

Simulink Model of Reference Frame Theory Based Three Phase Shunt Active Filter

P. Nammalvar, P. Meganathan, A. Balamuguran

Abstract—Among various active filters, shunt active filter is a viable solution for reactive power and harmonics compensation. In this paper, the SRF plan is used to generate current reference for compensation and conventional PI controllers were used as the controller to compensate the reactive power. The design of the closed loop controllers is reserved simple by modeling them as first order systems. Computationally uncomplicated and efficient SVM system is used in the present work for better utilization of dc bus voltage. The rating of shunt active filter has been finalized based on the reactive power demand of the selected reactive load. The proposed control and SVM technique are validated by simulating in MATLAB software.

Keywords—Shunt Active Filter, Space vector pulse width modulation, Voltage Source Converter, Reactive Power, Synchronous Reference Frame, Point of common coupling.

I. INTRODUCTION

REACTIVE power compensators based on voltage-sourced inverters (VSI), such as Static synchronous compensator (STATCOM) [6], are finding increasing applications at different power levels. There are several advantages to this when compared to conventional solutions such as dynamic speed response, maintaining unity power factor for varying loads, etc. [13]. Classic utility-side symptoms of reactive power problems are distorted voltage waveforms, blown shunt capacitor fuses, and transformer overheating [1]. For continuously varying load, which is the case in most of the process industries, these fixed tuned filters fail to compensate the reactive power effectively. The life span of passive elements is less due to load harmonics current sinking which in turn requires regular maintenance.

In order to avoid these problems, various active power filter configurations have been recommended so far. Of these configurations, parallel active filter has been accepted as one of the best/promising viable solutions to the present harmonic compensation [2]. Shunt active power filters compensate reactive current by injecting equal-but-opposite kneejerk compensating current. In this container the shunt active power filter operates as current source, injecting the reactive power

components generated by the load but by through phase shifted by 180° [3]. This principle is applicable to any kind of load that is considered a harmonic source. Furthermore, with a suitable control scheme, the active power filter can very well balance the current harmonics. In this way, the power distribution system sees the nonlinear load and the active power filter as an ideal resistor [2].

Shunt active power filters are normally implemented with pulse-width modulate voltage source inverters. In this category of application, the PWM-VSI operates as a current controlled voltage source. In this work, 2-level PWM-VSI has been used to put into operation such a system as shown in Fig. 1.

The control system is composed by an algorithm to determine the reference currents that are injected by the shunt active filter and another one to keep the voltages of the dc-link capacitors regulated and balanced. Many kinds of control strategies in shunt active filter have been developed so far [4].

In the present study, the synchronous reference frame strategy is used to generate current reference for compensation and conventional PI controllers were used as the controller. The synchronous reference frame strategy utilizes co-ordinate transformations to separate the reactive and harmonic content in the load current. The design of the closed loop controllers is kept simple by modeling them as first order systems [5], [8]. Space vector modulation (SVM) technique was originally developed as a vector move towards pulse-width modulation (PWM) used for three-phase inverters. It is an added complicated method for generating sine wave that provides an advanced voltage to the motor with lower total harmonic distortion. The restrictions space vectors needs to be practical according to the section where the output voltage vector is located. Computationally simple and competent SVM technique used to exploit DC bus voltage more efficiently and generates less harmonic distortion in a three phase voltage source inverter [7], [11], [13].

II. CURRENT REFERENCE GENERATOR, CONTROLLER AND PLANT

The first part of the design is to generate the current reference. There are several methods to generate current reference. The present study is based on the application of co-ordinate transformations to separate the reactive and harmonic content of the load current. The strategy used is the synchronous reference frame (SRF) strategy. Once the current reference has been generated, the next work is to design the controller. For this, one needs to analyze the system and identify the job of the controller.

