



# MITIGATION OF POWER QUALITY DISTURBANCES

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## ABSTRACT

Power Quality is a major concern of our modern industries and other consumers. Poor quality of supply will affect the performance of customer equipment such as computers, microprocessors adjustable speed drives, power electronic devices, life saving equipment in hospitals, etc. and result in heavy financial losses to customers due to loss of production or breakdown in industries or loss of life in a hospital. The two major power quality disturbances are voltage sag and harmonic distortion. In the event of voltage sag, due to insufficient energy, equipments may malfunction or trip. Harmonics introduced by nonlinear loads can pollute the input supply to the sensitive equipments and cause the connected equipments to malfunction. In this work, a Power Quality Provider (QPP) is proposed and modeled by simulation.. The QPP has a novel feature of performing dual functions of mitigation of sag and suppression of harmonics quickly, dynamically and simultaneously using a simple unique and novel control scheme. The QPP will be connected close the sensitive loads which are to be protected in the distribution network. For a case study the hospital distribution network which supplies many life saving equipments such as MRI, CTSCAN, computerized surgery equipment, etc. at Ipoh, Malaysia was chosen to conduct experiments. Experimental results prove the credibility of QPP in mitigating power quality disturbances effectively, such that the voltage at the sensitive loads are at the rated value and sinusoidal. The design, modeling and simulation are done using PSS/ADEPT and PSCAD software.

**Keywords:** Voltage Sag, Harmonics, PWM, VSI, Injection Transformer, QPP, Modulation, Power, Quality

## 1. INTRODUCTION

Electrical fault in a distribution network is almost impossible to avoid. Main causes for power quality disturbances may be due to insulation failure, tree falling, birds contact, lightning or a fault on an adjacent feeder. These disturbances may be in the form of voltage sag, swells, voltage imbalances, transients, interruptions and harmonics which can cause problems to the industries ranging from malfunctioning of equipments to complete plant shutdowns. Such disturbances occurring on high voltage end in distribution feeder will propagate downstream to the low voltage ends where sensitive loads are connected [1][2]. Out of these disturbances, voltage sag and harmonics are considered as the

major problems which can cause malfunctioning or tripping of equipment. A voltage sag condition implies that the voltage on one or more phases drops below the specified tolerance for a short period of time as shown in Figure 1.

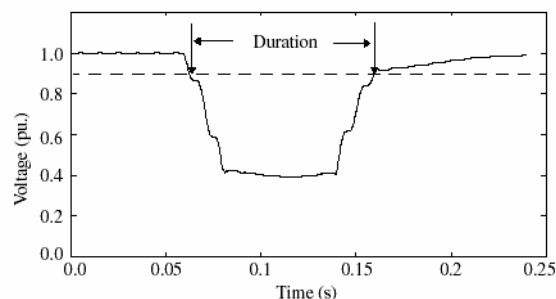


Figure 1: Voltage sag



Much research has been performed in an effort to solve power quality problems [3]. Many voltage mitigation schemes are based on inverter systems consisting of energy storage and power switches. Large energy storage is required when it is necessary to supply real power [4][5].

The costs related to power outages at commercial centre like financial institutions, customer service centre, manufacturing plants and other services will be tremendous. The adverse effect of voltage sag will lead to lot of financial impact on customers. It is estimated that voltage sag problem costs about USD150 billion in United States and thousands of billions all over the world every year.

Power electronic loads such as switch-mode power supply, adjustable speed drives, rectifiers, inverters, etc will inject current and voltage harmonics into the distribution network. Harmonics does not do any useful work and is a waste energy and downgrades the quality of supply in a system. Harmonics will reduce the power factor and, if seriously enough, it will destroy apparatus like ac motor in the system. The IEEE standard 519-1992 clearly defines the acceptable harmonic levels in the power systems. To achieve this standard, two types of filtering methods can be used; passive and active filters [6].

## 2. METHODOLOGY

The methodology undertaken is to investigate how power quality disturbances affect certain sensitive equipment in industries, commercial centres, major hospitals, etc.

The objective is to design a device which will perform dual functions of mitigation of voltage sag and suppression of harmonics dynamically and simultaneously. The device proposed is named as Quality Power Provider (QPP) which possesses certain features of the Dynamic Voltage Restorer (DVR). QPP is designed to perform the above dual functions with low power and energy ratings compared to an Uninterrupted Power Supply (UPS) or shunt connected Static Compensator (STATCOM). The QPP is a series conditioner based on pulse width modulated voltage source inverter (PWM-VSI) which is capable of generating or absorbing real and reactive power independently at its ac output terminals. It can inject an ac voltage in phase and

magnitude to compensate the sag in each of the three phases in series and in synchronism with the upstream voltages in the distribution system.

The designed model of QPP is a simulated device for the study of mitigation capability of sag caused by different types of faults such as line to ground and/or line to line faults which causes voltage sag. The design and configuration of QPP will vary depending upon the types of loads connected, maximum load power, and power factor. The load will affect the current rating of the VSI, injection transformer and the energy storage. Maximum depth and duration of voltage sag to be corrected must be known. The maximum depth of voltage sag will depend on the fault clearing time (FCT) and has a bearing on the voltage rating of VSI and injection transformer based on the amount of energy to be delivered.

