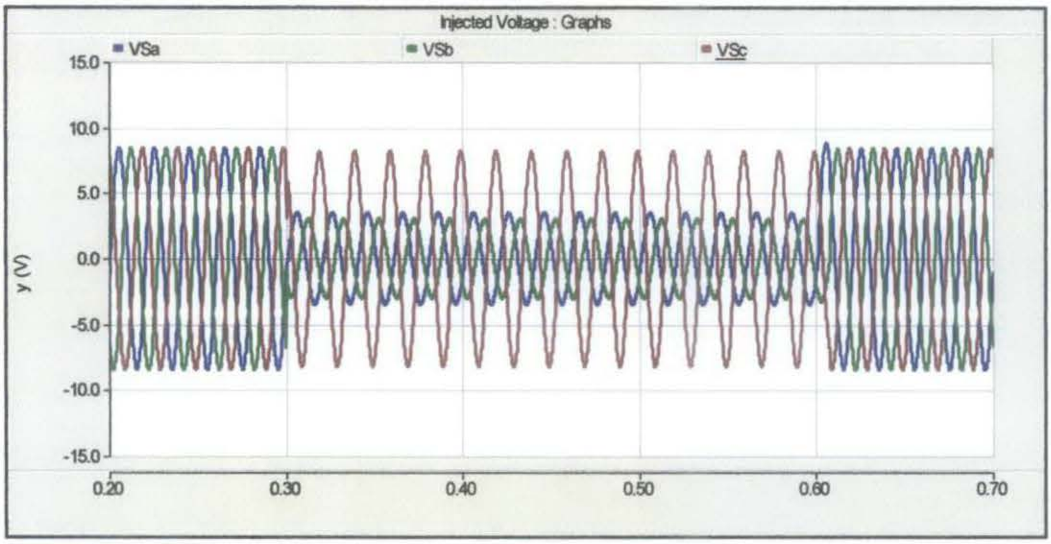



**Figure 33:** 3 phases voltage at double phase fault without DVR

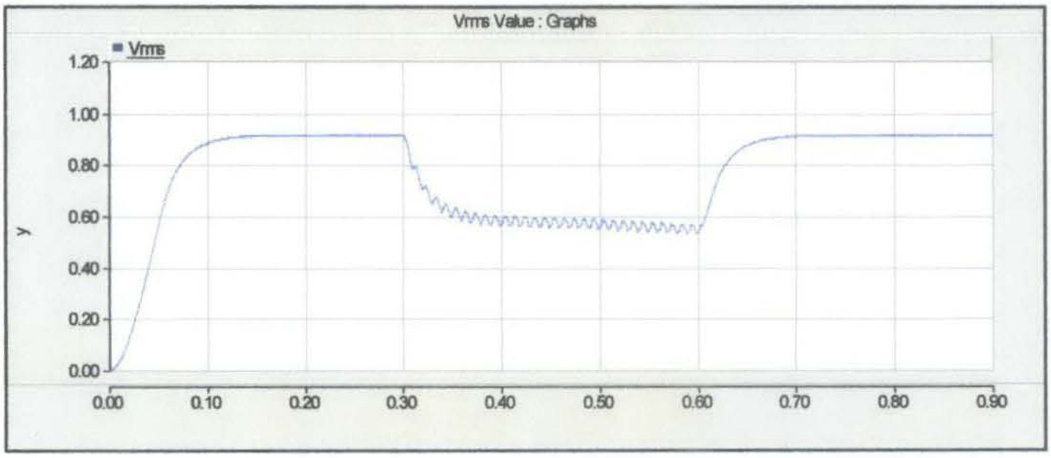



**Figure 34:** Voltage at load side without DVR

**Case 4 : Three phase to ground fault without DVR**

This section shows the simulations and results when three phase fault occurred at the system.

Voltage dip created at t = 0.3 - 0.6 s

Figure 35 shows all voltage phase drop from 9.0 p.u to 3.0 p.u during the voltage dip. Figure 36 shows the load voltage drop from 0.9 p.u to 0.15 p.u during the voltage dip.

