Modeling and Analysis of Three Phase Active Power Filter Integrated Photovoltaic as a Reactive Power Compensator Using the Simulink Matlab Tool

Setiyono
Departement of Electrical Enginering
Gunadarma University
Jakarta, Indonesia
setiyono@staff.gunadarma.ac.id

Sunny Arief Sudiro
STMIK Jakarta STI&K
Jakarta, Indonesia
sunny@jak-stik.ac.id

Eri Prasetyo Wibowo
IT Doctoral Program
Gunadarma University
Jakarta, Indonesia
eri@staff.gunadarma.ac.id

***Abstract*— This paper presents an analysis of modeling of reactive power compensation using renewable energy from sunlight through photovoltaic to eliminate harmonic signals in the electricity network with a three-phase active power system filter. Electric energy supply comes from three-phase electricity sources in the form of sinusoid. Non-linear loads such as electronic devices and electrical equipment connected to the grid generate harmonics signals; can make the format of electrical energy distorted. This nonlinear load draws electric current in the form of non-sinusoid. This format increase Total Harmonic Distortion (THD), thereby worsening the performance of electrical equipment. Active power filter is a very effective method in reduce of harmonics signal and increasing the quality performance of electricity. This power filter works by injecting compensation current into the grid. The energy that injected comes from the direct current output voltage (DC) of the photovoltaic link stored in the capacitor via a Voltage Source Inverter (VSI) switch. The compensation current has the same format as the harmonics current but differs in 180^0. The main parts of this power filter include the Reference Signal Generating Unit, PI Controller, VSI Switch Signal Ignition Gate Generator, Energy Storage Circuit (Battery), and Photovoltaic. Simulation modeling using Matlab Simulink Tools with the aim to reduce THD levels in accordance with IEEE 519 standards. Simulation results show a significant decrease in Total Harmonic Distortion (THD), where the grid before compensation contains THD of 29.74% and after injection of 2.25%. So this modeling is worth proposing as an active filter in a power system.**

Keywords*— Shunt active filter, Total Harmonic Distortion (THD), PI Controller, Photovoltaic (PV), Simulink Matlab Tools

I. Introduction

Power plants are required to serve consumers with good quality electricity. one of the good qualities of electricity is electricity that has the sinusoidal wave form. meanwhile on the consumer side, the use of non-linear loads such as electronic devices, televisions, personal computers, air conditioning systems, motor speed drives, electronic converters, energy saving lamps, resulting in source current wave distortion. In other words, the current source supply is not sinusoid shaped form. Adverse effects arising from this defect wave can reduce the quality of electricity [1]. Negative influences include increased overheating in distribution transformers, disruption of electrical equipment performance, interference with telecommunication lines with neutral wire, and the possibility of interruption of electrical power. the serious problem must be solved immediately including handling is to prevent the emergence of harmonics generated by the use of electronic equipment with a filter.

The scientists developed a filter by combining renewable energy sources, one of which was solar thermal energy [1] [3]. Renewable energy especially solar energy can be utilized as a reactive power compensator that is injected into the grid. Solar power generation is one of the best renewable energy sources that is clean and reliable. Sunlight falling on photovoltaic (PV) cells moves electrons in the solar cell that lead to the electrical energy generation [5]. Air temperature varies with time changes, so the power output of PV cells also changes from time to time [6]. To get the maximum power from a PV array under variable conditions, the Maximum Power Point Tracking (MPPT) algorithm is one of the methods in its calculation. Most researchers use the Perturb and Observe (P&O) algorithm because of its simplicity. By utilizing this solar energy, some researchers implement PV into an active filter to supply the reactive power used to eliminate the effects of harmonics. A simulation of improving power quality by using hysterical control to eliminate third-order harmonics on the load side have been presented and the result is that the system has succeeded in reducing THD below 5% but the model only applies to low voltage [2].

Models to improve power quality using active reactive power filters with PWM hysteresis control have been proposed. The goal is to harmonic compensation first. The result is that the power quality is increased and THD drops below 5% [3]. Other approach is a three phase three phase active power filter simulation model with hysterical control with balanced nonlinear load. As a result, THD decreases to within the specified value limit [4].

The article about making an active filter system where during the daytime the electricity supply to the load is served by PV through the active filter and at night using the main utility source. His research result, the filter system succeeded in reducing THD from 16.35% to 10.02% which confirms the good SAPF operation which improves power quality [1]. Research of making active power filters using PV as a supplier of reactive active power, the results of his research said that at an irradiance rate of 800 W/m2 the system supplies active currents, reactive currents and harmonic currents, but when radiation is reduced at 400 W/m2. Active currents are supplied by electricity networks while reactive currents and harmonic currents are served by active filters [7].