Data collection and monitoring on voltage disturbances were carried using power recorders at many industrial sites in Malaysia. Hitachi company (manufacturing TV yokes) and Nihoncanpack Company (manufacturing various tin-cans), Filrex Company (manufacturing surgery and other gloves), and Ipoh Hospital possessing many life saving equipment are few of them where power quality disturbances are severe. Power quality measurements were done at these places. For a case study, the 132/11KV distribution network at Ipoh Hospital was selected and the voltage sag and harmonic disturbances at different nodes of the network for different fault conditions were studied. The reason for selecting the hospital network is the power quality disturbances seriously affected the performance of many life saving equipment at ICU, MRI, computer aided surgery system, CT SCAN, etc.

To model the power system components and simulate the different type of faults causing voltage sag and harmonics, PSS/ADEPT and PSCAD software are used and the voltage severity is studied by introducing faults on selected nodes. The simulation results are analyzed and compared with the relevant standards for evaluating the quality of output. Actual physical sag measurements are taken using power recorders at the site and compared with the simulated results.

Simulation of harmonics is done by connecting a nonlinear load (3-phase rectifier) causing harmonics current flow which across the system impedance will result in voltage harmonic distortion. In this work, an Active Power Filter

(APF) connected in series with the Voltage Source Inverter (VSI) and the step up injection transformer is used for controlling the harmonic levels [7]. The series active power filter will inject the right amount of harmonic voltages, in series and in phase, so that the voltage at the sensitive load is sinusoidal. Voltage regulation and harmonic cancellation is possible with the use of series connected VSI. The harmonic control circuit is a part of QPP.

**3. Modeling and simulation of hospital network**

The simulated model of the detailed 132/11KV JAWA distribution network modeled using PSS/ADEPT. The complete model of JAWA network is given in Figure 1 Appendix A. The segment of above network that supplies Ipoh hospital 11KV switching station is shown in Figure 2.

The PSS/ADEPT software was used to study the load flow and voltage sag magnitudes at various nodes under fault conditions. Four types of faults, namely, Single Line to Ground Fault (SLGF), Line to Line Fault (LLF), Double Line to Ground Fault (DLGF) and 3 Line to Ground Fault (3LGF) were created at Node JawaT2 (Appendix A) and voltages were measured.

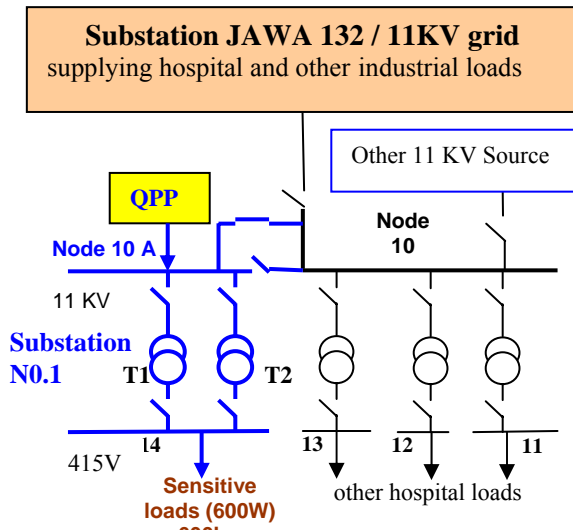


Figure 2: Hospital 11KV Switching Station

For a sample, the measured voltages at different nodes for LGF, LLF and DLGF are given in Tables 1, 2, and 3 respectively in Appendix B. It may be noticed that at Node 14 where sensitive loads are connected, the voltage sags are considerably high resulting in malfunctioning of the life saving equipment.

**A. Modeling and simulation of QPP**

The proposed QPP is connected at Node 10A which supplies the sensitive loads. The QPP is designed such that, it can mitigate the voltage sag and suppress the harmonics simultaneously restoring the voltage and frequency at the rated values. Figure 3 shows the simulated component modules of QPP.

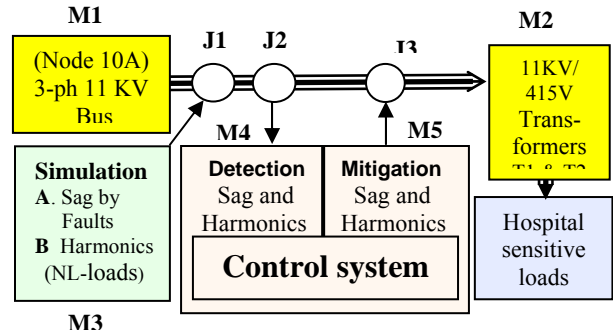


Figure 3: Component modules of QPP

Power module M1 represents the 3-phase 11KV source (Node 10A) connected to M2 which is the substation No.1 supplying power to sensitive loads (600W) of the hospital via two 11/0.415KV transformers, T1 and T2. In module M3(A) line faults are simulated and sag is created at junction J1. Module M3(B) generates harmonics at J1 by simulated three-phase uncontrolled rectifier used as the nonlinear load. Detection module M4 has the control system which measures the sag and harmonics detected at junction J2 and then feeds into the mitigation module M5. The distorted waveform due to sag and harmonic will be compared in M5, with the desired ideal wave generated by a sine wave generator synchronized with the system using the phase locked loop (PLL). The error signal will become the input voltage reference to the Pulse Width Modulator-Voltage Source Inverter (PWM-VSI).

