Simulation Model of Power Quality Provider

[1]P.A. Venkatachalam, [2]K.Chandrasekaran,
[3]Mohd Noh Karsiti, [4]K.S.Rama Rao
Electrical and Electronic Engineering Department, Universiti Teknologi PETRONAS, Malaysia,
e-mail : [1]paruvachi_ammasai@petronas.com.my, [2]chandthi@sreamyx.com, [3]nohka@petronas.com,
[4]ksramarao@petronas.com.my

***Abstract*— The quality of voltage and current delivered by the power utilities has become a major concern of the modern industries. These power quality problems are voltage sag and harmonic which can cause problems to the industries ranging from malfunctioning of equipments to complete plant shutdowns. In this paper, the proposed Quality Power Provider (QPP) modeled by simulation is able to compensate the power quality disturbances such as voltage sag and harmonics in the time of normal operation as well as performs its basic function during fault condition. The QPP has a unique and novel control which is able to track and extract the most common voltage disturbances fast, dynamic and simultaneously. As an experiment to verify and validate the performance, QPP is connected at a valorous point of typical sensitive simulated distribution network and different faults were created. Experimental results are demonstrated to prove the practicality of the mitigating device. The design, modeling and simulation is done using PSS/ADEPT and PSCAD software. The overall performance results showed that the Total Harmonic Distortion with QPP is 0.47 % as compared to 13.47 %. without QPP. The proposed QPP would increase the Power Quality 'value added' benefits to the system.**

***Keywords*—Sag, Harmonics, QPP, VSI, PWM, Injection transformer, STATCOM, Mitigation, Simulation, Active power filter, Modulation, PSCAD.**

I. INTRODUCTION

The voltage disturbances and harmonic distortions are two major power quality problems in a distribution system. Among the voltage disturbances voltage sag is one of the most severe power quality problems [1]. Voltage disturbance will affect voltage-sensitive equipment that eventually leads to malfunction due to insufficient energy available for its proper operation. The adverse effect of voltage sag is 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.

Voltage sags are normally described by the magnitude variation and duration, and also characterized by unbalance, non-sinusoidal wave shape and phase angle shift [2][3][4][5]. Voltage sags and short interruptions may be caused on the healthy feeder due to the line to ground or line to line faults on adjacent feeder. Apart from voltage sags and interruptions, transient voltage variations resulted from lightning strikes, switching of power line/capacitor bank and starting of large induction motors are common concerns related to power quality issues [2].

Power electronic loads such as three-phase rectifiers, adjustable speed drives (ASD), uninterrupted power supply (UPS) and microprocessors inject voltage and current harmonics into the utility system and cause harmonic distortion. Harmonic distortion will cause the current and voltage waveform from normal sinusoidal to a non-sinusoidal waveform and is one of the most elusive and problematic events in providing quality power supply.

II. METHODOLOGY

The research methodology undertaken is to investigate how power quality disturbances affect certain sensitive equipment in industries, major hospitals, etc and design a device which will perform dual functions of mitigation of voltage sag and suppression of harmonics dynamically and simultaneously. The device proposed named as Quality Power Provider (QPP), which possesses certain features of the Dynamic Voltage Restorer (DVR), 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 (PWM) voltage source inverter (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 for 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.
For a case study, the 132/11KV distribution network at Ipoh Hospital, Malaysia was selected and the voltage sag and harmonic disturbances at different load nodes for different fault conditions were studied. The reason for selecting the hospital network is the power quality disturbances affect the performance of many life saving equipments 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 [6,7,8,]. The series active power filter (SAPF) will inject the right amount of harmonic voltages, in series and in phase, so that the voltage at the load bus is sinusoidal. Voltage regulation and harmonic blocking is possible with the use of series connected VSI. The harmonic control circuit is a part of QPP.

a) *Modeling and simulation of hospital network*

The Ipoh hospital distribution network modeled using PSS/ADEPT is shown in Figure 1. The Ipoh hospital 11KV distribution system is connected to the main 132/11KV Substation JAWA. The Ipoh hospital local switching station has five distribution transformer rated at 11/0.415KV. Medical equipments such as CT Scan, MRI, etc. are supplied by two 11/0.415KV transformers at Sub No.1. These sensitive medical equipments require quality power supply. The PSS/ADEPT software was used to study the load flow and voltage sag magnitudes at various nodes by creating four types of faults, namely, line to ground fault (LGF), line to line fault (LLF), double lines to ground fault (DLGF) and three lines to ground fault (3LGF). For a sample, the voltages at different nodes due to LLF only are shown in Tables 1.

