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PERFORMANCE INVESTIGATION OF PHOTOVOLTAIC GRID CONNECTION FOR SHUNT ACTIVE POWER FILTER WITH DIFFERENT PWM GENERATION

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ABSTRACT

In this paper, photovoltaic (PV) system at maximum power point tracking is connected to a three phase grid incorporating with shunt active power filter (APF) is presented. The PV system used to generate power from the sun array and feeding to the grid while shunt APF used to improve power quality of the photovoltaic generation based on *d-q* theory. Two pulse width modulation (PWM) techniques namely; hysteresis and space vector have been applies and studies the effects of both techniques to the system performance. The simulations has been carry-out and demonstrate using MATLAB/Simulink (MLS) environment shows that the proposed system offers improvement on power quality and power factor correction. Almost 80% to 90% improvements of the THD with unity power factor are expected in the result obtained.

Keywords: *Photovoltaic (PV), Shunt Active Power Filter (APF), Grid Connected System*

1. INTRODUCTION

Electrical power is essential to people's modern life style. With the increasing development of the industry, the types and capacity of grid connected loads have been increased drastically within the recent five decade. As a result, the power quality becomes an important issue that must be facing by all the electrical consumers at all levels of usage. Sensitive equipment and non-linear loads are now a commonplace in both industrial/commercial sector and domestic environment. These nonlinear loads absorb non-sinusoidal current and generally consume reactive power. Harmonics current produce by a nonlinear loads are injected back into power distribution system through the point of common coupling (PCC). [1], [2] [1-2].

Harmonics voltages appear when the harmonics current passed through the line impedance, causing distortion at PCC. In most cases the direct effect of harmonics includes; communication interference, heating, solid-state devices malfunction, resonance and others, as in [3-6]. In additional, with the push of world economy modernization, the cost price of the traditional energy keeps rising. Therefore, the need to generate pollution-free energy has triggered considerable effort toward renewable energy system. Renewable energy source such as solar photovoltaic (PV), wind, hydroelectricity and biomass offers clean abundant energy. Among the renewable energy, PV have been extensively studies because it closely related with power electronics.

There have been many research efforts to improve the efficiency of the PV system. It aimed at the supplying grid with active and reactive power to reduce the harmonics in the system, [7-13]. The PV system supply real power from the PV arrays to load and support reactive and harmonics power simultaneously. This technique has good feature such as; easy to expand and applicable to almost everywhere, [12].

This paper present an analysis and simulation of a PV grid connected system incorporating shunt active power filter (APF) with different PWM generation feeding the nonlinear load. Two voltage source inverters (VSI) namely; PV inverter and APF inverter are connected to each other in the system. The PV inverter used to convert dc power to ac power whilst the APF inverter used as the

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harmonics compensation hence reduce low-frequency ripple problem in the system, [14]. The control algorithm for harmonics detection is based on synchronous rotating frame (SRF) to adjustment of the active and reactive power. The control of active and reactive power is based on the current control in *d-q* rotating reference system. Two PWM generations are used in this system to compares the performances of the APF namely are space vector modulation control and hysteresis current control.

2. PROPOSED SYSTEM

The overall proposed system is shown in Fig 1. The mathematical model reflecting the electrical quantities in the output of the PV cell and panel is provided, as in [15], [16].

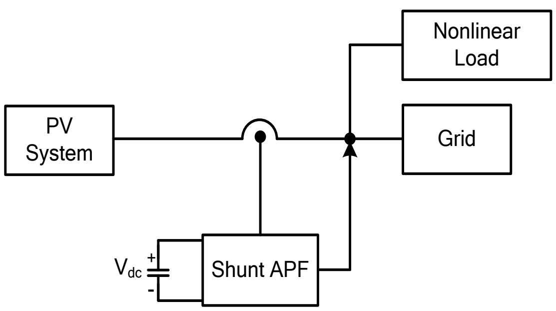

Figure 1: Overall Proposed System

2.1 Mathematical Modeling Of PV Cell And Panel

The equivalent circuit of the PV cell is shown in Fig. 2 which includes power supply and a diode.