**B. Sag detection and mitigation.**

The control scheme flow chart is shown in Figure 4. The dqo transformation or Park's transformation is used.

The dqo method gives the sag depth and phase shift information with start and end times [8][9]. In the balanced condition d is equal to system voltage and q is zero. Any variations in the input source voltage will change the values of d. The value of d is the reference voltage. The three-phase input ac voltages are converted into  $\alpha$ - $\beta$  voltages as shown in Figure 5 and then to d-q voltages [10] as shown in Figure 6. In Figure 5

the  $\alpha$ - $\beta$  voltage vector will be rotating at the angular speed  $\omega$  with the three-phase source voltage vectors  $V_a, V_b, V_c$ .

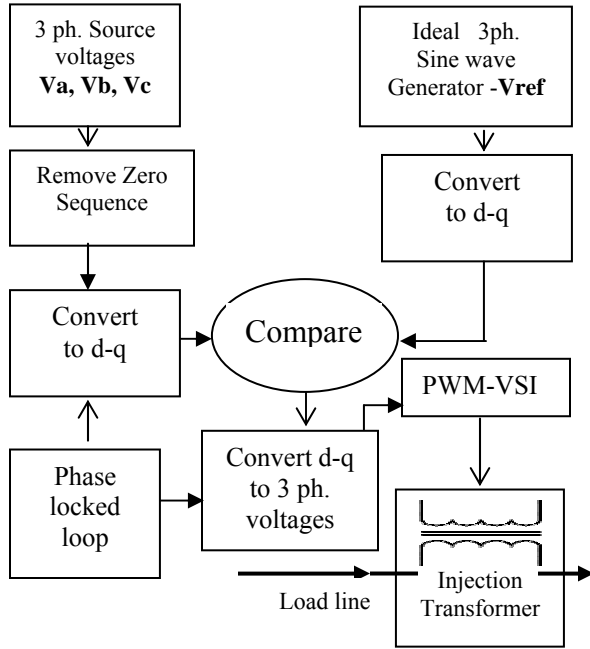


Figure 4: QPP Control Scheme Flow chart

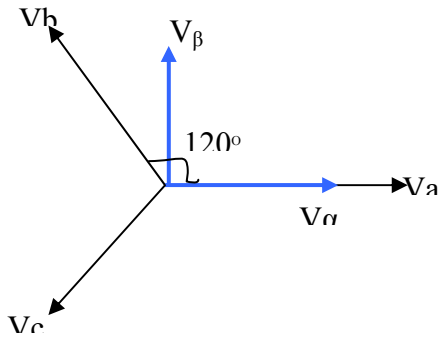


Figure 5: Three-phase source and  $\alpha$ - $\beta$  voltages

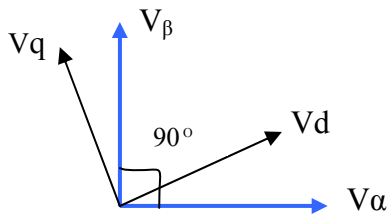


Figure 6: Space vector in the rotating plane

The transformation of  $\alpha$ - $\beta$  and d-q is by using

equation (1) and (2).

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (2)$$

where  $V_a, V_b,$  and  $V_c$  are the source phase voltages,  $V_\alpha$  and  $V_\beta$  are  $\alpha$ - $\beta$  components and  $V_d$  and  $V_q$  are d-q components.

The difference between the ideal sine-wave voltage  $V_{ref}$  and the distorted source voltage will produce the control voltage which determines the amount of sag compensation needed. The sinusoidal control voltage is compared with a high frequency triangular waveform generated by the triangular waveform generator to produce the gate switching pulses. These switching pulses will control the voltage source inverter to produce the output voltage which is injected to the supply via the step up injection transformer.

### C. Harmonic detection and compensation

The sinusoidal waveform generated by the sine wave generator is compared with harmonic distorted load voltage and synchronized with the PLL. As the series filter works as a fundamental sinusoidal current source, it automatically generates a harmonic voltage equal to the harmonic voltage drop. The voltage drop will be modulated with the triangular wave of high frequency that will generate the firing pulse to be used for the VSI switching operation which will produce the pulse output ac voltage. The pulse output voltage is filtered with low pass filter to remove the harmonics caused by the switching valves of VSI. The filtered voltage will be injected into the supply lines through the injection transformer [11][12].