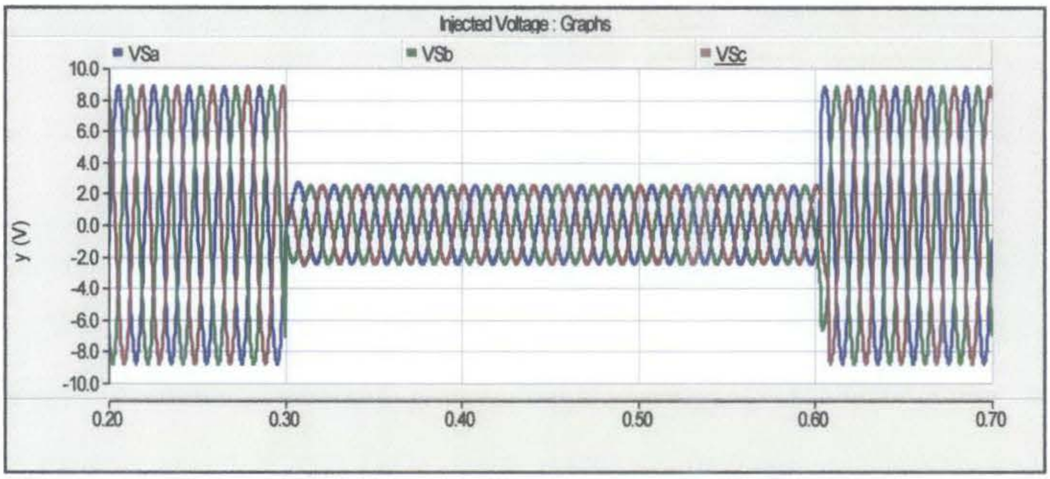



**Figure 35:** 3 phases voltage at three phase fault without DVR

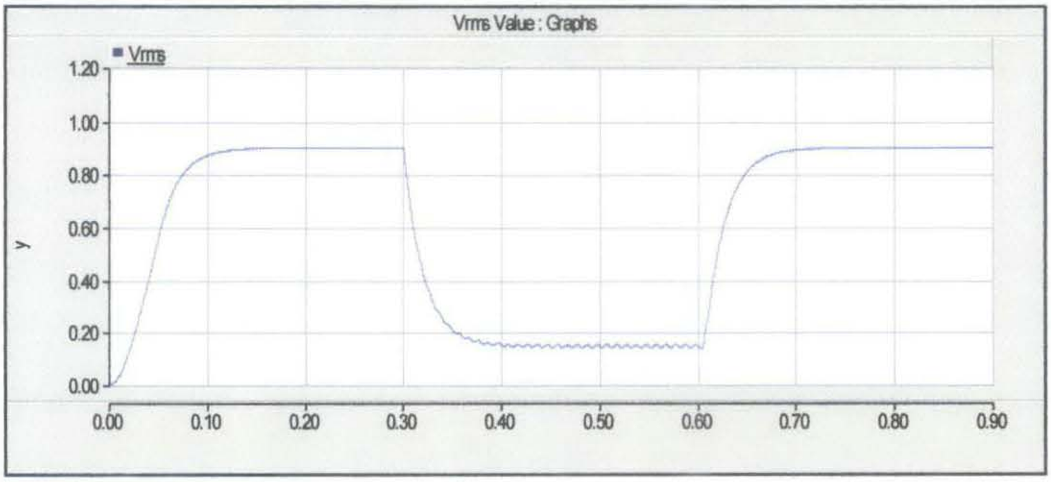



**Figure 36:** Voltage at load side without DVR

**Case 5 : Injected voltage with DVR**

This section shows the simulations and results when fault occurred at the system.

Voltage dip created at t = 0.3 - 0.6 s

Figure 37 shows the injection voltage from DVR system during the fault occurred.

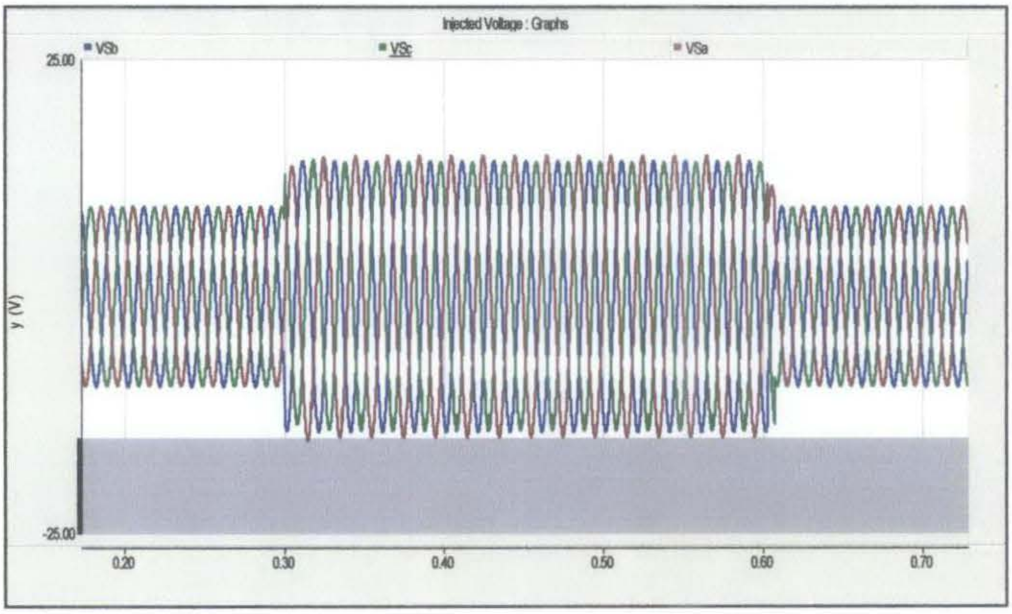



**Figure 37:** 3 phase injected voltage with DVR

**Case 6 : Single phase to ground fault with DVR**

This section shows the simulations and results improvement of load voltage when single phase to ground fault occurred at the system.