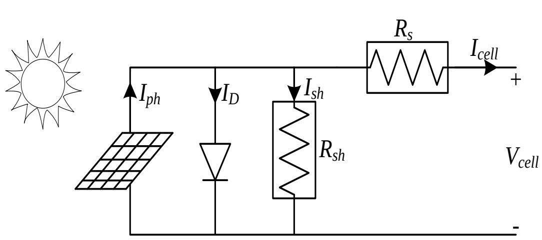

Figure 2: Equivalent Circuit Of A PV Cell

The photo current, I_{ph} depends on the solar radiation, G and the temperature, T of the environment. This situation explains in Eq. (1), [15]. I_{ph} (T_{ref}) is the photo current at the nominal temperature T_{ref}. On the other hands, Eq. (2) gives the formula of the photo current at the nominal temperature. K_0 is a constant given in Eq. (3). G_{ref} and I_{sc} are the nominal radiation given by the constructor and short circuit current respectively.

These equations are referring to Fig. 2 for single PV cell.

$$I_{ph} = I_{ph}(T_{ref})\ x\ \left(1 + K_0(T - T_{ref})\right) \quad (1)$$

$$I_{ph}(T_{ref}) = \frac{G}{G_{ref}}\ x\ I_{sc}(T_{ref}) \quad (2)$$

$$K_0 = \frac{I_{sc}(T) - I_{sc}T_{ref}}{T - T_{ref}} \quad (3)$$

Taking the consideration that the environment temperature is set at nominal one, therefore the PV current only depends on solar radiation which represented in Eq. (4).

$$I_{ph} = I_{ph}(T_{ref}) = \frac{G}{G_{ref}} I_{sc}(T_{ref}) \quad (4)$$

Diode current I_D characteristic is given in Eq. (5) where the I_O is the diode saturation current, while V_T represents the thermal voltage.

$$I_D = I_o\left(e^{V_D/V_T} - 1\right) \quad (5)$$

where; $V_D = V_{cell}\ (I_{cell}\ x\ R_s)$
Therefore, by using Ohm's law, the shunt current I_{sh} can be defined as;

$$I_{sh} = \frac{V_D}{R_{sh}} \quad (6)$$

Taking to account Eq. (1) and (5) and applying Kirchhoff's current law, I-V characteristic for PV are shown in Eq. (7)

$$I_{cell} = I_{ph} - I_D - I_{sh}$$
$$= I_{ph} - I_o\left(e^{V_D/V_T} - 1\right) - \left(\frac{V_D}{R_{sh}}\right) \quad (7)$$

2.2 Maximum Power Point Tracker (MPPT)

The maximum power point tracker (MPPT) produces maximum power under variable condition of solar radiation and environmental temperature. One of the most used methods of MPPT are the perturb and observe (P&O). The main advantage of this technique is that the search of the MPPT is done independently on the environment condition, however it required current and voltage sensor [12]. On the other hands, constant voltage methods is used to keeping the voltage in the PV terminal

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constant and closed to the MPPT line [16]. Therefore in this work, the PV terminal voltage is set constant and at maximum value.

3. SHUNT ACTIVE POWER FILTER MODEL AND CONTROLLER

The shunt active power filter (APF) were constructed with four essential elements in the 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). Fig. 3 shows the block diagram of shunt APF.

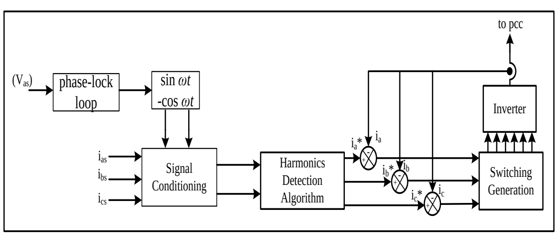

Figure 3: Block Diagram Of Shunt APF

3.1 Controller Design

The synchronous rotating frame or d-q theory is used as the main controller design without considering neutral wire. This method transforms three-phase into *d-q* coordinates (rotating reference frame with fundamental frequency) using Park transformations. This theory is extensively used in active filter because of the simplicity of the control design [5, 17-19]. The equations to transform *a-b-c* coordinate into *α-β-0* coordinate is presented in Eq. (8).