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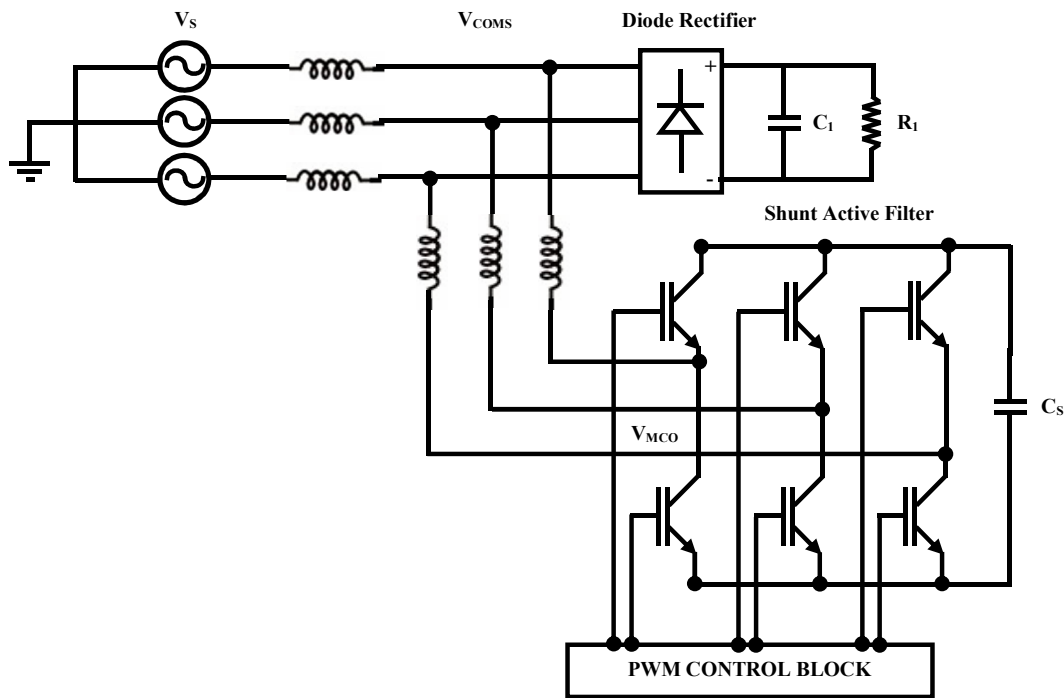


Fig. 1 Shunt Active Power Filter Topology

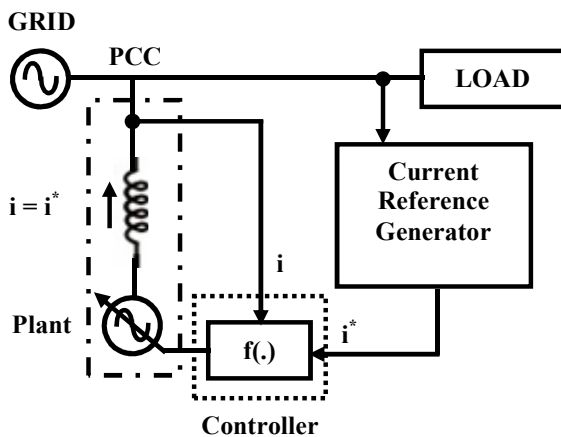


Fig. 2 Conceptual Representation of the Complete System

Remembering that the STATCOM is basically a voltage source inverter and that we have the current reference that needs to be tracked, it is clear that the only job that is left is to make the output current of the voltage source inverter follow the current reference. This can be done in two ways. One is by current control of VSI and the other is through voltage control of VSI. The present study utilizes the space vector modulation technique to control the VSI i.e. it follows a voltage-based control of VSI. This requires the current reference to be converted into an equivalent voltage. This is where the controller is to be employed. Thus, the job of the controller in the present case is to convert the current reference into an equivalent voltage reference to facilitate a voltage based control of the VSI [6], [8]. Combining the above facts, the complete system can be visualized as given in Fig. 2. Here, the

VSI is represented as a variable voltage source, as the output voltage of the VSI varies in response to the control signal (so that the output current tracks the reference i^*).

The synchronous reference frame strategy uses co-ordinate transformations to generate the current reference. It employs the well-known Clarke's Transformation and Park's Transformation for this purpose. Though, the transformations remind us of the 'primitive machine model' concept, it may be noted that here there is no need to satisfy the condition of 'Power Invariance' as the transformations are employed just to reduce the computations involved in generating the current reference and not to develop any equivalent system. Once the controller output is obtained, reverse transformations are employed to transform the quantities back to the actual three-phase system. Thus, 'Power Invariance' never gets into the picture. Consider a three-phase balanced system given by (1):

$$\begin{aligned} v_a &= V_m \sin \omega t \\ v_b &= V_m \sin(\omega t - \phi - 120^\circ) \\ v_c &= V_m \sin(\omega t - \phi + 120^\circ) \end{aligned} \quad (1)$$

