COMPARATIVE STUDY OF DIFFERENT PWM CONTROL SCHEME FOR THREE-PHASE THREE-WIRE SHUNT ACTIVE POWER FILTER

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Comparative Study of Different PWM Control Scheme for Three-Phase Three -Wire Shunt Active Power Filter

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Abstract **— Instantaneous reactive power theory was the most popular control theory used when dealing with harmonics compensations. In conjunction with the instantaneous theory, switching signal generation techniques plays an important role to ensure the correct compensation signal injected in the system.. Therefore, this paper discussed on comparative study of five (5) methods used in instantaneous theory namely; *p-q* method, modified *p-q*, *d-q* method, *p-q-r* method and vectorial with three (3) types of signal generation namely; carrier current control, hysteresis current control and space vector modulation control. Continuous reductions of the total harmonics distortion (THD) are expected at the supply current when applied different types of switching technique. The comparison was examining using MATLAB/Simulink (MLS) environment.**

Keywords **—instantaneous reactive power theory, shunt Active Filter, switching signal generation**

I. INTRODUCTION

Power electronics application is dependent on the use of power switching devices that inadvertently; results with a non-sinusoidal current being drawn from the supply, containing harmful harmonic components which are then fed back to the supply system creating various problems. Various methods have been proposed in an effort to solve these problems. Amongst others is the use of passive filters connected in parallel with nonlinear loads [1], resulting with improvements in power factor and harmonic suppression [2]; designed to exhibit lower impedance at a tuned harmonics frequency [3]. This approach is popular due to its simplicity, reliability, efficiency and low cost [4], but at the expense of providing incomplete solutions particularly when compensating random frequency variations in the current, tuning and parallel resonant problems.

In recent years, various active power filters (APF) configuration with their respective control strategies have been proposed and have been recognized as a viable solution to the problem created by harmonics [1-4]. Control is most important element in the success of implementation of active power filter. The APF control is based on the instantaneous reactive power theory with different approaches [5-17]. The instantaneous reactive power theory was first introduced by Akagi et al. [7] for controlling of APFs. The control strategy derived from the *p-q* theory was efficient to reduced harmonics in the supply current hence provide the sinusoidal source current with same characteristic with voltage supply. Two formulations have been precursor from the origin *p-q* theory with great interesting contributions with respect to the original theory namely; modified *p-q* theory [10, 11] and *p-q-r* theory [14-16]. On the other hands, *d-q* theory [12, 13] and *vectorial* theory [18] were developed at the end of 1980's. This formulation was found obtaining identical result as compared to *p-q* theory in balance nonlinear load conditions.

This paper presents a comparative study of five harmonics detection algorithms incorporating with three different signal generations conditions. A brief description of each algorithm with necessary equation is explained in Section II. Hence, switching generation of three types of switching techniques is briefly explained in Section III. The simulation results from the operations are compared in Matlab/simulink (MLS) environment presented in Section IV. Three-phase three-wire shunt APF circuit consists of main supply connected to a non-linear load as shown in Figure 1. Four essential elements in the APF are namely; (i) signal conditioning, (ii) reference current generation, (iii) signal generation and (iv) three-phase inverter. The signal conditioning circuit used to provide accurate system information from the voltage and current from the grid. The reference current generator is used to generate the required harmonics current to be amplified and injected into the lines, at the point of common coupling (pcc). The switching generation for the inverter is generated at the controller circuit by comparing the reference current (i_a*, i_b*, i_c*) with the injected currents (i_a, i_b, i_c).

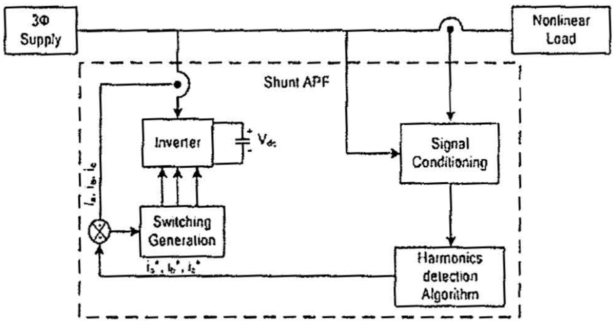

Figure 1. Block Diagram of Shunt Active Power Filter

II. INSTANTANEOUS REACTIVE POWER THEORY

This section discussed briefly about five (5) harmonics detection algorithms and relevant equations that have been studies.