$$\begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{8}$$

By employing Park transformation, the *α-β-0* coordinate is transform into d-q coordinate as shown in Eq. (9)

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{9}$$

where; $\theta = tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right)$

The phase angle, θ in *d-q* frame is same with fundamental frequency which makes the DC fundamental current component $(i_{\bar{d}}, i_{\bar{q}})$ and harmonics AC component $(i_{\tilde{d}}, i_{\tilde{q}})$ arise due to harmonics at the load [5]. By using low-pass filter (LPF) the DC component can be obtained. Subtracting the DC component with the previous component can determine the harmonics component for the system. Fig.4 shows the techniques to determine the harmonics component in the system.

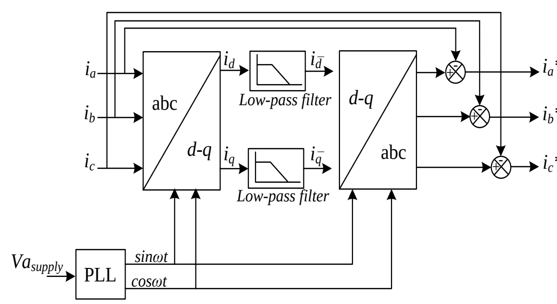

Figure 4: Harmonics Current Detection Using D-Q Theory

3.2 Switching Techniques

Two switching techniques namely hysteresis current control and space vector modulation control are employs to generate the required pulse width modulation (PWM) switching. Briefly explanations of the switching techniques explain in the subsequence.

3.2.1 Hysteresis Current Control

The earliest and most commonly proposed time-domain corrective technique is the hysteresis method, as in [20-21]. 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, [22]. The conditions of switching devices are tabulated in Table I.

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Table I: Hysteresis Band

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

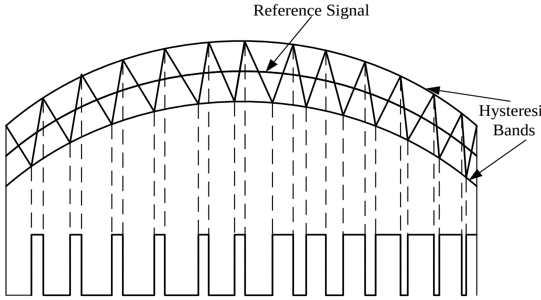

Figure 5: Hysteresis Method

3.2.2 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, [23]. It is shown that in the linear range modulation, the index modulation will goes high and reduce the inverter DC link voltage in APF, [24]. 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 least one switch must be turn "ON" due to the system inductance. In this work a basic switching vectors and sectors of hexagon axes SVM technique is used for generate the PWM

4. MODELING OF PROPOSED SYSTEM

To carry out the analysis of the proposed system, a simulation platform has been design. Fig. 6 shows the simulation scheme of the PV system connected to the three-phase grid system incorporating with the shunt APF with non-linear load. 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 at the APF used to attenuate the switching ripple hence prevent high harmonics switching frequency. The phase- lock-loop use to synchronize the harmonics phases with the grid phases.

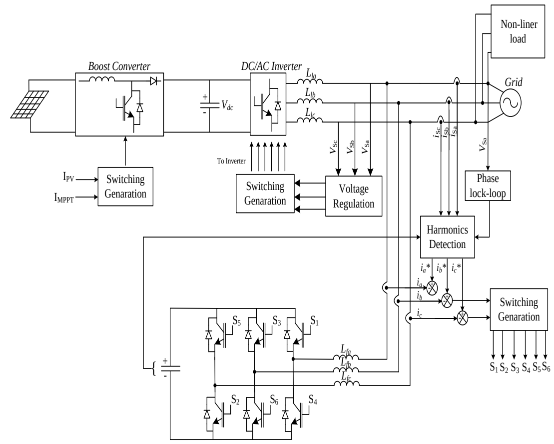

Figure 6: System Configuration

5. SIMULATION RESULT

This section presents the general simulation block diagram of the PV system connected to grid incorporating with active power filter (APF) feeding the nonlinear load in MLS environment. Fig. 7 shows the six module PV arrays that used in this system, while the overall simulation block diagram shown in Fig. 8. The simulation parameters of the PV module and the overall parameters using in this simulation are tabulated in Table II and Table III respectively.

