

## Harmonic Reduction in Variable Frequency Drives Using Active Power Filter

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### Abstract

In this paper Voltage Source Inverter (VSI) is used to supply a variable frequency variable voltage to a three phase induction motor drive in a variable speed application. One important complication is that, Voltage Source Inverter (VSI) used in VFD causes non-sinusoidal output voltage and current due to presence of harmonics. Shunt active filter with VSI topology is proposed for current harmonic elimination. The current control scheme proposed for SAPF is Synchronous Reference Frame theory applied to SVPWM. The reference current can be calculated by using Reference Frame Transformation, reference current are transformed from a-b-c stationary frame to d-q rotating frame. In SVPWM technique, the Active Power Filter reference voltage is generated and desired Active Power Filter output voltage is generated by SVPWM. The analysis of simulation results are carried out in MATLAB/SIMULINK model.

**Keywords:** active power filter, voltage source inverter, pulse width modulation, synchronous reference frame transformation, space vector modulation

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### 1. Introduction

In Variable Speed application, Voltage Source Inverter is commonly used to supply a variable frequency variable voltage to a three phase induction motor. In this PWM drives are more efficient and typically provide higher levels of performance. A suitable Pulse Width Modulation technique is employed to obtain the required output voltage of the inverter. The most common AC drives today are based on sinusoidal pulse-width modulation SPWM. Induction motor is rugged, reliable, and single-fed machine; it can directly absorb the reactive power from the utility with this device, we can get two advantages: one is that we can get a low start current; the other is that we can change the motor speed conveniently by controlling the output frequency of the ASD.

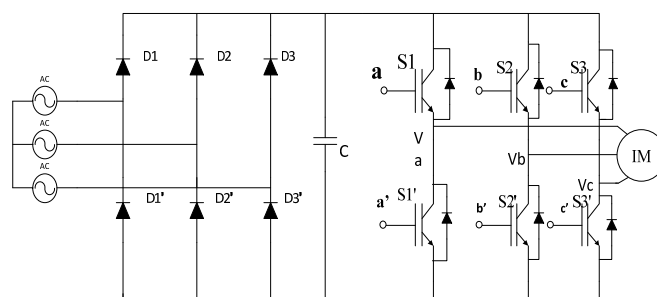


Figure 1. Conventional Induction Motor Drive

Two basic types of inverters are exist in general. Current source inverter (CSI), employing a dc link inductance across the inverter and this provides a switched current waveform at the motor output terminals. CSI are robust in operation and reliable due to the insensitivity to short circuits and noisy environment. Voltage Source Inverter (VSI), employing a

dc link capacitor and providing a switched voltage waveform and they are commonly used when compared to Current Source Inverter since the use of Pulse Width Modulation (PWM) in them allows efficient and smooth operation, which is free from torque pulsations and cogging. Furthermore, the frequency range of VSI is higher and they are usually more expensive when compared to CSI drives of the same rating. Both Voltage Source Inverters and Current Source Inverters are used in adjustable speed AC drives. However, Voltage Source Inverters with constant Volts/Hertz (V/f) are more popular, where the need of high accuracy of speed control is not crucial and for the applications without position control requirements [1].

Sinusoidal Pulse Width Modulation technique is applied to Voltage Source Inverter, in sinusoidal PWM instead of maintaining the width of all pulses the same as in the case of multiple PWM, the width of each is varied in proportion to the amplitude of a sine wave evaluated at the same pulse. The distortion is reduced significantly compared to multiple PWM. A high-frequency triangular carrier wave  $V_c$  is compared with a sinusoidal reference  $V_r$  of the desired frequency. The intersection of  $V_c$  and  $V_r$  waves determines the switching instants and commutation of the modulated pulse which is shown in Figure 2. The modulation index controls the harmonic content of the output waveform [2-4].