### D. Rating of QPP

The maximum demand of sensitive loads at node 14 is 600KW and 142KVAR. The proposed QPP is connected at Node 10A and must have a capacity of 600KW. This is the maximum power to be delivered by the dc energy storage. QPP is a compensator to supply the missing voltage during sag and harmonics. The maximum energy compensation by QPP will not exceed 50% since



most electronic devices will fail to operate below 50%. The maximum capacity of QPP is 600KW (hospital sensitive load) for a duration period not exceeding 500ms [13]. Thus, the QPP need be rated for 300KW. Figure 7 in Appendix C shows the control and power modules of QPP.

#### 4. SIMULATIONS AND RESULTS

In the simulation, a 11KV three-phase supply was used, and the load was connected at the 400Volts side. The QPP is design to maintain the voltage at the sensitive load at its rated value and sinusoidal waveform, during sag or harmonics or both at the source side or at the load side.

The following are the various simulation experiments conducted to check the performance of the QPP. Test results for LGF, DLGF and without any disturbances are shown in Appendix D. Experiment was conducted with QPP both in off and on mode, with sag and harmonics load connected. In the entire above test, the QPP is able to maintain the voltage at the load at its rated value and sinusoidal.

The Total Harmonic Distortion (THD) measured without QPP was 13.47 % and with the QPP in operation it drop to 0.47 % well below the IEEE 519 standard as shown in Figure 13 (a) and (b) in Appendix E. The standard states that the individual harmonic distortion and total harmonic distortion (THD) should not exceed 3 % and 5 % respectively.

#### 5. DISCUSSIONS

The various test results are shown in Appendix D and E. When the source supply is distorted with sag and harmonics, the load is the replica of it without the QPP. However, when QPP is in active mode, the voltage at the load is at its rated value and sinusoidal. The QPP has the capacity and capability to mitigate sag as well as harmonics. The total harmonic distortion level (THD) has improved from 13.47 % without QPP to 0.47% with QPP connected.

#### 6. CONCLUSIONS

In this paper, a complete simulated QPP system has been developed by using the PSCAD software. The simulation results have proven the voltage restoring capability of a novel series compensator or QPP which is based on reference voltage tracking control strategy. The QPP is fast and dynamic and is able to perform a dual function simultaneously to restore the load

voltage at its rated value. By proposing QPP in the power system, it is able to improve the power quality.

Sensitive equipments need to have a good quality of power supply to ensure efficient operation without mal-operation. This paper will be beneficial to those who are keen on power quality disturbances in distribution network.