Voltage dip created at t = 0.3 - 0.6 s

Figure 38 shows the improvement of load voltage when DVR connected to the system.

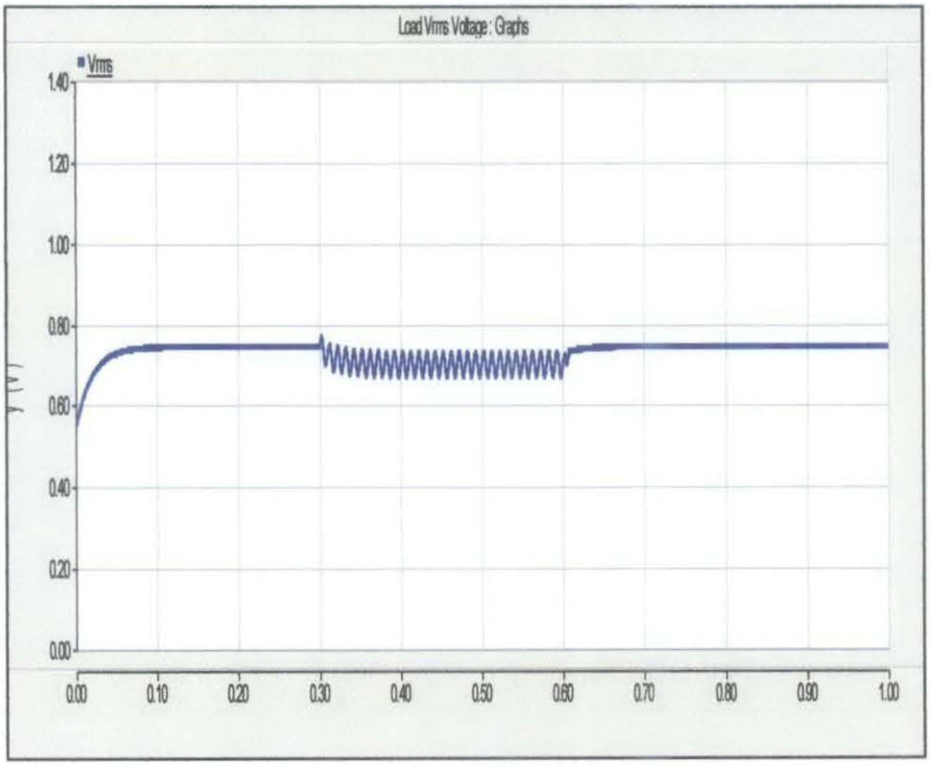



**Figure 38:** Voltage at load side with DVR for single phase fault

**Case 7 : Double phase to ground fault with DVR**

This section shows the simulations and results improvement of load voltage when double phase to ground fault occurred at the system.

Voltage dip created at t = 0.3 - 0.6 s

Figure 39 shows the improvement of load voltage from 0.15 p.u up to 0.9 p.u when DVR connected to the system.