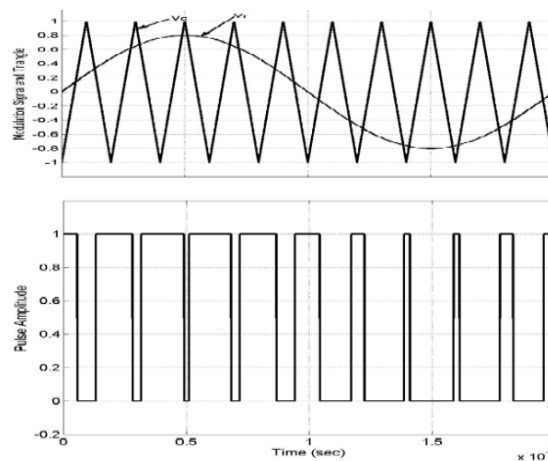


Figure 2. Sinusoidal Pulse Width Modulation Waveform

But at the same time, AC inverter can also cause harmonics in this drive and these harmonics will reduce the power factor and the motor performance gets affected in this system. The harmonic effects in induction motor are noise vibration, shaft deflection, overheating, excessive losses, harmonic torques, oscillation, low efficiency and shorten induction motor life operation.

Because of these problems, the harmonic filters have to be designed by considering all of those factors. There can be different types of filters that are used in order to reduce the harmonic distortion. Passive filters have been used as a solution to solve harmonic current problems, but they present several disadvantages, namely: they only filter the frequencies they were previously tuned for; their operation cannot be limited to a certain load; resonances can occur because of the interaction between the passive filter and other loads, with unpredictable results. To cope with these disadvantages, recent efforts have been concentrated in the development of active power filters. In which active harmonic filters are electronic devices that eliminate the undesirable harmonics on the network by inserting negative harmonics into the network. The Active Power Filters are normally available for low voltage networks [5-7].

## 2. Active Power Filter

Active Power Filter offers a flexible and versatile solution for mitigation of harmonic current and voltage to improve the voltage quality problems. Active filters have the advantage to compensate for harmonic without fundamental frequency reactive power concerns. The rating of

the active power can be less than a comparable passive filter for the same non-linear load and the active filter will not introduce system resonances that can move a harmonic problem from one frequency to another.

They are connect to low and medium voltage distribution system in shunt or in series. The Active Power Filters consist of active components such as IGBT-transistors and gate pulse are generated by using Synchronous Reference Frame theory applied to space vector pulse width modulation.

### 2.1. Series Active Power Filter

Series Active Power Filter is connected to the system through a coupling transformer. The compensation voltage is used to cancel the voltage harmonics of the load source

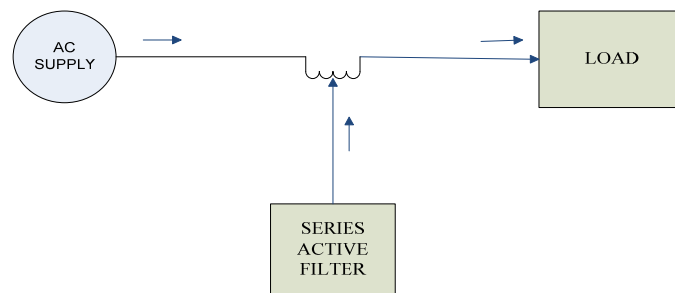


Figure 3. Series Active Power Filter

### 2.2. Shunt Active Power Filter

The main aim of an shunt Active Power Filter (APF) is to generate compensating currents into inverter output for canceling the current harmonics contained in the induction motor load current. This will thus result in sinusoidal. The current compensation characteristic of the shunt active power filter is shown in Figure 4.