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Appendix A

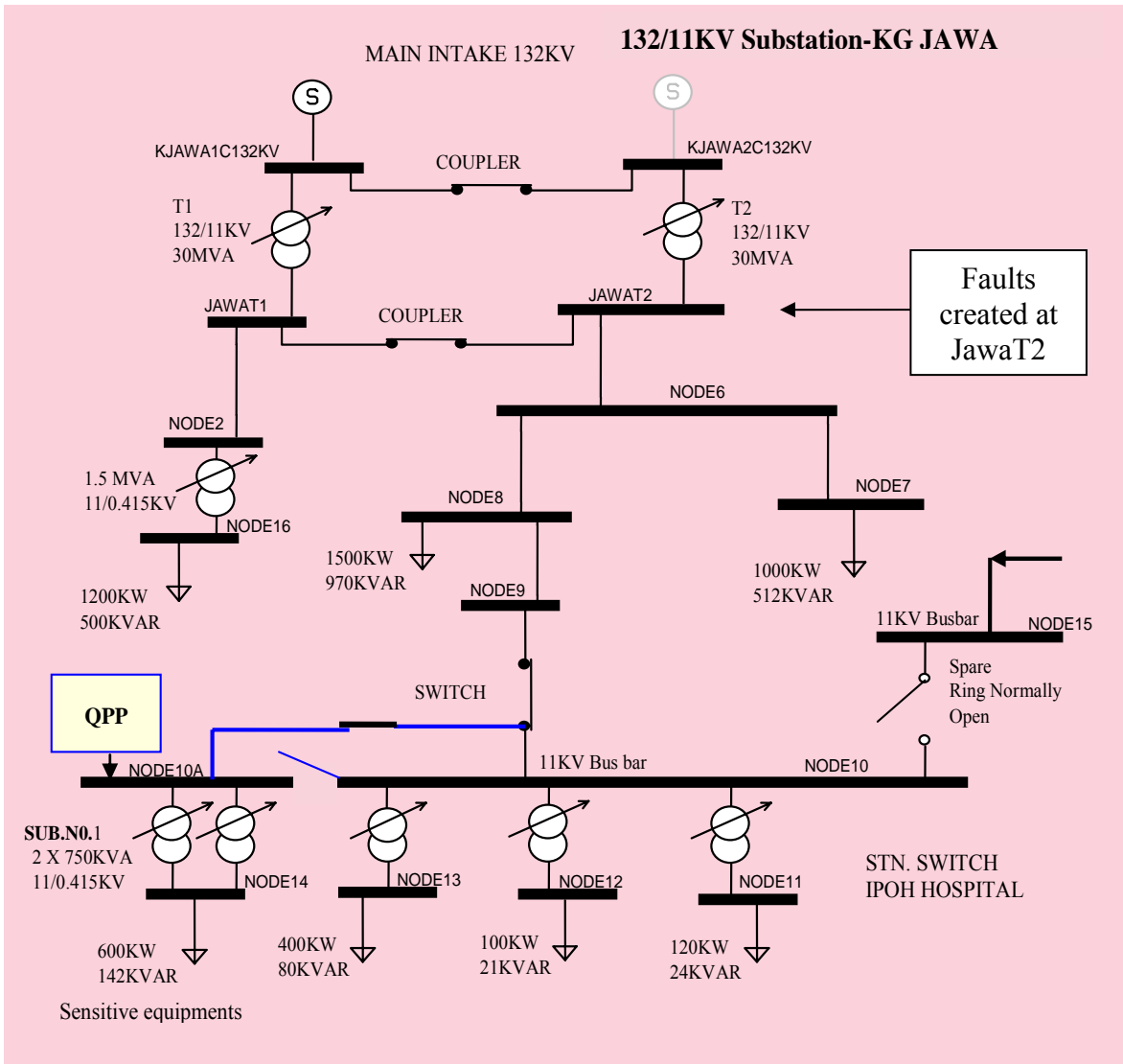


Figure 1: Ipoh Hospital network modeled using PSS/ADEPT



## Appendix B

Table 1.0: Single Line-to-Ground Fault on Phase A created at Node JAWAT2

|         | JawaT2 | Node 6 | Node 7 | Node 8 | Node 9 | Node 10 | Node 10A | Node 11 | Node 12 | Node 13 | Node 14 |
|---------|--------|--------|--------|--------|--------|---------|----------|---------|---------|---------|---------|
| Phase A | 0.0V   | 0.0V   | 0.0V   | 0.0V   | 358V   | 358V    | 358V     | 249V    | 249V    | 249V    | 249V    |
| Phase B | 8287V  | 8065V  | 8065V  | 7982V  | 7959V  | 7959V   | 7959V    | 178V    | 178V    | 178V    | 178V    |
| Phase C | 11594V | 11416V | 11404V | 11326V | 11291V | 11291V  | 11291V   | 241V    | 241V    | 241V    | 241V    |

Table 2.0: Line-to-Line Fault on Phases A &amp; B created at Node JAWAT2

|         | JawaT2 | Node 6 | Node 7 | Node 8 | Node 9 | Node 10A | Node 10 | Node 11 | Node 12 | Node 13 | Node 14 |
|---------|--------|--------|--------|--------|--------|----------|---------|---------|---------|---------|---------|
| Phase A | 3245V  | 3130V  | 3123V  | 3078V  | 3060V  | 3060V    | 3060V   | 209V    | 209V    | 209V    | 209V    |
| Phase B | 3245V  | 3130V  | 3123V  | 3078V  | 3060V  | 3060V    | 3060V   | 0V      | 0V      | 0V      | 0V      |
| Phase C | 6491V  | 6259V  | 6247V  | 6157V  | 6121V  | 6121V    | 6121V   | 209V    | 209V    | 209V    | 209V    |

Table 3.0: Double Line-to-Ground Fault on Phase AB created at Bus JawaT2

|         | JawaT2 | Node 6 | Node 7 | Node 8 | Node 9 | Node 10A | Node 10B | Node 11 | Node 12 | Node 13 | Node 14 |
|---------|--------|--------|--------|--------|--------|----------|----------|---------|---------|---------|---------|
| Phase A | 0V     | 0V     | 0V     | 0V     | 0V     | 0V       | 0V       | 203V    | 203V    | 203V    | 203V    |
| Phase B | 0V     | 0V     | 0V     | 0V     | 0V     | 0V       | 0V       | 0V      | 0V      | 0V      | 0V      |
| Phase C | 9474V  | 9248V  | 9236V  | 9148V  | 9113V  | 9113V    | 9113V    | 203V    | 203V    | 203V    | 203V    |