A. p-q and Modified p-q Formulation

The *p-q* theory transform the three-phase system voltages and current from phase coordinate to *0-α-β* coordinates based on Clarke-Coordinate transformation, which represent by the following matrix (1);

$$[A] = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} A_{sa} \\ A_{sb} \\ A_{sc} \end{bmatrix} \quad (1)$$

where *A* can be either current or voltage. In the new coordinate system, three power terms are expressed namely; zero-sequence instantaneous real power (p_o), instantaneous real power $(p_{\alpha\beta})$ and instantaneous imaginary power $(q_{\alpha\beta})$.

$$\begin{bmatrix} p_o \\ p_{\alpha\beta} \\ q_{\alpha\beta} \end{bmatrix} = \begin{bmatrix} v_o & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

Finally allows the expression of current as a function of power quantities

$$\begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_o v_{\alpha\beta}^2} \begin{bmatrix} v_{\alpha\beta}^2 & 0 & 0 \\ 0 & v_o v_\alpha & -v_o v_\beta \\ 0 & v_o v_\beta & v_o v_\alpha \end{bmatrix} \begin{bmatrix} p_o \\ p_{\alpha\beta} \\ q_{\alpha\beta} \end{bmatrix} \quad (3)$$

Where; $v_{\alpha\beta}^2 = v_\alpha^2 + v_\beta^2$

On the other hand, the modified p-q formulation defines the instantaneous real power (p_u) and instantaneous reactive power vector $(\vec{q})$ as follows;

$$p_u = v_o i_o + v_\alpha i_\alpha + v_\beta i_\beta$$
$$\overrightarrow{q(t)} = \vec{v} \times \vec{i} = [q_o \quad q_\alpha \quad q_\beta]^T \quad (4)$$

It assume that the three instantaneous imaginary power $q_o(t)$, $q_\alpha(t)$, $q_\beta(t)$ are not independent, where; $v_o q_o + v_\alpha q_\alpha + v_\beta q_\beta = 0$.

$$\begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_{o-\alpha-\beta}^2} \begin{bmatrix} v_o & 0 & v_\beta & -v_\alpha \\ v_\alpha & -v_\beta & 0 & v_o \\ v_\beta & v_\alpha & -v_o & 0 \end{bmatrix} \begin{bmatrix} p_u \\ q_o \\ q_\alpha \\ q_\beta \end{bmatrix} \quad (5)$$

Where; $v_{o-\alpha-\beta}^2 = v_o^2 + v_\alpha^2 + v_\beta^2 \quad (6)$

B. d-q Transformation

The transformation of d-q uses matrix *[P]* with $\theta(t) = \omega t$ as the phase current transformation. For this case, ω represent the voltage fundamental wave pulsation. *d-q* formulation only works in the instantaneous active current *id* and instantaneous imaginary current *iq*. Park transformation is used to transform the supply current into stationary coordinate.

$$[P] = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta_1(t) & \cos\theta_2(t) & \cos\theta_3(t) \\ -\sin\theta_1(t) & -\sin\theta_2(t) & -\sin\theta_3(t) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (7)$$

C. p-q-r Formulation

In this formula, current are translated from *0-α-β* to *p-q-r* coordinates by means of the following;

$$\begin{bmatrix} i_p \\ i_q \\ i_r \end{bmatrix} = \frac{1}{v_{o-\alpha-\beta}} \begin{bmatrix} v_o & v_\alpha & v_\beta \\ 0 & -\frac{v_{o-\alpha-\beta}}{v_{\alpha\beta}} & \frac{v_{0-\alpha-\beta}}{v_{\alpha\beta}} \\ v_{\alpha\beta} & -\frac{v_o v_\alpha}{v_{\alpha\beta}} & -\frac{v_o v_\beta}{v_{\alpha\beta}} \end{bmatrix} \begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (8)$$

D. Vectorial Formulation

The technique does not need to undergo any transformation. Same power variable as original theory are define in instantaneous imaginary power $\vec{q}\,(t)$ in phase coordinates.