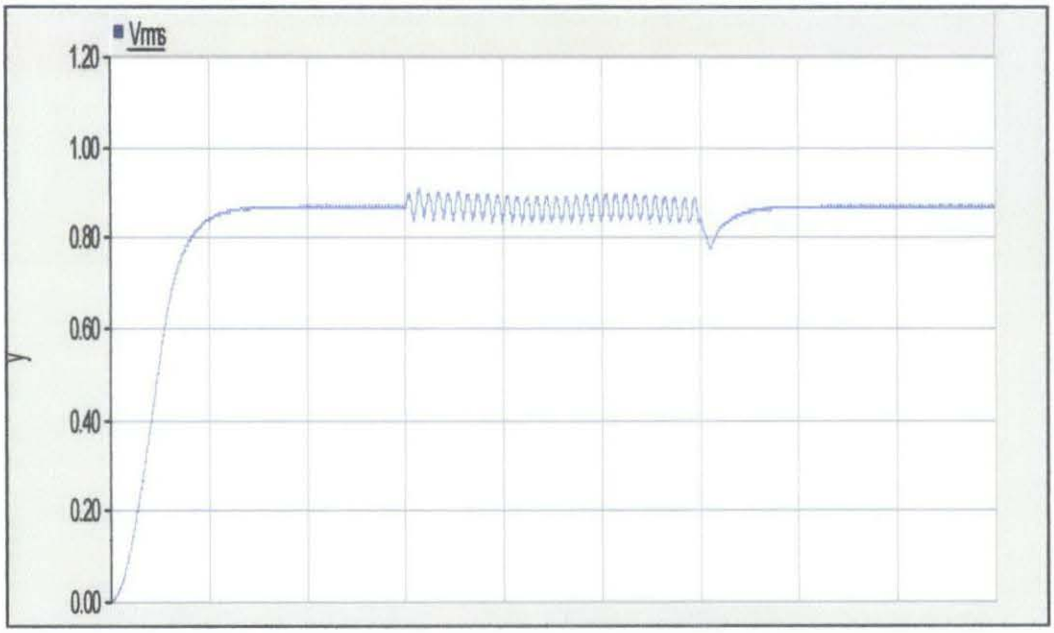



**Figure 39:** Voltage at load side with DVR for double phase fault

**Case 8 : Three phase to ground fault with DVR**

This section shows the simulations and results improvement of load voltage when three phase to ground fault occurred at the system.

Voltage dip created at t = 0.3 - 0.6 s

Figure 40 shows the improvement of load voltage from 0.6 p.u up to 0.9 p.u when DVR connected to the system.

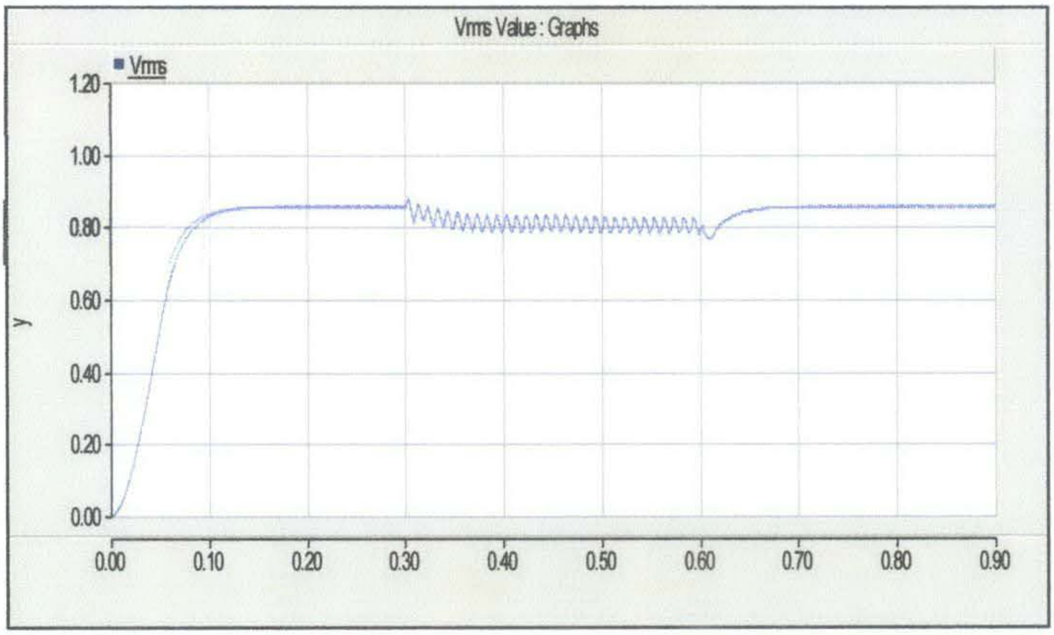



**Figure 40:** Voltage at load side with DVR three phase fault

# CHAPTER 5
# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

Voltage dips are most common problems faced by the consumer. Many industries face the problem of voltage dips problem leading to loss in production cost. The common solution for this problem is to use full UPS system but it is more costly.

This project describes a solution to the voltage dip problem and the compensation technique using custom power electronic device DVR which was designed by using PSCAD software. The design and also the application of DVR for voltage dip and the simulation results for different fault were presented. A PWM based control scheme was implemented to generated 3-phases signal and this PWM scheme only require voltage measurement. To control the voltage, PI controller has been developed to control the voltage automatically. It uses a closed loop control system to detect the phase difference and magnitude error between the voltage during and before the voltage dip. In addition to mitigation of voltage dip, the simulation result indicates that DVR provides additional benefit of output voltage improvement. The DVR injects appropriate voltage component to correct rapidly any voltage dip to keep the load voltage balanced and constant at the nominal value. The efficiency and effectiveness in voltage dip compensation is demonstrated by the simulation results ensuring high quality in power supply.

## 5.2 Recommendation

In order to verify the simulation results, understanding the behavior of the Dynamic Voltage Restorer is important to mitigate the voltage dips by selecting the right configuration of DVR. This project mainly concentrated on about mitigation of the output voltage whereas the other power quality issues are not taken into account. So in future work, voltage and current harmonics also need to be considered as one of the power quality issues and DVR is to be designed to mitigate the voltage and current harmonics.

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