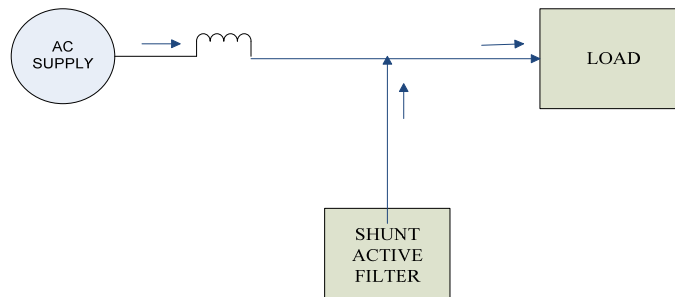


Figure 4. Shunt Active Power Filter

## 3. Synchronous Reference Frame Theory

In this Synchronous Reference Frame theory based d-q model is discussed. Reference frame transformation refers to transformation from a-b-c to d-q-0 axes. Coordinates from a three-phase a-b-c stationary coordinate system to the d-q-0 rotating coordinate system is carried out. Here first transformation is from a-b-c to alpha-beta coordinates and second transformation is from alpha-beta to d-q-0 co-ordinates. Two different transformation matrix need to be required Clarke Transformation and park transformation [9, 13].

Instantaneous voltage and current in three phase circuit it is mathematically expressed in Space Vector form. These three vectors a-b-c are displaced by an angle of  $120^\circ$  from each other is shown in Figure 5.

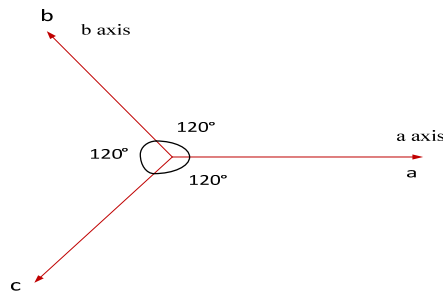


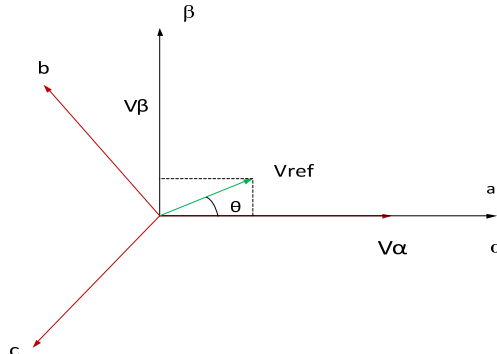
Figure 5. Vector Diagram for a-b-c axis

### 3.1. Clarke Transformation

The forward Clarke (1943) transform does a magnitude invariant translation from a three phase system into two orthogonal components. If the neutral - ground connection is neglected, the sum of variables in a three-phase system (a-b-c) is equal to zero, and there is redundant information. Therefore, the system can be reduced to two variables, called  $\alpha$  and  $\beta$ . The Clarke transform is given by:

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

Reference frame theory based d-q model is presented. Instantaneous voltages in the a-b-c coordinates are transformed to two axis coordinates represented by  $\alpha$  and  $\beta$  shown in Figure 6.

Figure 6. Vector Diagram for a-b-c to  $\alpha - \beta$  axis

### 3.2. Park Transformation

The Park (1929) transform is a vector rotation, which rotates a vector (defined by its quadrature components) through a specified angle. The Park transformation is given by following set of equation:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (2)$$

In three phases balanced system neutral current is zero, and zero sequence current does not exist. Voltage in  $\alpha$  and  $\beta$  reference frame is express as shown in Equation (2). The Voltage in  $\alpha$  and  $\beta$  reference frame is further transform in rotating reference frame with  $\omega_r$  as angular velocity in d-q reference frame. Instantaneous voltages in the  $\alpha - \beta$  coordinates are transformed to d-q coordinates shown in Figure 7.