Development of further research on the same topic is still ongoing. This study presents a shunt active power filter modeling on a three-phase four-wire power system to eliminate the effect of harmonics due to the use of non-linear loads with a PV module composer. The simple method of this filter is to inject an anti-harmonics signal through a series of Voltage Source Inverter (VSI) which acts as a parallel active filter. The compensation current injected into the net comes from energy storage (battery) that is charged by photovoltaic using the help of sunlight. Mathematically this active power filter can be expressed as a relationship of three electrical currents expressed in (1), as in:

$$I_s = I_L - I_C \quad (1)$$

Where

I_S = Source Current , abc
I_L = Load Current , abc
I_C = Compensation Current abc

Fig. 1 is a simple concept of parallel active power filter connected PV modules, consisting of four main parts namely a three-phase line voltage source, a non-linear load in the form of a three-phase diode rectifier, a voltage source inverter as an active power filter and a PV module. Is, *abc* is the source channel currents a, b and c, likewise IL, abc and IC, abc are load current and compensation current, abc. Compensation current is the current that originates from the charge flow capacitor which is filled in by the PV module. The battery is useful for storing energy when the compensation process is no longer needed by grid.

II. TOTAL HARMONIC DISTORTION (THD)

Total Harmonic Distortion (THD) is a measure that states the amount of harmonic content in an electric network. This index is defined as a comparison of the rms (root mean square) value of the harmonic component to its basic component and is expressed in percentage. There are two types of harmonics in electricity, namely voltage harmonics and current harmonics. The THD index for voltage and current can be expressed in (2) and (3):

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} x100\% \quad (2)$$

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} x100\% \quad (3)$$

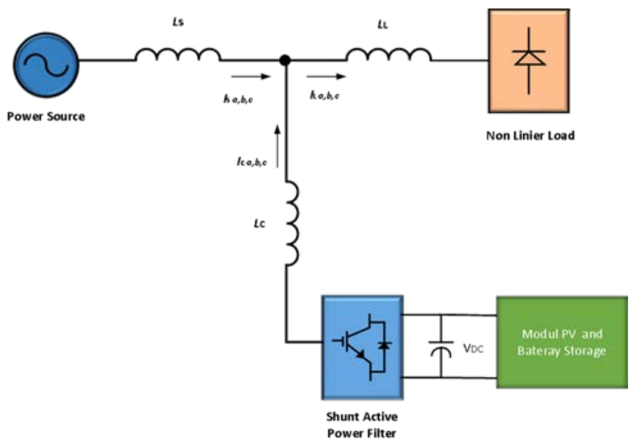

Fig.1. A set of Shunt Active Power Filter Integrated Photovoltaic Module

TABLE I. THE RULE OF IEEE 519 – 1992 STANDARD

	Order of harmonics in% of I_L				
I_{sc}/I_L	<11	11≤h≤17	17≤h≤23	23≤h≤35	35≤h
<20	4.0	2.0	1.5	0.6	0.3
20<50	7.0	3.5	2.5	1.0	0.5
50<100	10.0	4.5	4.0	1.5	0.7
100<1000	12.0	5.5	5.0	2.0	1.0
>1000	15.0	7.0	6.0	2.5	1.4

This study is focus on reducing harmonic currents. Harmonics in the power system cannot be eliminated to zero percent, but there are certain limits where harmonics can still be tolerated to appear on the electricity network. As a reference the current distortion limits for general distribution systems (120 V to 69kV) according to IEEE Standard 519-1992 are shown in Table 1 [9].

III. RESEARCH METHOD

This model was built for the simulation of a system with a large capacity so that it is expected to help design a large job before it is implemented in a real circuit. This research was conducted by making 3 (three) models, namely (a) power system model with linear load, (b) power system model with non-linear load, (c) non-linear load power system model equipped with active photovoltaic integrated power filter. All models are built using Matlab Simulink Tools version 2018a. Before designing the system modeling, the design of the circuit illustrations for each model is designed first and specifically for modeling the power filter (c) the circuit will be electrically equipped. Power system modeling with power filter has a more complex sequence. Parameters of simulation results that will be analyzed and become the topic of discussion are the wave forms of the channel currents, load currents, compensation currents and THD index. The expected THD index must comply with table 1 of the IEEE 519 rule, which is the THD level below 4%..

Modelling Power Systems with Linear Load

Fig. 2 shows an illustration of a power system circuit with linear load. A three-phase power source is built to produce a three-phase current source with a 120^0 phase difference. The load is simulated by installing resistors with the same value in each phase.