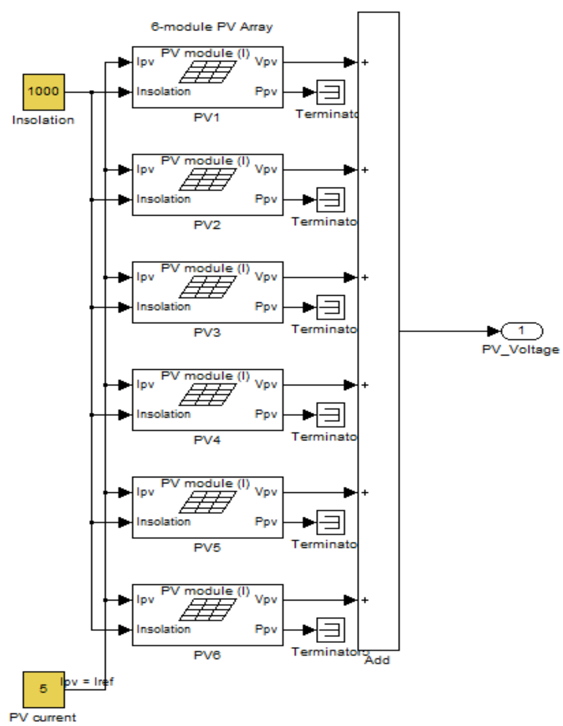

Figure 7: Six Module Of PV Array

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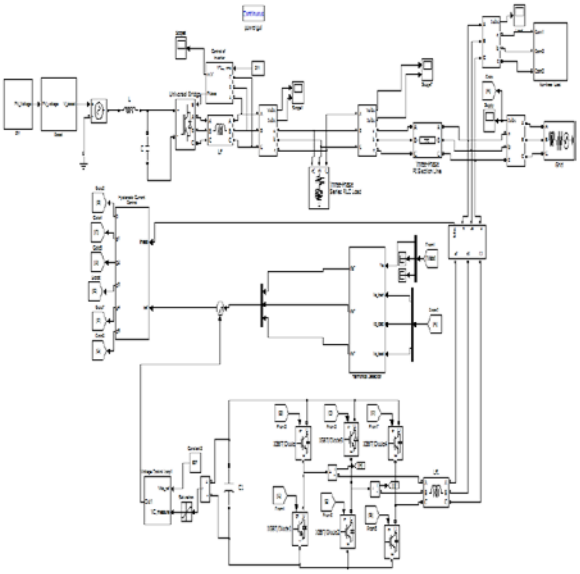

Figure 8: Simulation diagram of the PV grid connected incorporating with shunt APF

Table 2 Parameters Of Pv Model

Parameters	Value
Short circuit current	*5.45A*
Open circuit voltage	*22.2V*
Current at Pmax	*4.95A*
Voltage at Pmax	*17.2V*

Table 3 Simulation Parameters Of The System

Parameters	Value
Voltage Source	*311 Vrms*
DC link Voltage (V_{dc})	*537V*
DC link capacitor	*C1=2000µF*
Non-linear Load	*R = 100Ω, C = 2000µF*
DC Filter	*L=1mH, C= 2300 µF*
Filter Inductor (L_F)	*5mH*
Low-pass filter	*20Hz*

In the simulation studies, each six PV model have the same parameters values stated in Table I. The pulse width modulation (PWM) was generated using hysteresis current control which is set 10% of the maximum current injected while the 20 kHz switching frequency is set for SVPWM. Results spectrums obtained by the simulation when apply shunt APF are shown Fig. 9 until 11 respectively. Additional to the results spectrums, Fig. 12 shows the injection for correction waveforms provides by the shunt APF. Hence, the powers factor improvement before and after apply shunt APF are shown in Fig. 13 and 14 respectively.