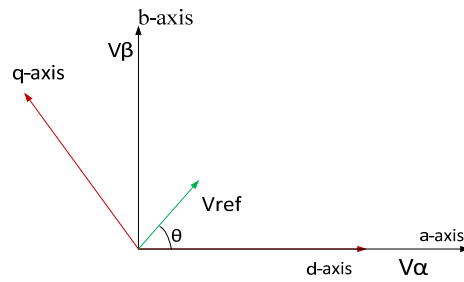


Figure 7. Vector Diagram for  $\alpha - \beta$  axis to d-q axis

### 3.3. Proportional Integral Controller

The PI controller is very important part for the SAPF. It consists of proportional term and integral term. With this element, the best control performance of the SAPF is obtained. PI focuses on the difference (error) between the Process Variable (PV) and the Set-Point (SP), the difference between harmonics current reference signal  $I_H$  and the filter current  $I_f$ . PI controller algorithm involves two separate parameters; the Proportional and the Integral.

The Proportional value determines the reaction to the current error; the Integral determines the reaction based on the sum of recent errors. Average sum of these two actions is used to adjust the process of the plant. By correctly "tuning" these two constants in the PI controller algorithm, the PI controller can provide control action designed for specific process requirements [10].

### 3.4. Closed Loop Current Control Scheme using Synchronous Frame Theory

The control scheme shown in Figure 8 consists of inner current control loop and outer voltage control loop. The PI controller of the voltage control loop gives a current command required to maintain the DC bus voltage to set value. This is added to the AC component of d axis of the load current. It gives the current reference value for d axis component. The reference for q axis is obtained after the orientation of load current [10].

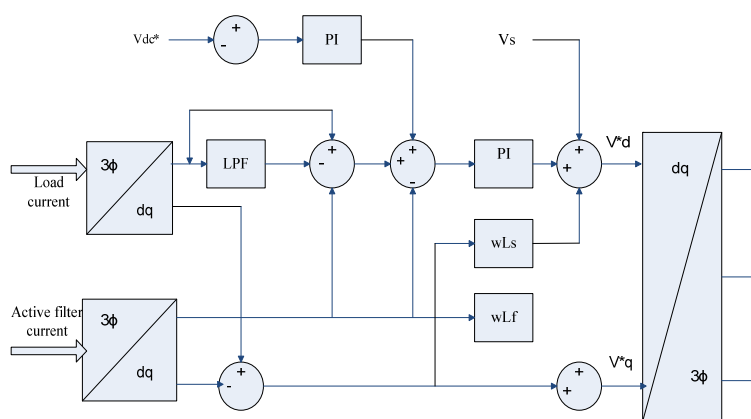


Figure 8. Block Diagram of Closed Loop Current Control Scheme Using Synchronous Frame Theory

## 4. SVPWM

SVPWM signals can be generated directly from the instantaneous reference phase voltages. Each reference phase voltage is compared with the triangular carrier, and the pole voltages for individual phase are generated independently of each other. To obtain the maximum possible peak amplitude of the fundamental phase voltage in linear modulation, a common mode voltage  $V_{offset}$  is added to the reference phase voltages, where the magnitude of  $V_{offset}$  is given by:

$$V_{offset} = - \frac{(V_{max} + V_{min})}{2} \quad (3)$$

Where  $V_{max}$  the maximum magnitude of the three is sampled reference phase voltages and  $V_{min}$  is the minimum magnitude of the three sampled reference phase voltages [3, 8, 12].

## 5. Simulation Results

### 5.1. Variable Frequency Drive without Active Power Filter

This section represents the simulation result of Variable Frequency Drive before connecting Active Power Filter by using MATLAB/SIMULINK. Figure 9 and Figure 10 shows output current waveform and FFT analysis of VFD without connecting active filter.