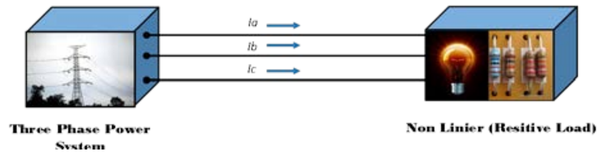

Fig.2. Illustration of a Resistive Load Power System

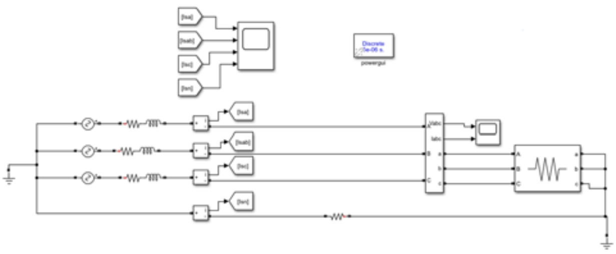

Fig.3. Modeling of a Resistive Load Power System

TABLE II. PARAMETERS OF LINEAR LOAD POWER SYSTEMS (RESISTIVE)

Power System Description	Value
Three Phase Power Source	380 VL-L (Voltage Line to Line)
Line Impedance	L = 1mH R = 1 ohm
Resistive Load	R= 10 ohm/phase

Fig. 3 is a modeling of a three-phase four-wire load-resitive power system circuit without a power filter, and in Table 2 is a description and parameter values of the power system are built.

Modelling Power Systems with Non-Linear Loads

Fig. 4 is an illustration of a non-linear, three-phase power system without power filter. The load is represented by electrical and electronic equipment such as personal computers, air conditioners, refrigerators, electric motors and energy saving lamps.

Fig. 5 is a modeling of a three-phase four-wire power system without the non-linear load active power filter series. Table 3 is the parameter values that exist in the modeling series in Fig. 5.

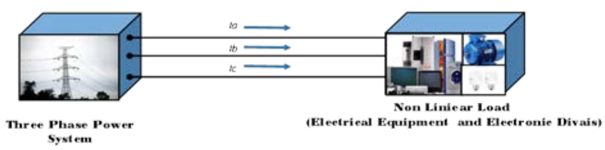

Fig.4. Illustration of Nonlinear Load Power Systems (Electronic Devices and Electrical Equipment)

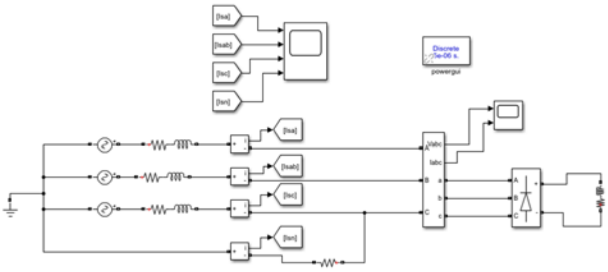

Fig.5. Modeling of Nonlinear Loaded Power Systems

TABLE III. PARAMETERS OF LINEAR LOAD POWER SYSTEMS (RESISTIVE INDUCTIVE)

Power System Description	Value
Three Phase Power Source	380 VL-L (Voltage Line to Line)
Line Impedance	L = 1 mH R = 1 ohm
Load Diode Rectifier with Inductive Resistive Load	R= 50ohm/phase, L = 0.01 H/phase

Modelling a Non-Linear Load Power System with Active Power Filter

Fig. 6 illustrates a non-linear, three-phase, four-phase power system equipped with an active power filter and a PV module as an external DC source. 3 Three phase lines are connected to the load and a neutral wire line is connected to one of the line of three phase power system with a resistive element.

Fig. 7 is a modeling of the non-linear load active power filter. Table 4 is the component values designed in the modeling. The main problem of circuit is that it keeps the source current Is, abc remains sinusoidal even though the load draws a non-sinusoidal current. The relationship of each current appears in (1).

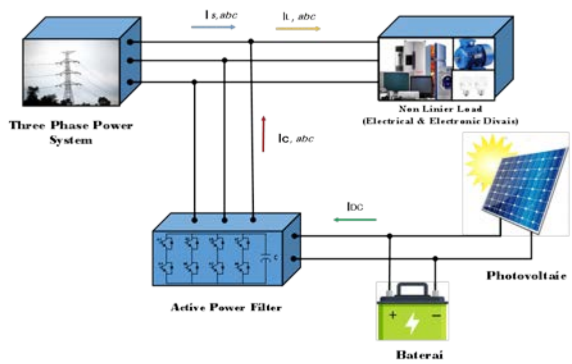

Fig.6. Illustration of Power Systems with Active Power Filter Integrated with Photovoltaic

Photovoltaic and DC Link

Fig. 6 Photovoltaic converts solar energy into a source of DC electricity which is then stored on battery storage media. The DC – DC converter functions to increase the DC voltage of the battery and keep the DC link voltage (500 V). During the daytime the PV is designed to compensate the distribution system, while at night the task is taken over by the battery.