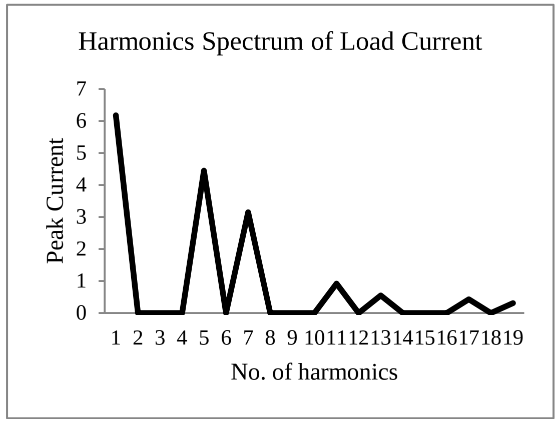

Figure 9 : Harmonics Spectrum Of Load Current

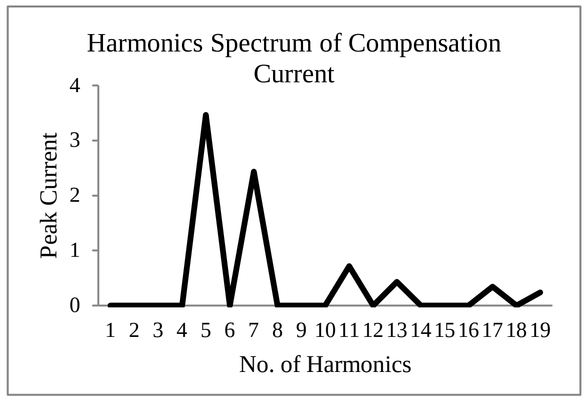

Figure 10: Harmonics Spectrum Of The Compensating Current

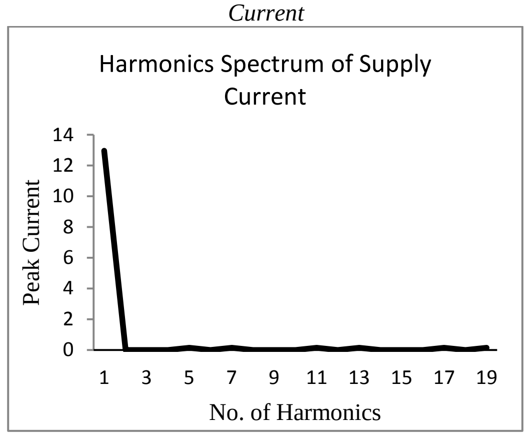

Figure 11: Harmonics spectrum of supply current using hysteresis control

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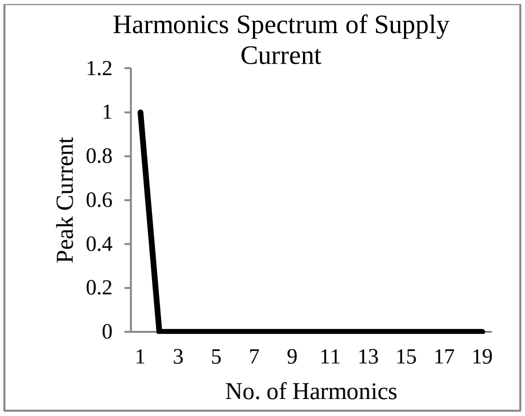

Figure 12: Harmonics Spectrum Of Supply Current Using SVPWM

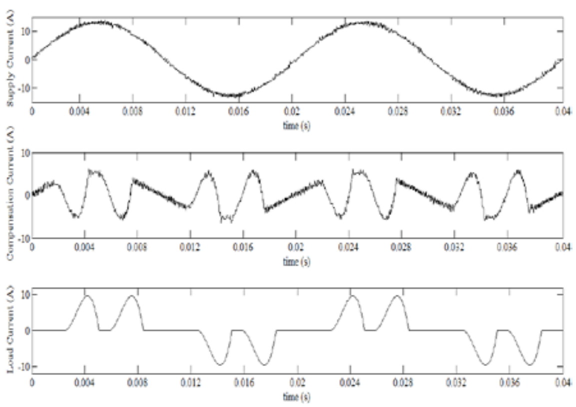

Figure 13: Supply, Injecting And Load Current After Compensation Using Hysteresis PWM