$$\vec{q}(t) = \vec{v}_q \vec{i} = \frac{1}{\sqrt{3}} \begin{bmatrix} v_b - v_c \\ v_c - v_a \\ v_a - v_b \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \equiv \vec{q}_{\alpha\beta}(t) \quad (9)$$

The equation that determines the currents are as follows;

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{p}{v^2} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} + \frac{1}{\sqrt{3}} \frac{p_o}{v_o^2} \begin{bmatrix} v_o \\ v_o \\ v_o \end{bmatrix} + \frac{1}{\sqrt{3}} \frac{q}{v^2} \begin{bmatrix} v_b - v_c \\ v_c - v_a \\ v_a - v_b \end{bmatrix} \quad (10)$$

III. SWITCHING TECHNIQUE

Switching technique can be divided into two categories; current control and voltage control. Carrier and hysteresis fall under current control while space vector fall under voltage control category. Briefly explanations of the switching techniques explain in the subsequence.

A. Carrier Current Control

This method used to generate two switching function consists of positive and negative cycle of PWM as shown in Figure 2. The pulses are the result of intersection between the error signals with frequency of carrier signal. Furthermore, the switching frequency is also the carrier operating frequency. This method used in current control loop to force the actual current according to the reference.

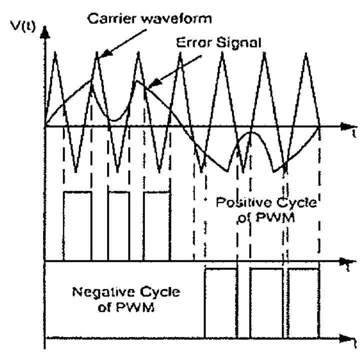

Figure 2. Carrier Current Control

B. Hysteresis Current Control

The earliest and most commonly proposed time-domain corrective technique is the hysteresis method [19, 20]. Preset upper and lower tolerance limits are compared to extracted error signal. No switching action is taken as long as the error is within the tolerance band. Switching action occurs when the errors leaves the tolerance band. These technique yields instantaneous and fast response controller [21]. The conditions of switching devices are tabulated below:

Switch	Hysteresis Band (HB)
Lower switch on	$i_{ref} - i_{act} < -HB$
Upper switch on	$i_{ref} - i_{act} > HB$

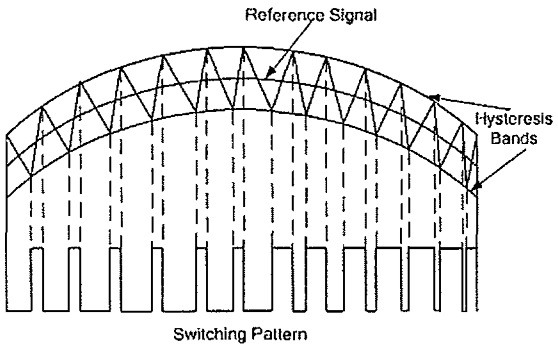

Figure 3. Hysteresis Method

C. Space Vector Modulation

Space Vector Modulation has been widely use in APF system. This method have an advantages over carrier based such as lower Total harmonics Distortion (THD), higher efficiency easier digital implementation and wider linear modulation range [22]. It is shown that in the linear range modulation, the index modulation will goes high and reduce the inverter DC link voltage in APF [23]. In implementation of SVM technique, there are TWO (2) rules that must be followed. First rule, each leg have two switches that cannot gated at the same time and at lease one switch must be turn "ON" due to the system inductance.

IV. Modelling APF System in Three-Wire System

To carry out the comparative analysis among five compensation strategies with different types of signal generations, a simulation platform has been design. Figure 4(a) shows the simulation scheme with control system for the APF in three-phase three-wire system. The non-linear load was constructed using full bridge rectifier connected in parallel with a resistor and a capacitor as the load. AC link inductors use to attenuate the switching ripple hence prevent high harmonics switching frequency. In Figure 4 (b), (c) and (d) shows the harmonics detection algorithm for *p-q*, *d-q* and *vectorial*. While modified *p-q* and *p-q-r* block diagram are based on *p-q* algorithm block with additional transformation needed. In the system low pass filter used to obtain the ac components that arise due to the harmonics of the load current.