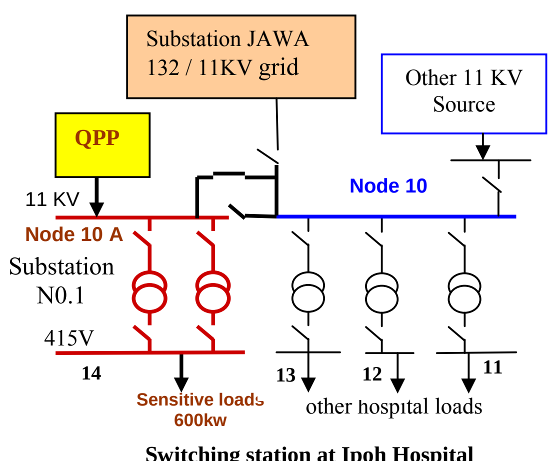


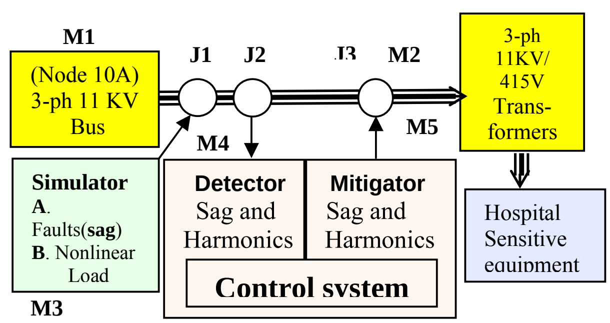
Fig. 1. Ipoh Hospital 132/11KV Distribution Network

TABLE 1
VOLTAGE AT NODE 10A AND NODE 14 FOR LLF

Node 10A	Node 10	Node 11	Node 12	Node 13	Node 14
3060V	3060V	209V	209V	209V	209V
3060V	3060V	0V	0V	0V	0V
6121V	6121V	209V	209V	209V	209V

b) *Modeling and simulation of QPP*

QPP is connected at node 10A which supplies the sensitive loads. Figure 2 shows the simulated component modules of QPP. Power module M1 represents the 3-phase 11KV bus (node 10A) connected to M2 which is the substation No.1 supplying power to sensitive loads of the hospital via two 11/0.415KV transformer. Module M3A is the simulator to create the faults like LGF, DLGF, LLF and 3LGF and thus the voltage sag at junction J1. Module M3B generates harmonics (by simulated three-phase uncontrolled rectifier used as the nonlinear load) causing harmonic distortion in the system. Module M4 is the control system which measures the sag and harmonics sensed at junction J2 and then feeds into the sag mitigation and harmonic suppression module M5. Inside the module M5, the distorted voltage waveform due to sag and harmonic will be compared with the pure reference sine wave simulated using the phase locked loop (PLL) and d-q transformation. The d-q technique is used to minimize steady-state error, harmonics, unbalances and to track phase shift easily during sag.



M5

Fig. 2. Different modules of QPP

In this work, QPP has been implemented with a three-phase Pulse Width Modulated-VSI (PWM-VSI) with energy storage batteries to supply power to mitigate sag and harmonics by injecting voltages to compensate the sag and the harmonic deviations. Thus QPP will perform dual functions of sag mitigation and harmonic suppression dynamically and simultaneously.

c) Functional units of QPP

The main functional units of QPP are PWM-VSI, injection transformer, Series Active Power Filter (SAPF). The functions of these units in brief are given below.

PWM-VSI

The PWM pulses will be produced based on the input reference sinusoidal signal and the carrier triangular wave operating at high frequency. The output pulse train is used to turn-on and turn-off the inverter. The output will be pulsed output with harmonics which is then filtered to obtain the output voltage. The voltage control is achieved by modulating the output voltage waveform within the inverter The rating of the PWM-VSI is low in voltage and high in current because of using the step up injection transformer. The main advantage of using PWM VSI is due to fast switching speed of the insulated gate bipolar transistor (IGBT) power switches. The PWM technique is simple with high response. The switching frequency chosen is 2000Hz.

Injection transformer

The series connected injection transformer is used to step up the injected voltage from the inverter to the main supply system. Injection transformer should be selected correctly to ensure the maximum reliability and effectiveness. The injection transformer is designed to keep at least twice the normal steady state flux to avoid from the saturation.