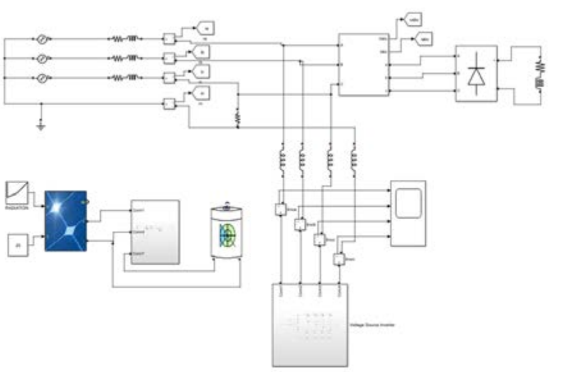

Fig.7. Modeling a Power System with Photovoltaic Integrated Active Power Filter

TABLE IV. PARAMETERS OF NON LINEAR LOAD POWER SYSTEMS (RESISTIVE-INDUCTIVE)

Power System Description	Value
PV Voltage	213 V
Baterai Voltage	500.5 V
Capasitor Voltage	500 V
Power Source	220/380 V
Load	Diode Rectifier R= 10 ohm L = 10 mH
VSI Reactor	3.3 mH
Line Impedance	0.1 ohm 0.1 mH

The energy flowed by the PV is only for reactive power compensation, but when compensation is no longer needed this power is channeled to the battery for storage. Compensation currents are obtained from the process of sending (discharging) and absorbing (replenishing) the energy of the capacitor charge which works to form certain patterns with fluctuating voltages.

Voltage Source Inverter (VSI) and Controller

VSI uses 8 IGBT transistors gives a compensation current from the capacitor to the grid. Three pairs of switches are connected to the phase lines and one pair of switches is connected to neutral wire lines. On the DC Link side are installed two series capacitors to serve and make alternating wave patterns of compensating currents, and in parallel arrangement with VSI.

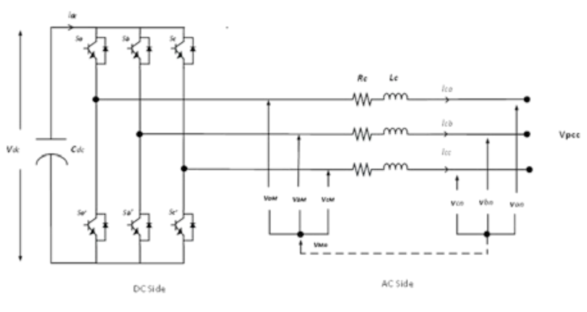

Fig.8. The equivalent series of parallel active power filters

PI controller is used to maintain the dc capacitor voltage so that it is always greater or equal to the source voltage. The use of PI controller is very effective and easy to implement steady state error control [6]. This control together with the hysteresis control is used to generate ignition pulses for 8 VSI switches in injecting the compensation current into the power system's line.

In Fig. 8 and according to the KVL law the voltage $v_{an}, v_{bn}, v_{cn}, v_{nn}$ PCC (Point of Common Coupling) can be calculated by equation 4 -6 below [7] [8]:

$$v_{an} = L_c \frac{di_{ca}}{dt} + R_c i_{ca} + v_{aM} + v_{Ma} \quad (4)$$

$$v_{bn} = L_c \frac{di_{cb}}{dt} + R_c i_{cb} + v_{bM} + v_{Mb} \quad (5)$$

$$v_{cn} = L_c \frac{di_{cc}}{dt} + R_c i_{cc} + v_{cM} + v_{Mc} \quad (6)$$

Assuming that this power system is balanced, the relationship of each voltage can be expressed by (7) and (8):

$$v_{an} + v_{bn} + v_{cn} = 0 \quad (7)$$

$$i_{an} + i_{bn} + i_{cn} = 0 \quad (8)$$

From (4) – (6) v_{Mn} can be expressed as follows:

$$v_{Mn} = -\frac{1}{3}\sum_{k=a,b,c} v_{kM} \quad (9)$$

The relationship of V_{dc} with the inverter output voltage v$v_{aM}, v_{bM}, v_{cM}, v_{nM}$ is expressed in (10) :

$$v_{kM} = C_k V_{dc} \quad (10)$$

Where k is *a,b,c,n* in phase a, phase b, phase c, and phase n.

Substitution (4) – (6) , using (7) and (8) equation from the three-phase compensation current shown in (11) :

$$\frac{di_{ck}}{dt} = \frac{1}{L_c} v_{kn} - \frac{R_c}{L_c} i_{ck} - \frac{1}{L_c} d_{nk} V_{dc} \quad (11)$$

Fig.9 is modeling a 4 wire voltage source inverter, with a capacitor on the dc side with a voltage of 500 V. Capacitor fluctuation voltage is supplied through the inverter switch.

Current Reference Generation and Gating Pulses

The reference current is needed to control the switch on the VSI switch. Fig. 10 explains the flow of generating the reference current through several process blocks. The first part is the PLL block in charge of detecting and measuring the source voltage to identify the phase angle of each source channel. Parts of this PLL include the abc to dq transform unit, the variable frequency detector, the PID controller along with the gain regulator, the low pass filter and the controlled oscillator. PI control on figure 10 are non-integrated controls whose control actions have the proportional and integral nature of the error signal which means that any process eventually returns to the same output with the same set of inputs and noise [5].