The system being balanced, just two parameters can define it completely rather than three parameters (V_a, V_b, V_c) as given above. Knowing any two of (V_a, V_b, V_c), we can always write down the third one since $V_a + V_b + V_c = 0$ (Though a sinusoidal system is considered here for simplicity, any non-sinusoidal balanced three phase system can be represented by just two parameters) [7]. This fact that two parameters are enough to describe a balanced three phase system should be convincing enough to accept the transformation of a three phase balanced system (a, b, c) to a two axis system ($\alpha-\beta$) as shown in Fig. 3. The $\alpha-\beta$ plane is

often called a stationary frame of reference to distinguish it from the other two-axis plane [10], [12].

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

This transformation lets us deal with just two equations in the place of three equations. Thus, it saves a lot of computational effort. As will be seen from the following discussions, it provides a simpler means to generate the current reference. Park's transformation is nothing more than finding the components of the load current along the direction of the voltage space vector and at quadrature to it. The voltage space vector has been taken as the d-axis and an axis primary the d-axis by 90° is full as the q-axis. The benefit of establishing the voltage space vector as one of the axis in the d-q plane is that the d-component and q-component of fundamental current would directly give the active and reactive components respectively and ac components current in it gives the harmonics [8].

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (3)$$

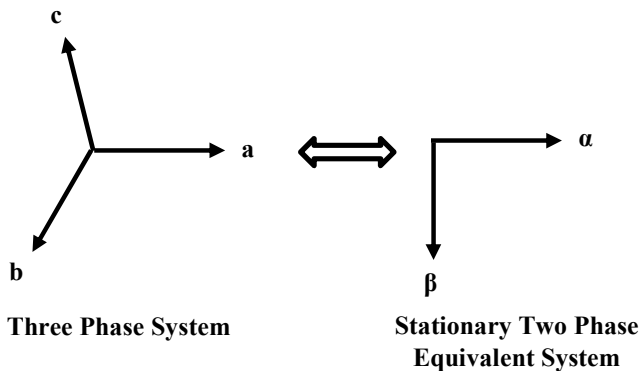


Fig. 3 $\alpha - \beta$ Plane

III. REFERENCE CURRENT GENERATION IN THE D-Q PLANE

The block diagram representation of the control strategy used is given in Fig. 4. The three phase current of the load and converter are transformed into the synchronously rotating reference frame using the Clarke's and Park's transformation method. The unit vector required for the orientation of converter and load currents along the grid voltage is generated. The load current will be a composite current containing active and reactive component. After orientation, q-axis load current is extracted using low pass filters in Fig. 4. These filtered d-axis and q-axis currents are the active and reactive parts respectively of the fundamental load currents [5], [8]. There is a DC bus PI controller whose output is added with the d-axis harmonics reference to generate the total d-axis current reference for the current controller. There are separate PI controllers to control the d-axis and q-axis current of the

converter.

The outputs of these current controllers are added with feed forward terms given in (4) and (5) to generate the d-axis and q-axis voltage references for the converter. Finally d-axis and q-axis voltage references are converted back to 3-phase stationary voltage references using the unit vectors [5]. These reference signals are fed to the PWM modulator to generate the gate pulses for the converter.

$$\begin{aligned} V_d &= i_d R + L \frac{di_d}{dt} - \omega L i_q + V_g \\ V_d &= PI(i_d) - \omega L i_q + V_g \end{aligned} \quad (4)$$

$$\begin{aligned} V_q &= i_q R + L \frac{di_q}{dt} + \omega L i_d \\ V_q &= PI(i_q) + \omega L i_d \end{aligned} \quad (5)$$

where, $V_d, V_q = d$ and q axis voltage command; $L, R =$ Inductance and resistance of the coupling inductor; $i_d, i_q = d$ and q axis current of the converter; $PI(i_d), PI(i_q) = d$ and q PI controller outputs

IV. SPACE VECTOR PWM

The Space Vector Modulation was tried out in the present study as it optimally utilizes the DC bus voltage in the linear modulation range. However, the implementation of the space vector modulation technique by means of sector identification and dwelling time calculation is computationally complex [9]. The principle of space vector PWM in three-phase mathematical system can be represented by a space vector. For example, known a set of three-phase voltages, a space vector can be distinct by (6)

$$v(t) = \frac{2}{3} \left[v_a(t)e^{i\theta} + v_b(t)e^{j\frac{2\pi}{3}} + v_c(t)e^{i\frac{4\pi}{3}} \right] \quad (6)$$

where $V_a(t), V_b(t),$ and $V_c(t)$ are three sinusoidal voltages of the same amplitude and frequency but with $\pm 120^\circ$ phase shifts. The space vector at any given time maintains its magnitude. Therefore the space vector modulation was implemented by the conventional naturally sampled sinusoidal, with a special type of zero sequence component mixed to the sine references. This modified sinusoidal PWM references can be shown to be same as the space vector references.