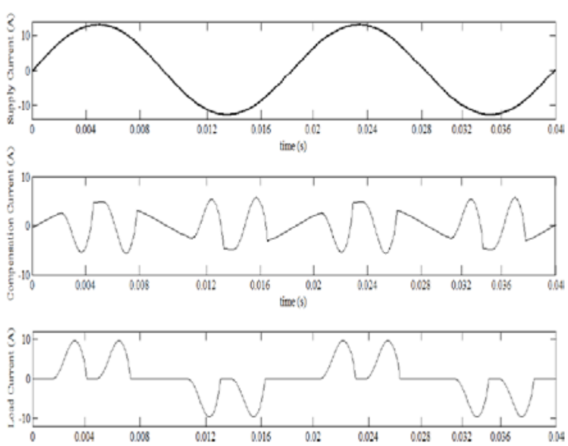

Figure 14: Supply, Injecting And Load Current After Compensation Using SVPWM

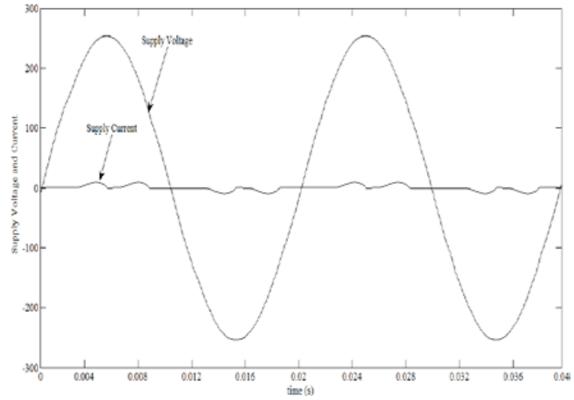

Figure 15: Voltage and current supply before compensation

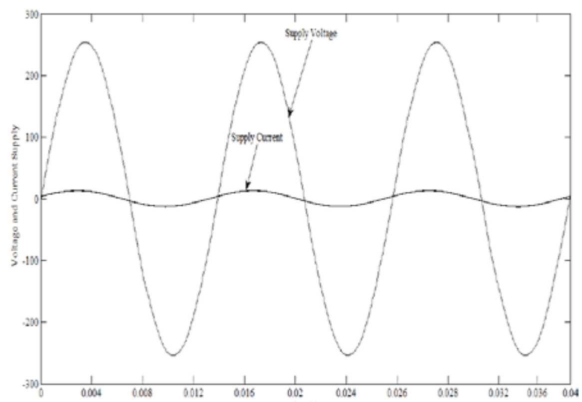

Figure 16: Voltage And Current Supply After Compensation

Analysis of the waveform as shown in Fig. 9 through 16 found the total harmonic distortion (THD) is approximately at 90.27% with a power factor of 0.59 leading. When subjected to compensation, the waveform is now continuous, almost sinusoidal and in phase with the supply voltage. Refer to Fig. 13 and 14, it visually shown that when employs SVPWM technique the supply waveform become smoother and low ripple compared to hysteresis. In addition, the THD level is reduced from 2.58% when apply hysteresis control to 0.84% using SVPWM with almost unity power factor operation achieved. A summary of result is as tabulated in Table IV.

Table 4 THD Before And After The Compensation

Switching technique	**Power Factor**	**THD (%)**
Without shunt APF	0.59	90.27
Hysteresis PWM	0.90	2.58%
SVPWM	0.97	0.84%

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6. CONCLUSION

In this paper a photovoltaic (PV) system connected to a three phase grid incorporating with shunt active power filter is successfully done in Matlab/simulink environment. The PV system is operate at the maximum power point which use to supply maximum voltage to the grid while shunt APF modeling employs *d-q* transformation as the harmonics control strategy to eliminated the harmonics in the system. As the result obtained from the simulation shows that SVPWM offers better sinusoidal supply waveform with 90% improvement of THD reduction with almost unity power factor are achieved in the system.

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