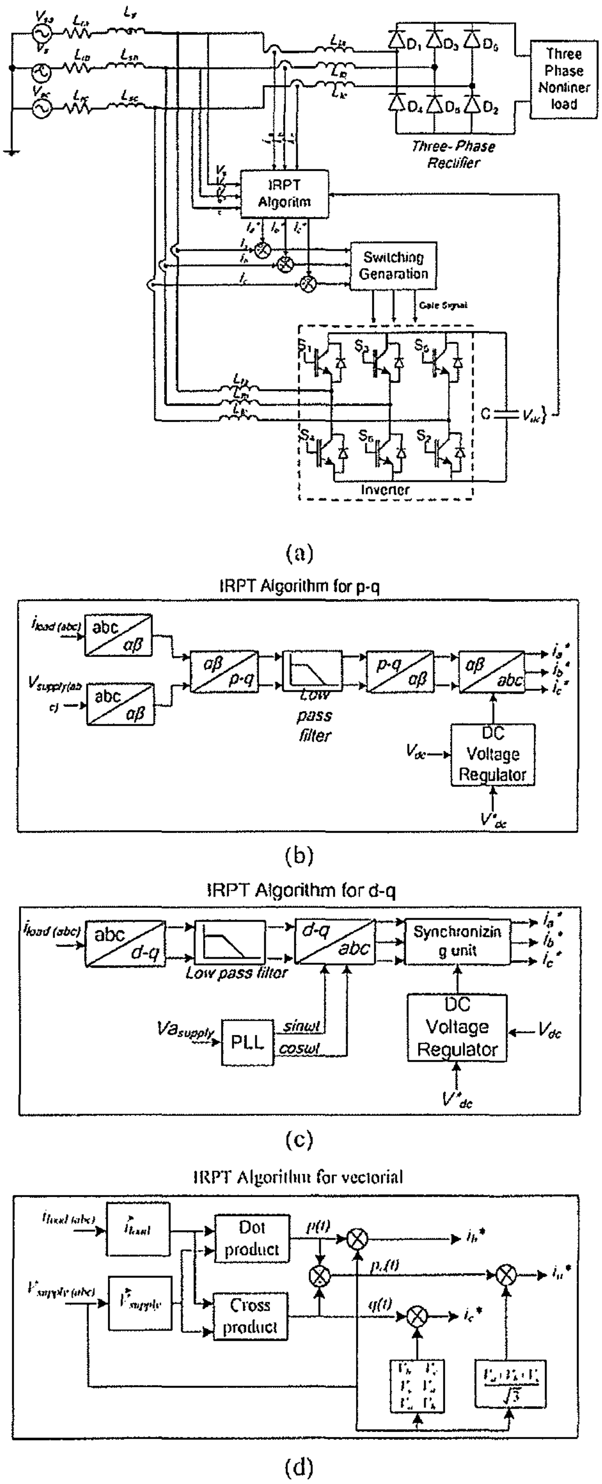

Figure 4. APF schematic diagram ;

(a) Shunt APF layout scheme

(b) Block diagram of IRPT algorithm for *p-q*

(c) Block diagram of IRPT algorithm for *d-q*

(d) Block diagram of IRPT algorithm for *vectorial*

V. SIMULATION RESULT

This section presents the general simulation block diagram of the shunt APF in MLS environment in Figure 5, while the simulation parameters are tabulated in Table II.

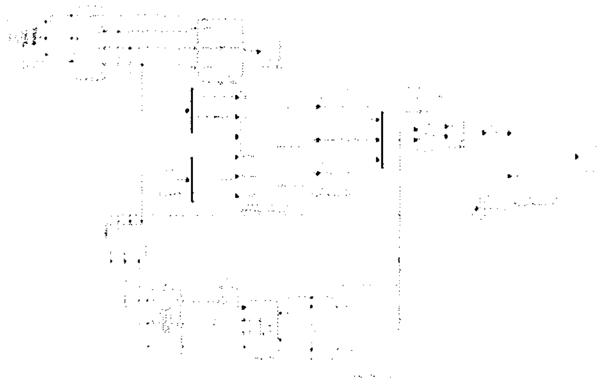

Figure 5. Simulation diagram of shunt APF in MLS environment

Table II
Simulation parameters of the APF

Parameters	Value
Voltage Source	*311 Vrms*
DC link Voltage (V_{dc})	*400V*
DC link capacitor, C	*1000μF*
Non-linear Load	*R = 1kΩ, C = 1200μF*
Load Inductors (L_l)	*1mH*
Filter Inductor (L_f)	*5mH*
2nd order Butterworth filter	*20Hz*