Series active power filter

The series active power filter (SAPF) is applied to protect the sensitive loads to harmonic voltages. The series connected injection transformer is used to inject the right amount of harmonic voltages in series with the input lines so that the voltage at the load bus is at its rated value and sinusoidal. Figure 3 shows the inverter circuit.

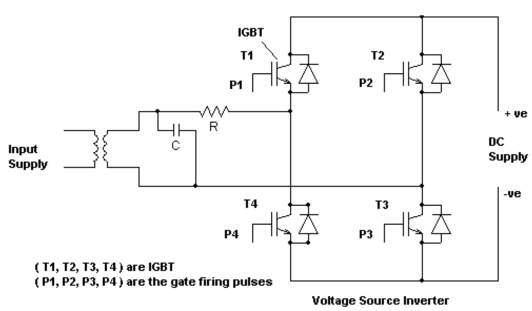


Fig. 3. Voltage Source Inverter

As shown in Figure 3, rapid switching of back and forth of the insulated gate bipolar transistor (IGBT) allows the current to flow back to the DC source following two alternate paths through one end of the primary winding and then the other. The alternation of the direction of current in the primary winding of the transformer produces the alternating voltage in the secondary circuit. Due to the switching action of IGBT the injection voltage leaving the inverter will have harmonics which is filtered by low pass RC filter [4]. The switching gates are energized by a dc energy source rated at 400V.

III. SAG AND HARMONICS

A. Sag Detection

Voltage sag detection is based on the d-q voltage component. The d-q component gives the sag depth and phase shift information with the start and end times [4]. The three-phase ac voltage is converted into α-β [4] voltages and then to d-q voltages as shown in Figure 4. To obtain a constant voltage, the voltage is fed into a low pass filter, thus d will be constant and q is zero for a balance condition. Thus in a balanced condition d is equal to system voltage and q is zero. Thus any variations in the input source voltage will change the values of d. The value of d is the reference. This is how sag is detected.

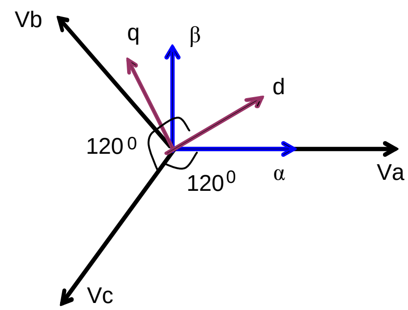


Fig. 4. Phasor diagram of source, d-q and α-β voltages

The transformation of α-β and d-q is by using (1) and (2)

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

$$\begin{bmatrix} Vd \\ Vq \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} V\alpha \\ V\beta \end{bmatrix} \quad (2)$$

where Va, Vb, and Vc are the source phase voltages, Vα and Vβ are α-β components and Vd and Vq are d-q components.

B. Sag Mitigation

The difference between the reference and the actual voltages will determine the amount of sag compensation need. The output is modulated using Pulse Width Modulation (PWM) to produce the required pulses to switch on the switches. The injection voltage is filtered and injected through the series injection transformer so that the load voltage is maintained at its rated value. The injection voltage is added to the source voltage to compensate for the missing voltage thus the voltage at the load is at its rated value.

C. Harmonics Detection

(SAPF) will also perform the function of harmonics suppression. The distorted harmonic signal will be the portion of the sine wave that is missing in the current. This is the signal that is compared with the reference signal to detect the harmonic content.

D. Harmonic Suppression

The distorted voltage is forced to be sinusoidal by comparing with the ideal sine wave of the reference voltage Vref. The sinusoidal waveform of the Vref comes from the source voltage which is filtered and kept in phase with the help of the PLL block.

By keeping the load voltage constant, and with the same magnitude of the source voltage, good voltage regulation at the load end is obtained. The reactive power (Q^{h}_{SAPF}) requirement of the series active filter for harmonic compensation is given by:

$$Q^{h}_{SAPF} = V^{h}_{L} I_{S} \qquad (3)$$

where h is harmonics, V^{h}_{L} is the rms harmonic voltage at the load and I_S is the line current through the series winding. The harmonic compensation is achieved by blocking the harmonic currents from the source to the load. The series active power filter generates a harmonic voltage equal to the harmonic voltage drop across the series winding. In this way, harmonics cannot flow to the load.