PLL Block

The PLL block (3ph) is a Phase Lock Loop (PLL) closed loop system, this section is to track the frequency and phase of a sinusoidal three-phase signal using an internal frequency oscillator. The control system regulates the frequency of the internal oscillator aiming to keep the phase difference to 0. The figure 10 shows the internal diagram of the PLL.

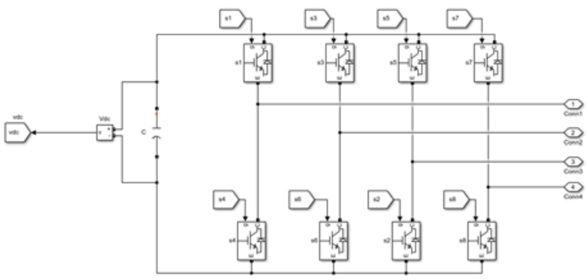

Fig.9. VSI 4 Leg modeling in which 3 Leg pairs serve 3 phase line switches and a pair to serve neutral line.

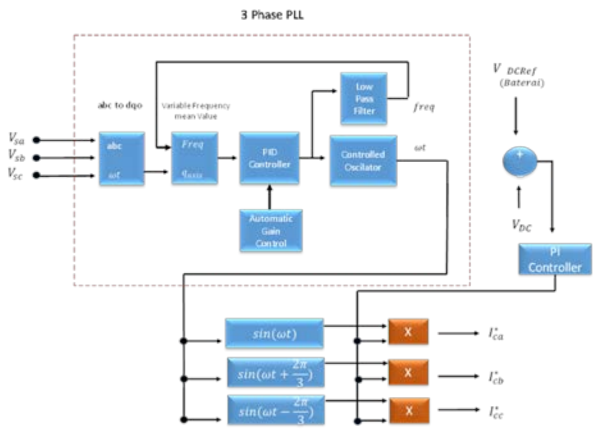

Fig 10. Current References Flow Generation

The first step, the three-phase input signal is converted to a rotation frame dq0 (Park transform) using the angular speed of the internal oscillator. The quadrature axis of the signal, proportional to the phase difference between the abc signal and the internal oscillator rotation frame, and filtered by the Mean (Variable Frequency) block.The Proportional-Integral-Derivative (PID) controller, with optional automatic gain control (AGC), maintains phase 0 differences by controlled oscillator performance. The PID output, according to the angular velocity, is filtered and converted to frequency, in hertz, which is used as the average value of the wave magnitude. A three currents with a phase difference of 120^0, the output of the controlled oscillator I * max (Ét) is inputted (multiplied) into 3 sinusoidal functions which have set the difference in phase angle to 120^0 ($I^*_{refa}, I^*_{refb}, I^*_{refc}$)) [7] [8].

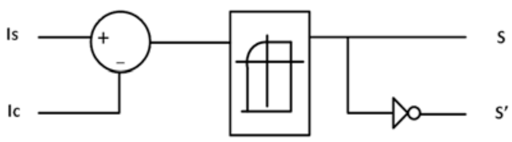

Fig.11. Hysteresis Band Current Controlled Method

The Vdc capacitor voltage is compared with the reference value Vdc * (Battery) to keep the energy stored in the capacitor constant. PI controller is used to adjust the error difference between the capacitor voltage and the reference voltage (battery). The output of the PI controller is multiplied by three sinusoidal signal quantities $I^*_{refa}, I^*_{refb}, I^*_{refc}$ from PLL. The channel reference source current is then compared with the channel currents Ia, Ib, Ic, and the result of comparison of each phase is called the reference compensator current from the active filter. The result of the comparison between this current and the APF output current is sent to the hysteresis controller to produce a modulation pulse to regulate the performance of the VSI switch. DC link voltage (VDC) of capacitor compared to the reference voltage (VDCref) . The PV or battery in produces an error value. This error value is processed by the PI controller resulting in a zero steady error in each reference current pattern. The output of the PI control is the peak value consisting of the active load power component and the power loss component to keep the capacitor voltage constant.