Steps involved in the derivation of new space vector modulating signals from three phase sinusoidal references are [5], [9].

1. Find the three phase references for sinusoidal pulse width modulation (SPWM).
2. Compute the minimum of the absolute references at each instant.
3. Add half the value of the reference sinusoid of minimum absolute value at each instant to all three SPWM references, as offset.
4. Compare the modified SPWM references to triangular carrier wave to generate the space vector PWM (SVPWM) pulses.

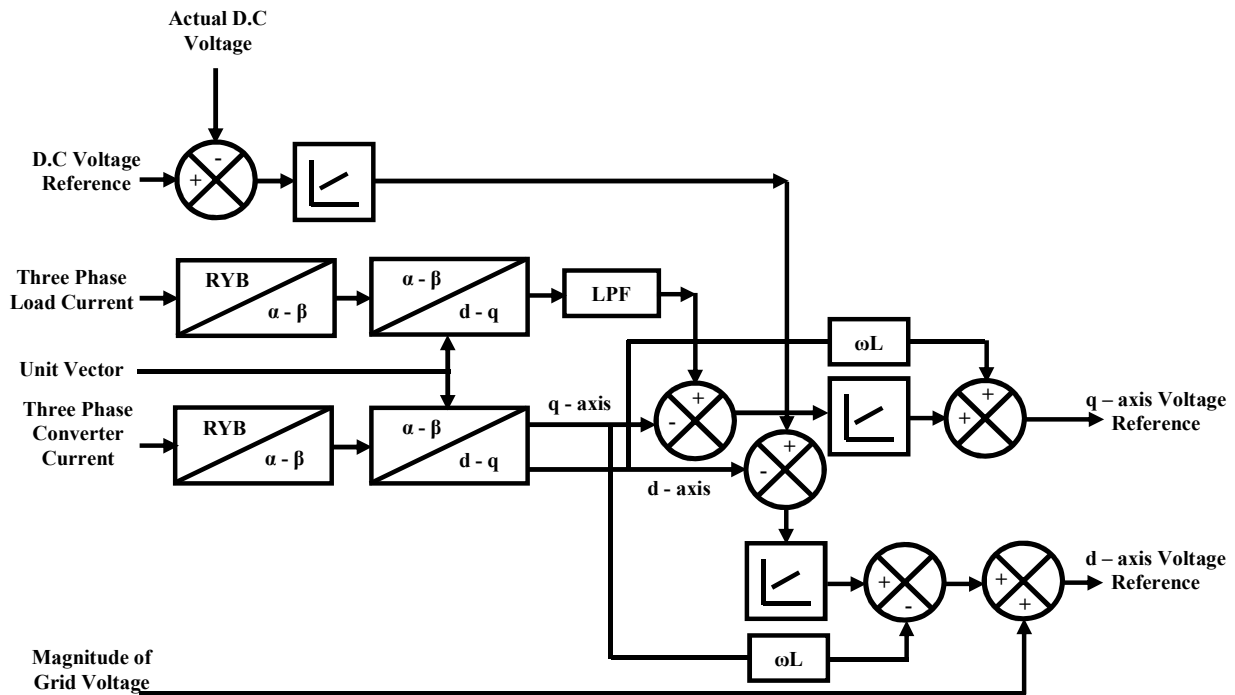


Fig. 4 Block Diagram of Control Circuits

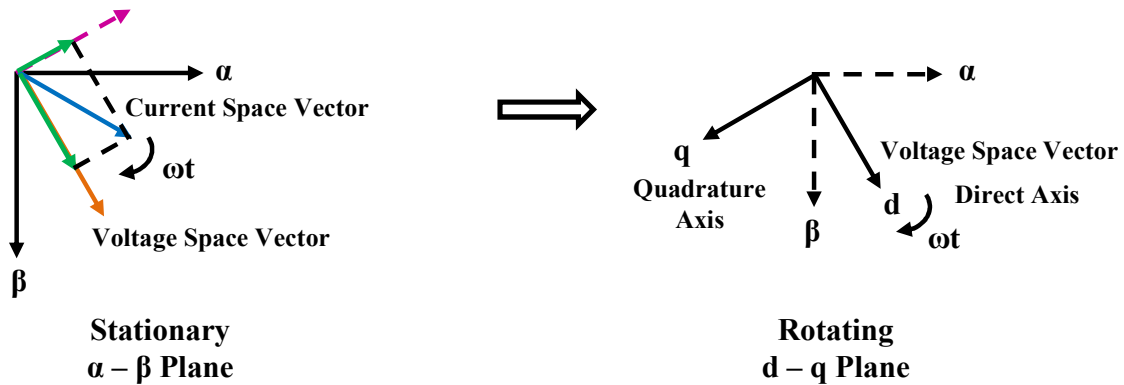


Fig. 5 d-q Plane

The SPWM reference, the offset and the modified SPWM reference for one phase generated are shown in Fig. 5. Though the phase voltage reference of modified space vector modulation is not sinusoidal (and contains a zero sequence component), the line to line voltage will be purely sinusoidal as the zero sequence component will get cancelled in the line to line voltage.

Equating real and imaginary part, we obtain (7) and (8):

$$v_\alpha = \frac{2}{3} \left[v_a + v_b \cos\left(\frac{2\pi}{3}\right) + v_c \cos\left(\frac{2\pi}{3}\right) \right] \quad (7)$$

$$v_\beta = \frac{2}{3} \left[v_b \sin\left(\frac{2\pi}{3}\right) + v_c \cos\left(\frac{2\pi}{3}\right) \right] \quad (8)$$

The SVPWM reference is same as that of space vector modulation proving the equivalence. Naturally SVPWM compares a low frequency target reference waveform ref V

(usually a sinusoid) against a high frequency carrier waveform. The phase leg is switched to the upper DC rail when the reference waveform is greater than the triangular carrier and to the lower DC rail when the carrier waveform is greater than the reference waveform.

V. SIMULATION RESULTS

The control algorithm discussed in previous section has been validated by simulating in MATLAB software.

These extracted currents are given as a reference signal to shunt active filter in Fig. 6. The equivalent and opposite of the reactive current load current was supplied by the shunt active filter. Therefore the load draws only active current from the grid. The shunt active filter was simulated in MATLAB software and a detailed implementation study was carried out to understand the challenges in the hardware implementation.

The schematic diagram of the shunt active filter is shown in Fig. 8.