In the simulation studies, the switching frequency is set 20kHz for carrier and SVPWM, while the hysteresis band is set 10% of the maximum current injected. Total harmonic distortion (THD) from the simulations was found achieve the standard IEEE 519 standard from each algorithm. Even though, the THD result different from each algorithm, however the waveforms show otherwise. Figure 6 and 7 shows the waveform of supply current after the compensation with different algorithm and switching generation. Whilst, the (*phase b*) corrected supply current, compensation current and load current shown in Figure 8. All results from the simulation are tabulated in Table III.

Table III
THD AFTER THE COMPENSATIONS WITH SWITCHING FREQUENCY 20kHz

After Compensation	Carrier Signal (%THD)	SVPWM (%THD)
p-q	4.79	2.43
Modified *p-q*	4.71	2.38
d-q	4.81	2.40
p-q-r	4.78	2.20
Vectorial	4.80	2.35

THD AFTER THE COMPENSATIONS WITH 10% OF HYSTERESIS BAND

After Compensation	Hysteresis (%THD)
p-q	2.50
Modified *p-q*	2.42
d-q	2.49
p-q-r	2.31
Vectorial	2.41

It clearly shown that in Table III, SVPWM offers the best reduction of harmonics compares to others switching techniques. High percentage of distortion exist in *d-q* algorithm when apply the carrier signal which effect the overall power is shown in Figure 7. On the other hands, Figure 8 shows the best reduction of THD when applying SVPWM in *p-q-r* algorithm.

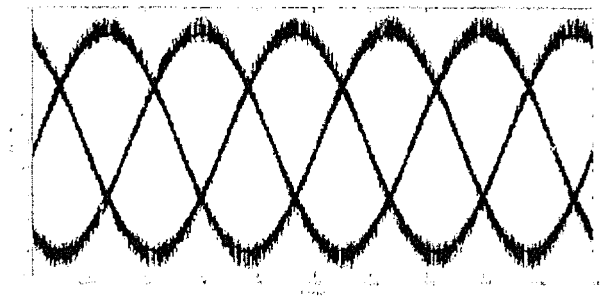

Figure 6. Supply current after compensation using carrier signal

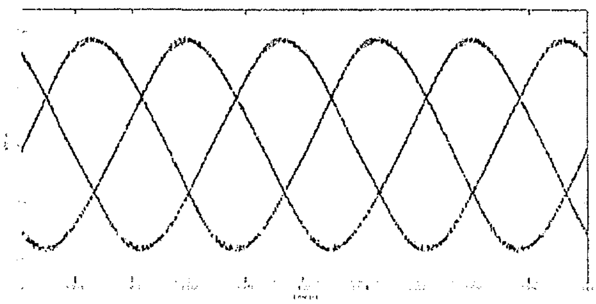

Figure 7. Supply current after compensation using SVPWM

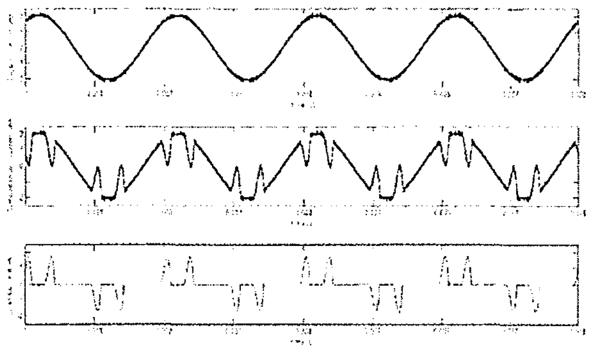

Figure 8. Supply, compensation and load current after compensation

VI. CONCLUSION

In this paper, the most commonly control algorithms of the instantaneous reactive power theory have been compares with three switching generations; carrier, hysteresis and SVPWM for three-phase three-wire active shunt active power filter system. From the simulation results, it can be concluded that all the control strategies combine with different types of switching techniques passed the THD requirement of IEEE 519 standard, which SVPWM switching techniques offer the best switching generation compares to another two techniques in terms of THD and switching control.

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