Firing Gate VSI

The VSI switch needed firing signal, to injected of current compensation to the grid. [10] [11]. There are several techniques for generating gate pulses including [12]:

1) Hysteresis current controller technique.
2) PWM controller technique
3) Space Vector PWM

In this study using the first method of Hysteresis current controller technique. The gate ignition signal is obtained from processing the reference current by the Hysteresis Current Control unit as shown in Fig. 11.The hysteresis current controller works like a comparator ie comparing the actual current of the source ($i_{refa}, i_{refb}, i_{refc,}, i_{refn,}$) and compensation reference currents (i_{ca}, i_{cb}, i_{cc})with the output form of an ignition pulse for VSI. The hysterical current control method works based on the PWM (Pulse Width Modulation) rule. This controller will issue pulses of one logic if the actual current is greater than the carrier current (PWM carrier) and will issue a logic of logic 1 if the actual current is smaller than the carrier current. The ignition pulse pulses are on the width of the reference current path [1]. A modeling of the pulse generation to serve a VSI switch pair that works in a complementary manner so the output pulse of this controller is reversed with a NOT gate. Thus we need four hysterical current control pairs that produce eight types of ignition pulses.
The ON and OFF times of the four switch pairs form the injection current flow patterns originating from the DC Link VSI voltage source. Figure 12 is the flowchart of the VSI switch gate firing signal generation process requiring 4 complementary pairs of pulses.

IV. Simulation Result and Discussion

Power System with Linier Loads Test before Filtered

A simulation of three phase power system modeling with linear load in the form of line voltage and load currents which have sinusoidal form. Each voltage and current waveform has a phase difference of 120^0. The format of each voltage and current can be expressed in (12) – (17):.

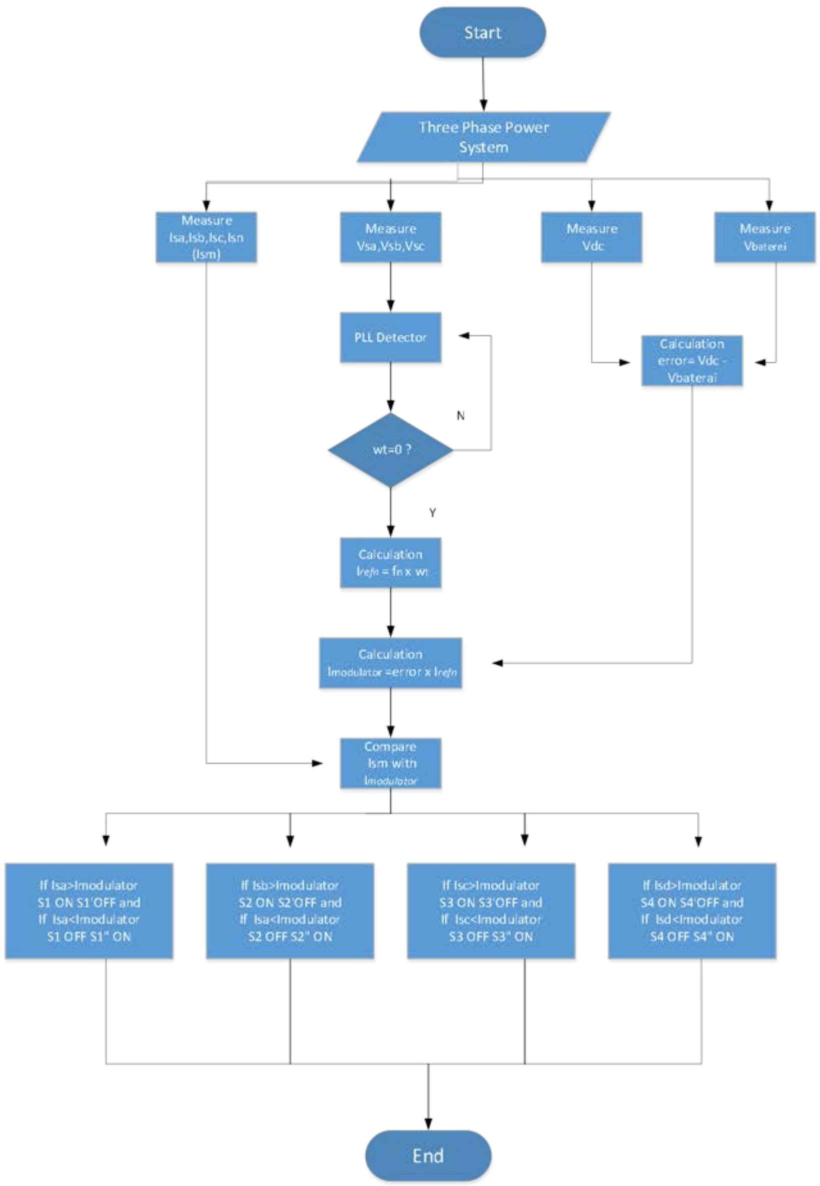

Fig.12. Flowchart of VSI Switch Firing Signal Generation

$$v_{sa} = v_{max} sin\omega t \quad (12)$$

$$v_{sb} = v_{max} \sin(\omega t + 120^0) \quad (13)$$

$$v_{sc} = v_{max} \sin(\omega t - 120^0) \quad (14)$$

$$i_{sa} = i_{max} sin\omega t \quad (15)$$

$$i_{sb} = i_{max} \sin(\omega t + 120^0) \quad (16)$$

$$i_{sc} = i_{max} \sin(\omega t - 120^0) \quad (17)$$

Simulation results, v_{max} *and* i_{max} are 380 V and 35 A.