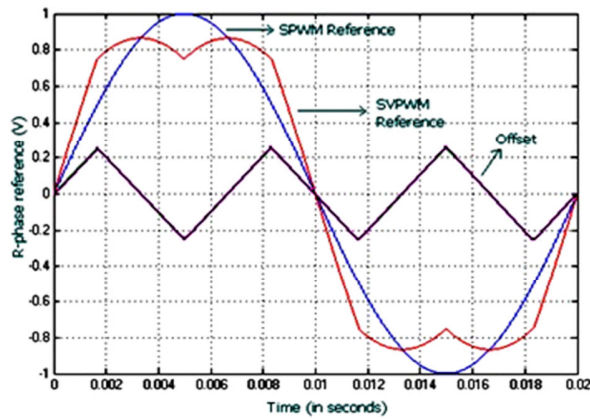


Fig. 6 Generation of SVPWM Reference Signal

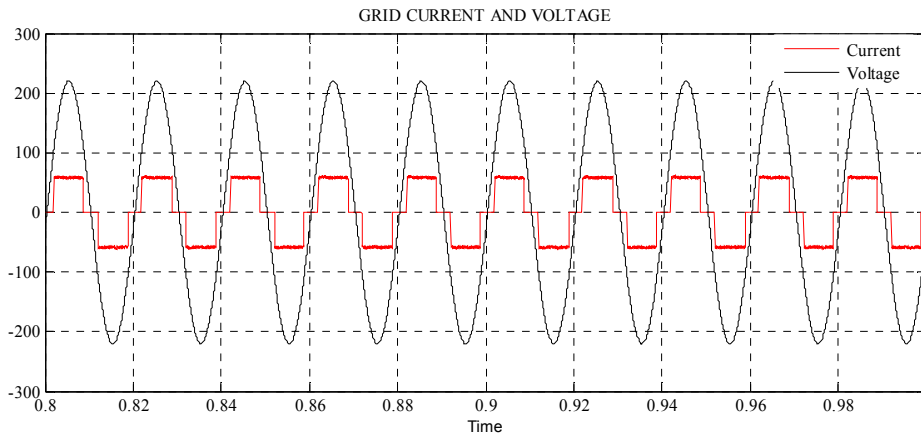


Fig. 7 Voltage and Current Waveform before Compensation

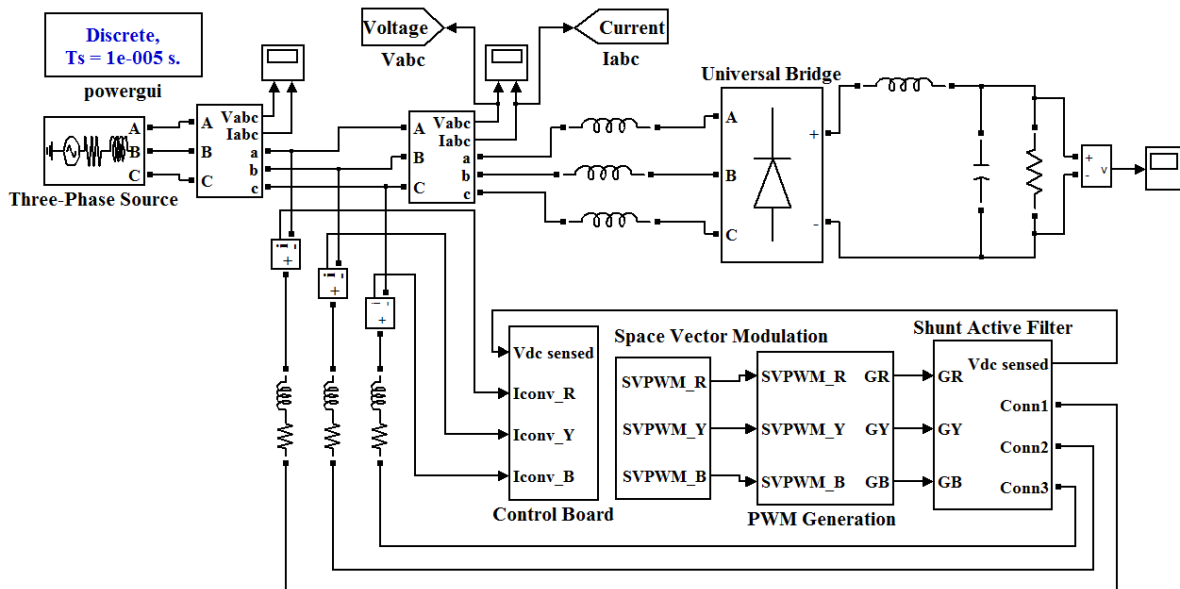


Fig. 8 Simulation Circuit Diagram of Shunt Active Filter

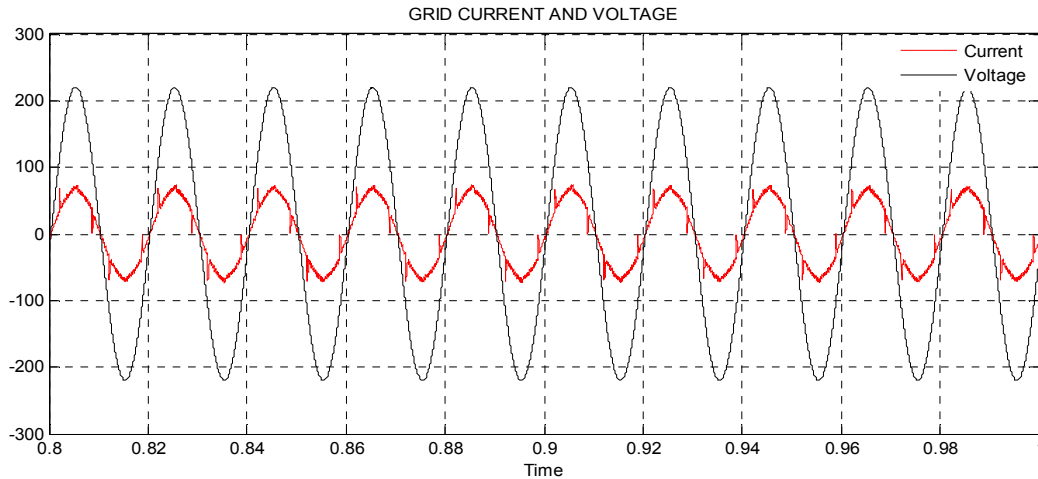


Fig. 9 Voltage and Current Waveform after Compensation

By considering grid voltage, drop across choke and losses, the DC bus voltage was fixed at 600V. Then the voltage controller of the shunt active filter was activated and the DC bus voltage was boosted to 600V. Once the DC bus voltage reached 600V, the current controller was activated to start harmonic compensation.

The reactive content of the load current extracted using synchronous reference frame control method and it will be the current reference to the converter. Once the active filter was crooked-on, I_{sa} became sinusoidal and in phase with present the fleeting that occurred when the active filter inverter was turned-on. The current distortion and the harmonics were immediately corrected again. Due to the ever increasing number of nonlinear loads, revised regulations impose more stringent limits to harmonic pollution injected by this SAF.

The current increased in amplitude because the demanded energy becomes better with the original load, but the source current vestiges sinusoidal and in phase with the voltage. The ripple observed in the supply current waveform when the shunt active filter in use occurred due to the inverter commutation.

However, it only seems to be pertinent because the loads used to obtain the experimental results be fairly small. Operating with superior loads the current ripple would be trifling. Besides, this is an elevated frequency wave, which is just drinkable by the power system.