$$V^{h}_{L} = \sqrt{\Sigma \left(V^{j}_{L}\right)^{2}} \qquad (4)$$

where V^{j}_{L} represents the rms value of the voltage drop produced by the j[th] harmonic current with the j[th] harmonic impedance of series active power filter

$$V^{j}_{L} = I^{j}_{S} \; Z^{j}_{L} \qquad (5)$$

where I^{j}_{S} is the j[th] harmonic current in the line current. With an uncontrolled rectifier load, then the j[th] harmonic current can be found in terms of the fundamental line current I_S :

$$I^{j}_{S} = \frac{I_{S}}{j} \quad (j = 6n\pm1, \text{ with } n= 1, 2, 3\ldots) \qquad (6)$$

the (j = 6n±1) gives the harmonics in odd terms which is great concern in power system. Using (4),(5) and (6) and substituting in (3) yields the reactive power of series active power filter:

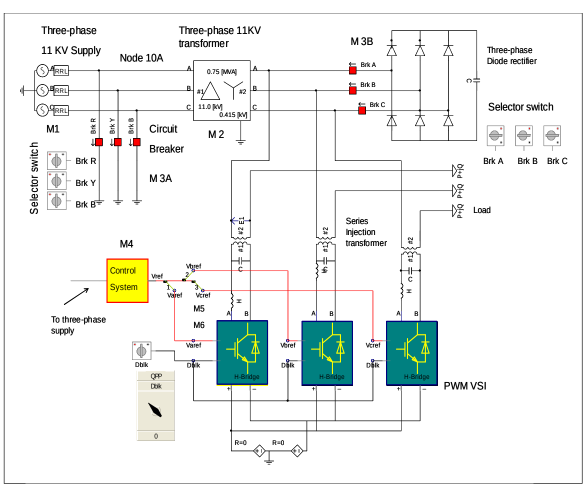


Fig. 5. Power and control modules of QPP

$$Q^{h}_{SAPF} = V^{h}_{L} \, I_{S}$$

$$= I_{S} \sqrt{\Sigma \, I^{j}_{S} \, Z^{j}_{L}} = I^{2}_{S} \sqrt{\Sigma \left(\frac{Z^{j}_{L}}{j}\right)^{2}} \qquad (7)$$

Assuming that the series impedance Z is small and the term represented by the square root in (7) is small, then

$$\frac{Q^{h}_{SAPF}}{S_{Load}} \approx X \qquad (8)$$

where X is approximately between 3 % - 10% range.

Rating of QPP

The maximum demand of sensitive loads at node 14 is 600KW and 141KVAR. The proposed QPP is connected at bus 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% of its maximum capacity of 600KW for a duration period not exceeding 500ms which is the fault clearing time of protection system. Thus, the QPP need be rated for 300KW.

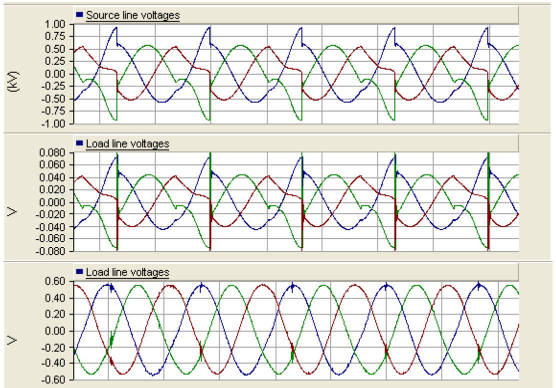
Power Losses

The efficiency of the power switches (IGBT) is about 97 %. The overall power losses for the QPP is about 3 % of the total KVA rating [7].

In the simulation, a 11KV three-phase supply was used, and the load was connected at the 415Volts side. The primary objective of QPP is to maintain the voltage at the load at its rated value with sinusoidal waveform when sag and/or harmonics are detected.

IV. SIMULATIONS AND RESULTS

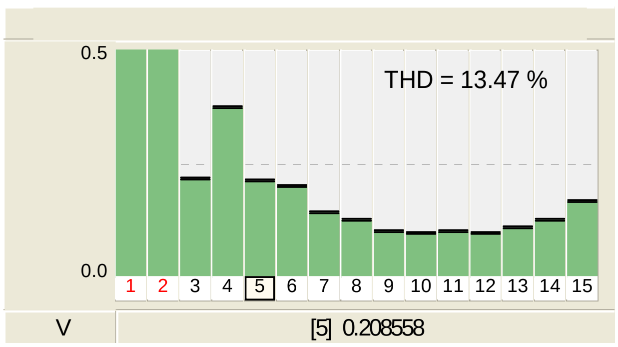
The following simulation experiments were conducted to check the performance of the QPP, with LLF created to cause sag and a simulated nonlinear load connected to introduce harmonics, at node 10A.. The distorted and mitigated voltage waveforms are shown in Figure 6.. Experiments were conducted with QPP in non-active and active modes. When QPP is in active mode, the load line voltage is at its rated value and sinusoidal.