The THD index is measured on the magnitude of the current source and current load then compared with the IEEE 519-1992 standard whether or not suitable. If the THD value is below the IEEE 519 standard rule, the modeling can be said to be successful, but if the index value is above the standard, the modeling still needs to be improved or not yet successful. Fig. 13 A flow chart of the THD current measurement appears.

Fig. 14 shows the value of the THD index of the line current and load current of the power system by 0%, this shows that the power system has a line current format in the form of pure sinusoid without distortion

Power System with Non Linier Loads Test before Filtered

The simulation results in this experiment show that the line current is a distorted sinusoidal waveform. It can be seen in Fig. 15 that the line current wave ripple are positive and negative cycles. But on the other hand the line voltage is still a sinusoidal voltage. This explains that current harmonics do not necessarily cause voltage harmonics. Fig. 16 shows THD power system index with non-linear load before filtering value is measured at a distorted load current of 29.74%.

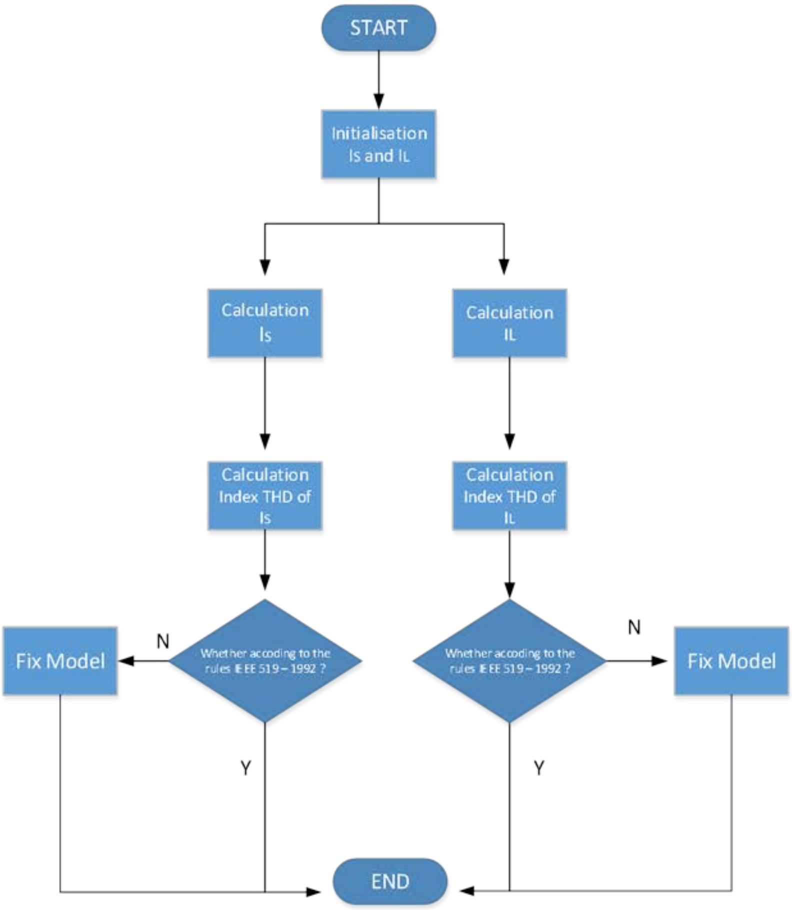

Fig.13. Flow chart of THD Channel Flow and Load Current measurement

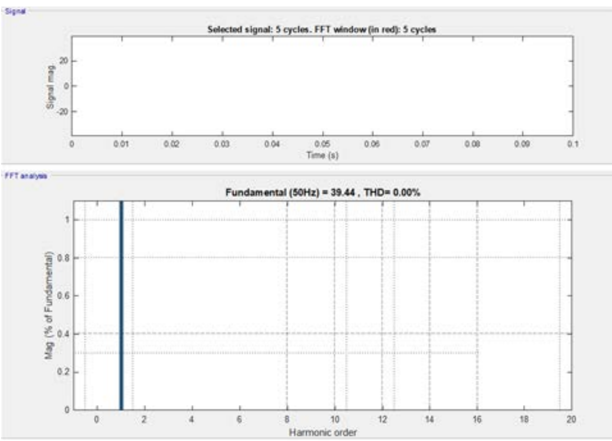

Fig.14. Power system THD index at linear load

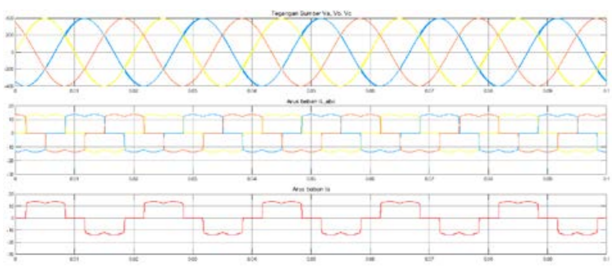

Fig.15. Voltage and Current Source of Power System Line at Nonlinear Loads

According to the IEEE 519 standard rules this figure illustrates that the power system is not in good condition so it is necessary to reduce the THD level to the recommended level below 4%.