Appendix C

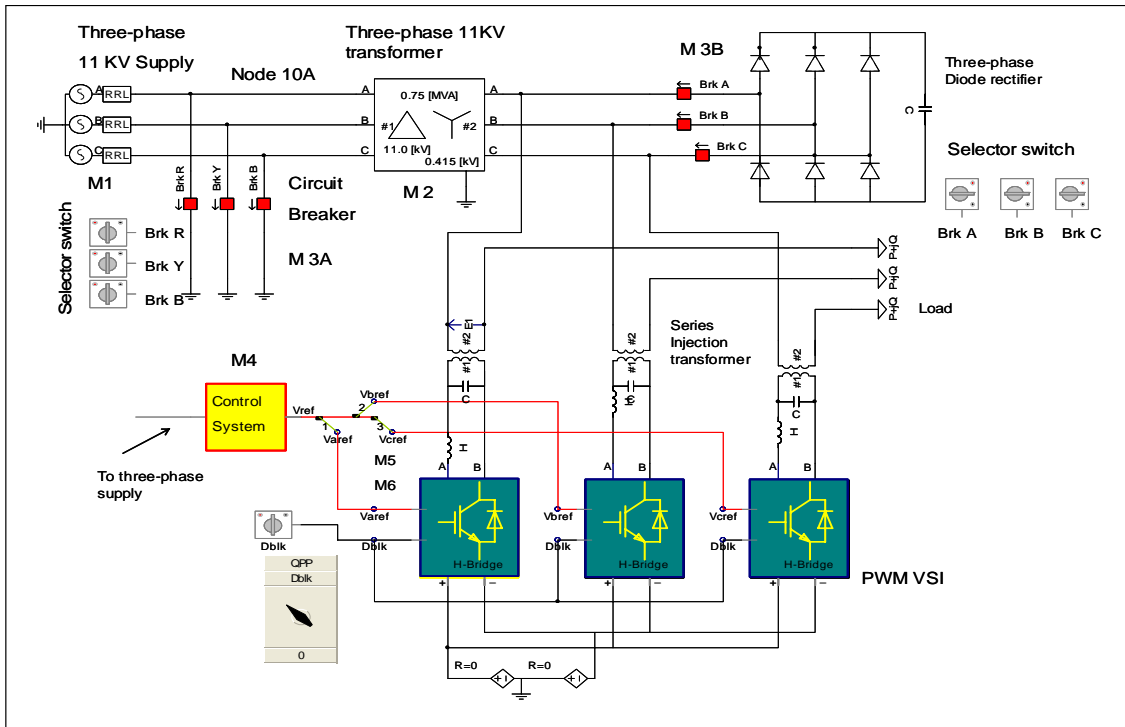


Figure 7: Control and power modules of QPP

Appendix D

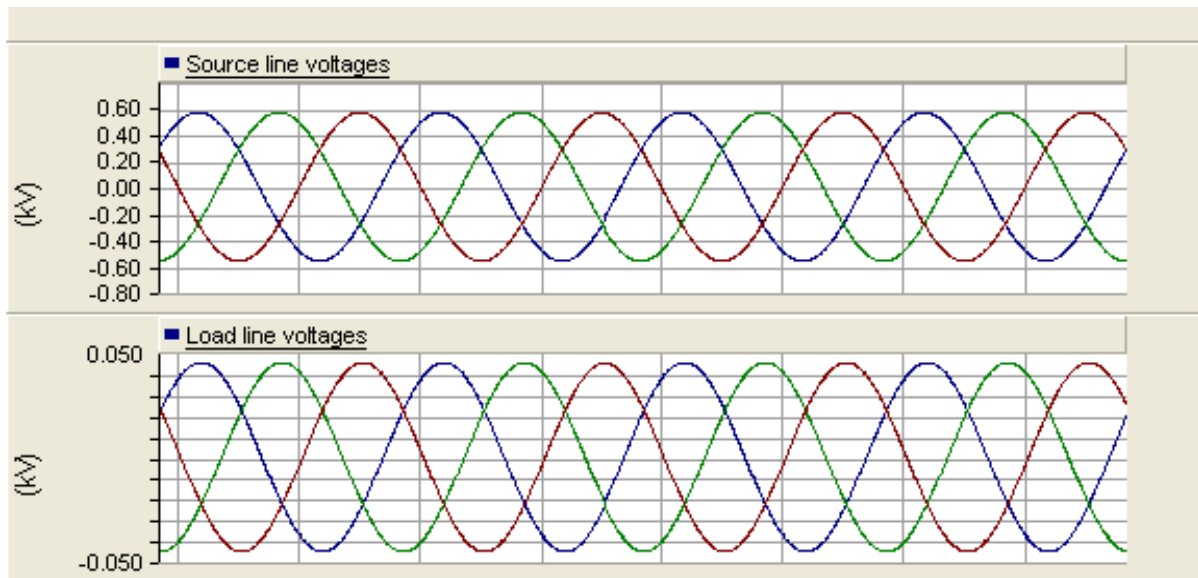


Figure 8: No disturbances in the network system, hence the source line voltage and load line voltage is sinusoidal