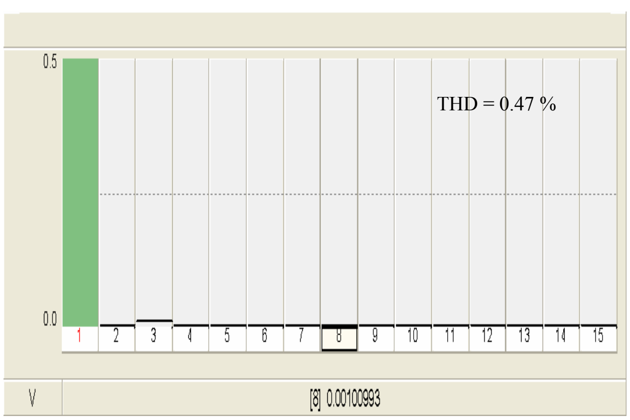
(a)
(b)
(c)

Fig. 6. Sag and harmonics due to LLF at Node 10.
(a) and (b) QPP not active; (c) QPP active

The Total Harmonic Distortion (THD) measured with QPP non-active was 13.47 % and QPP active THD dropped to 0.47 % well below the IEEE 519 standard of 5% . Results are shown in Figure 7 (a) and (b).



(a)



(b)

Figure 7: Mitigation of Total Harmonics by QPP
(a) QPP not active; (b) QPP active

V. DISCUSSIONS

Experiments to measure the performance of QPP have been conducted for various faults such as LGF, LLF, DLGF and 3GLF with QPP in active and non active modes. The sample results shown in Figures 6 and 7 relates to the experiment for line to line fault (LLF) to demonstrate how QPP performs. The simulated circuits of QPP can be implemented in hardware and QPP is connected to node 10A. Then the sensitive equipment at the hospital will get quality power for safe operation.Similarly QPP can be designed for any other distribution network. But the design and structure of modules of QPP will depend upon the type and nature of loads there.

VI. CONCLUSIONS

In this paper, a complete simulated QPP system developed for a distribution network has been presented. The simulation results have proven the voltage sag and harmonic restoring capabilities of QPP. The QPP is fast and dynamic and is able to perform a dual function simultaneously to restore the load voltage to its rated value with normal sinusoidal wave thus providing quality power. QPP can be used by any industry or organization which needs quality power.

REFERENCES

[1] Math H.J Bollen, "Understanding Power Quality Problems" Mc Graw-Hill, New York,1999.
[2] Dungun R.C "Electrical Power System Quality" Mc Graw Hill New York, 1996
[3] N.H. Woodley, L .Morgan and A. Sundram, "experience with an inverter-based dynamic voltage restorer." IEEE Trans. on Power Delivery, Vol.14, no.13,pp. 1181-1186,1999.
[4] Changjiang Z Chan, V.K. Ramachandramurthy, A. Arulampalam, C. Fitzer, N. Jenkins "Dynamic Voltage Restorered Based on Voltage-Space- Vector PWM Control" IEEE Trans. On Industry Applications, Vol. 37, N0.6, Nov/Dec 2001, pp.1855-1863
[5] J.G Nielson and F. Blaabjerg. "Comparison of system Topologies for Dynamic Voltage Restorer".in Conf. Rec. IEEE/IAS, vol. 4, pp.2397-2403, 2001
[6] Z. Wang, Q. Wang, W. Yao, "A series Active Power Filter Control Approach" Power Electronics, IEEE Trans. on Volume: 16 Issues: 3 May 2001
[7] Peng, F.Z.Akagi, H. and Nabae, "A New Approach to Harmonic Compensation in Power System" in IEEE Trans. on Industry Applications, vol 26, Nov/Dec 1990
[8] Peng, F.Z., Akagi H, and Nabae, "A compensation Characteristics of the Combined System of Shunt Passive and Series Active Filters" IEEE Trans., Vol. 1A-29, Jan/Feb 1993