Power System with Non Linier Loads Test After Filtered

Fig. 16 is a one-phase current waveform in the form of a distorted sinusoid. Harmonic waves that cause channel current waves to be distorted at frequencies of the order 5, 7, 11, 13, 17 and 19. Or harmonic waves at frequencies of 250 Hz, 350 Hz, 650 Hz, 850 Hz, and 950 Hz at maximum amplitude of 23% of its base amplitude.

Fig. 17 is a compensated current waveform each phase $i_{ca}, i_{cb}, i_{cc}, i_{cn}$. This format is the wave pattern produced by the VSI switch performance in injecting reactive power from the capacitor to the grid.

The source current format has an almost sinusoidal shape. This source current format is obtained by adding up the negative current load from the compensation current $(\boldsymbol{i_S = i_L - i_C})$.

Fig. 18 explains the THD index of the power system after the filter is installed. The source current is approaching the sinusoid but still has a little ripple but its existence is still tolerable. It appears that the THD value fell from 29.74% to 2.25% or reduced by 27.49%.

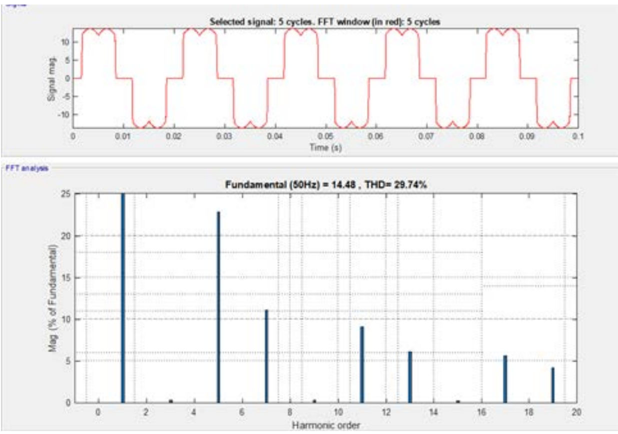

Fig.16. THD index of line source and load current system of power systems at nonlinear loads

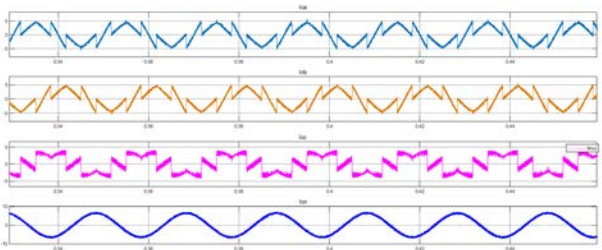

Fig.17. Compensastion Current $i_{ca}, i_{cb}, i_{cc}, i_{cn}$

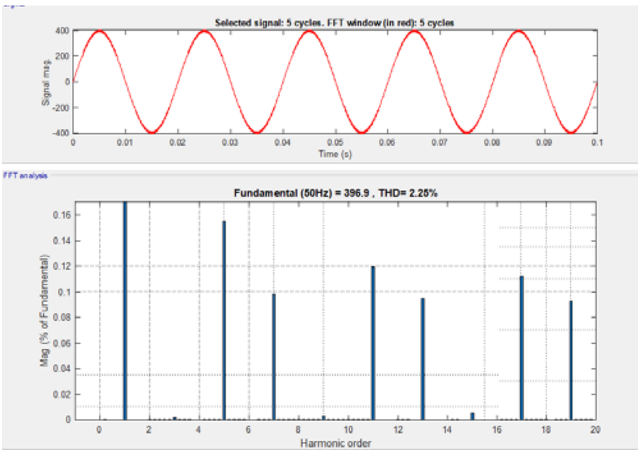

Fig.18. THD index Power System After Filtered

The amplitude of harmonic currents that is still disturbing lies in the order 5,7,11,13,17 and 19 with the amplitude of the source line voltage at a value of 22.5%, 11.25%, 9%, 6%, 6.5, respectively. % and 4.5%.

V. Conclusion

Modeling active filter combining solar energy with a three-phase four-wire electricity network has been successfully built using Matlab Simulink tools. Solar energy is stored in batteries and injected into the net through a capacitor on the DC link Voltage Source Inverter (VSI).The DC link capacitor voltage is kept constant so that the compensation process is operating properly. Simulation results show that the THD of the system can be pressed quite significantly, from 30.02% to 2.25%. This indicates that this modeling is feasible to be implemented as a power system. For further research this power filter system can be developed making reactive power compensation control valid throughout the day ie during the day and night. Research development on this topic can also be applied to single phase power systems.

Acknowledgment

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