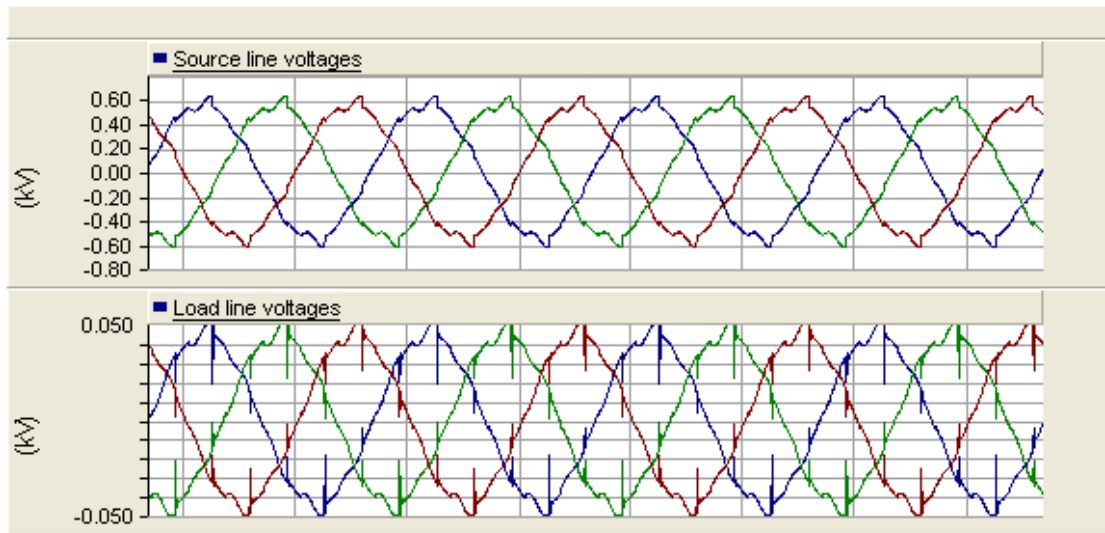


Figure 9: With the nonlinear load connected in both the source and load line voltages are distorted with QPP is OFF

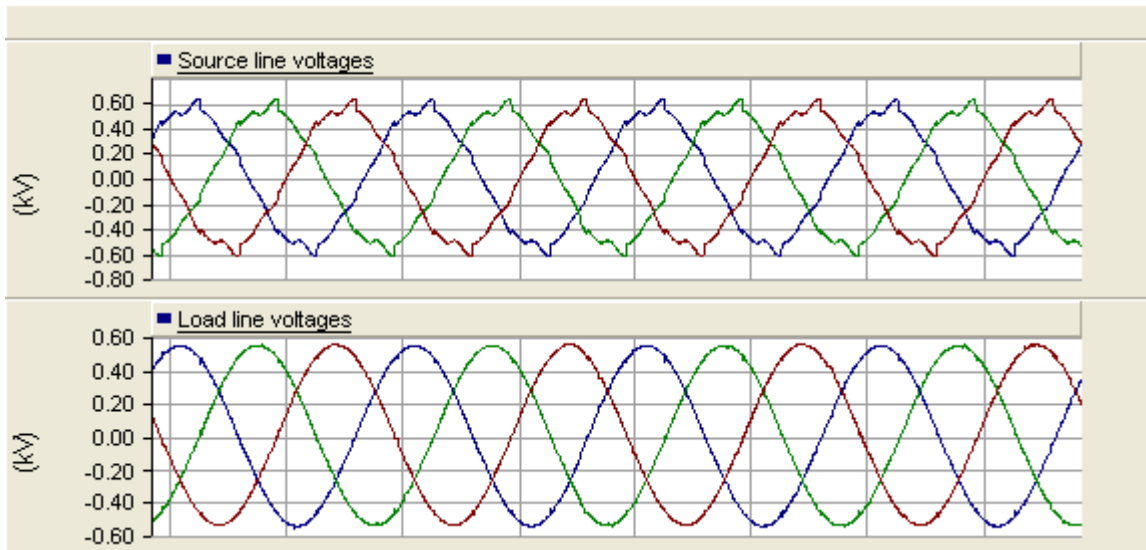


Figure 10: Source line voltage is distorted and load line voltage is sinusoidal with QPP ON

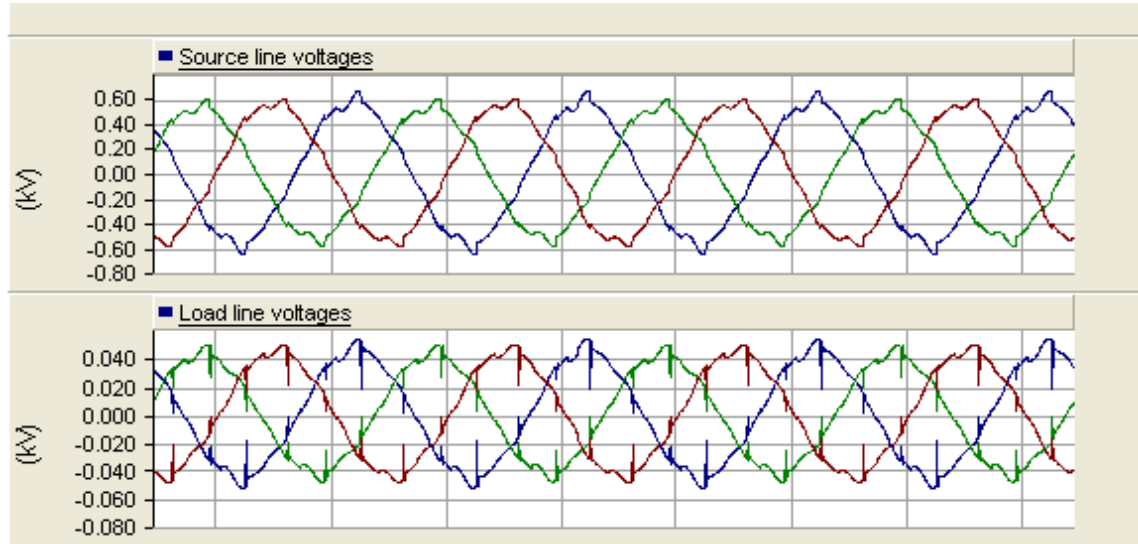


Figure 11: DLGF with harmonics and the source line voltage is distorted and load line voltage is sinusoidal with QPP OFF