Figs. 7 and 9 show the AC bus voltage and current, converter and grid current before and after reactive current compensation. It is found that Shunt active power filter compensate reactive current by injecting equal-but-opposite reactive compensating current.

To determine the reduction of harmonic current compensation of total harmonic distortion by using the FFT analysis in MATLAB Simulink models in Figs. 10 and 11.

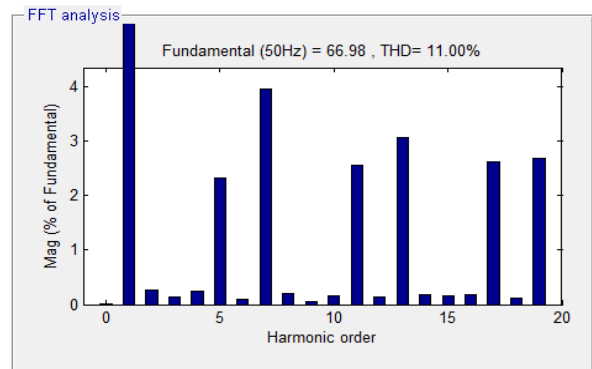


Fig. 10 THD Analysis of Before Compensation

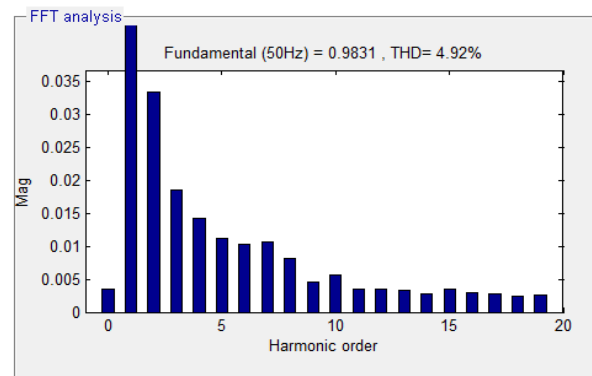


Fig. 11 THD Analysis of After Compensation

VI. CONCLUSIONS

This paper begins with surveying the conventional reactive and harmonic compensation equipment's and found active filters are being developed as a viable alternative to passive filters for meeting harmonic distortion limits imposed on distribution systems. The controllable parameters of the STATCOM for compensating the reactive and harmonic current were derived. In the present study, the synchronous reference frame based control strategy was used for compensating the reactive power drawn by the fluctuating

industrial load. Typical rectifier load was designed with RL circuit and simulated in MATLAB to finalize the rating of shunt active filter based on the reactive demand of the load. The control strategy and modified space vector modulation were validated by simulating using MATLAB software and the result studied. The study showed that the reactive power demand of the load was effectively compensated and maintained unit power factor.

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