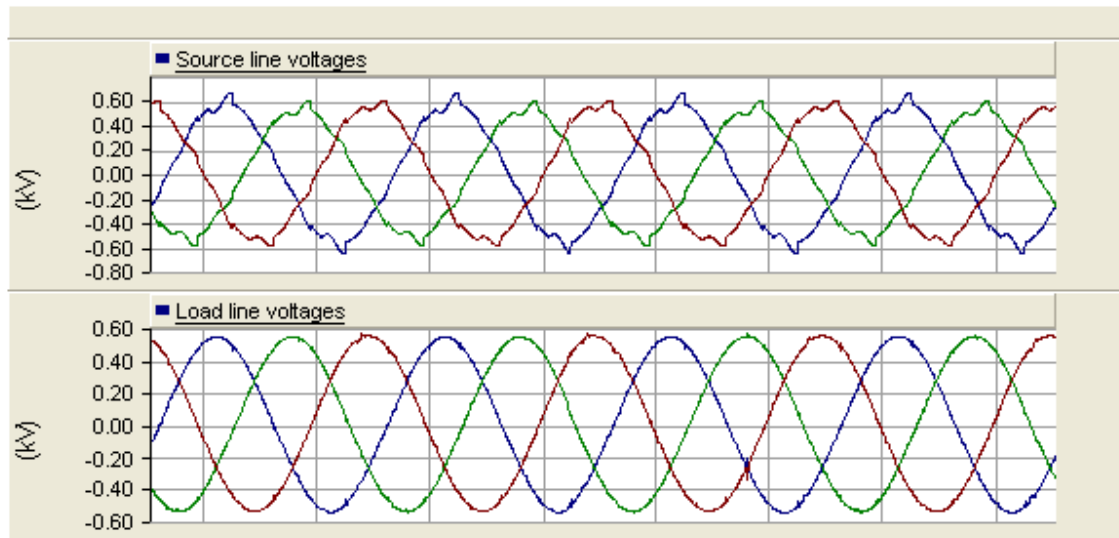
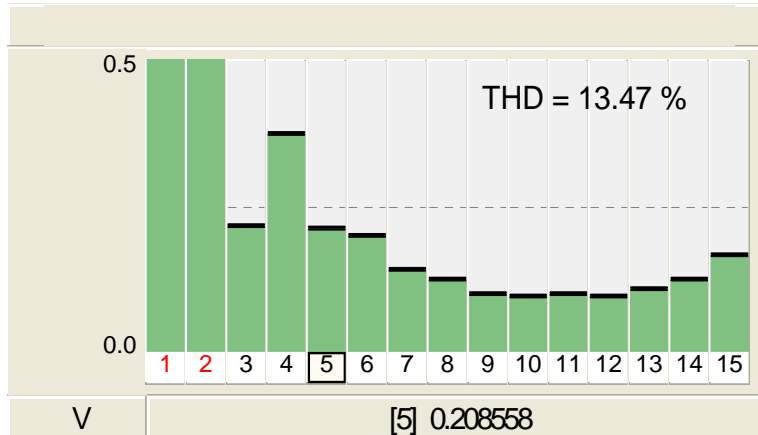
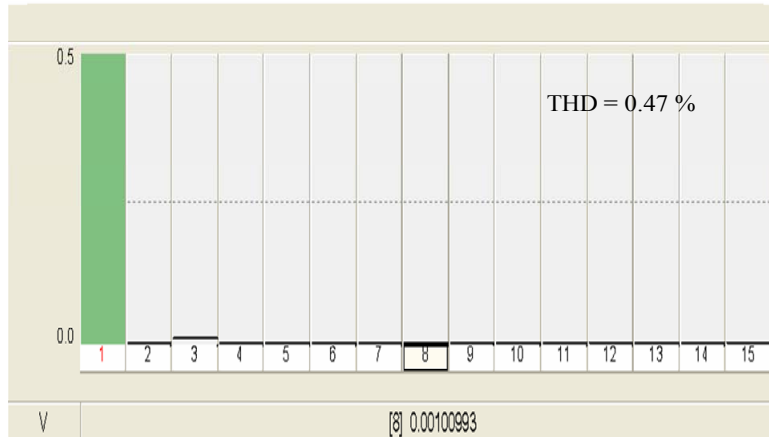


Figure 12: DLGF with harmonics and the source line voltage is distorted and load line voltage is sinusoidal with QPP ON

Appendix E



(a)



(b)

Figure 13: (a) THD without QPP is 13.47 % (b) THD with QPP is 0.47 %