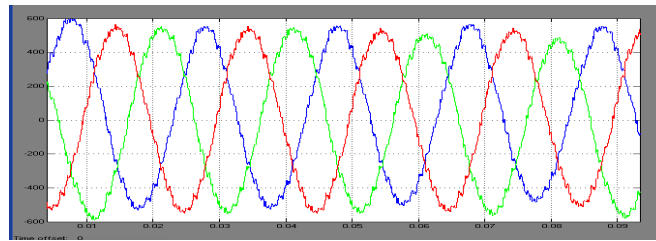


Figure 9. Output Current Waveform of VSI Fed Induction Motor

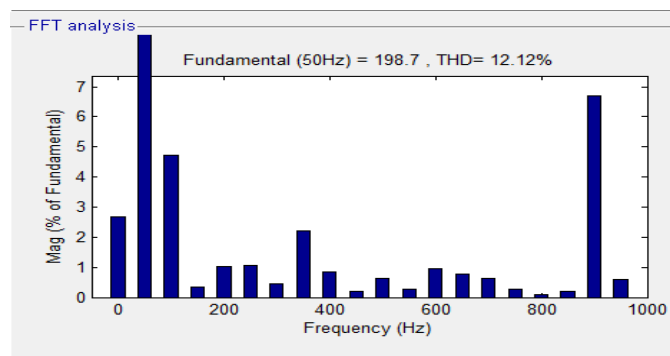


Figure 10. THD Level for VFD Without Filter

### 5.2. Synchronous Reference Frame Transformation

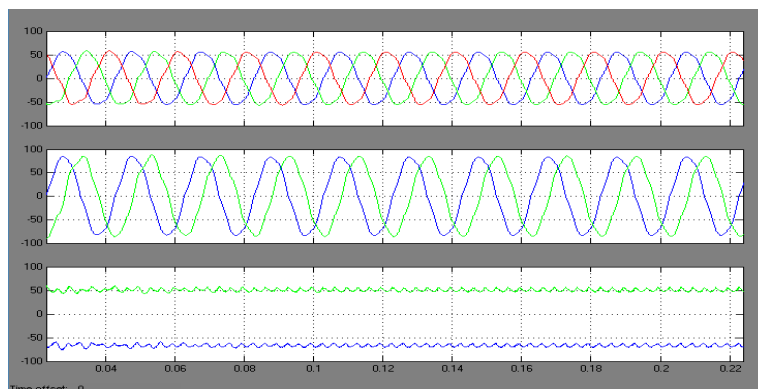


Figure 11. Output Waveform of Reference Frame Transformation

The 3 $\phi$  sine waves with 120 degree phase shift are converted to 2 $\phi$   $\alpha$ - $\beta$  and then converted to d-q axis. The transformation circuit is developed in the MATLAB/SIMULINK. Figure 11 shows the  $V_a$ ,  $V_b$ ,  $V_c$  sine wave with 120 degree phase shift is converted to 2 $\phi$  wave form ( $\alpha\beta$ ) that is 90 degree phase shift each other when  $\alpha$  is 0 degree and  $\beta$  is 90 degree. Again  $\alpha$ - $\beta$  is transformed to d-q axis.

### 5.3. SVPWM Pulse Generation

Three phase reference voltage is compared with the triangular carrier wave to produce gate pulse to VSI used in Shunt Active Power Filter. Figure 12 reference and triangular waveform and Figure 13 shows the gate pulse for VSI inverter.

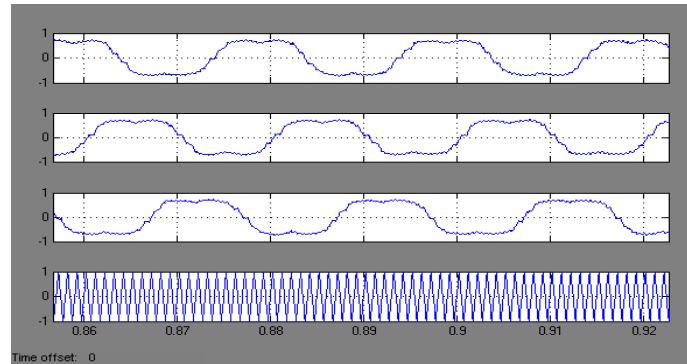


Figure 12. Three Phase Reference Voltage and triangular waveform

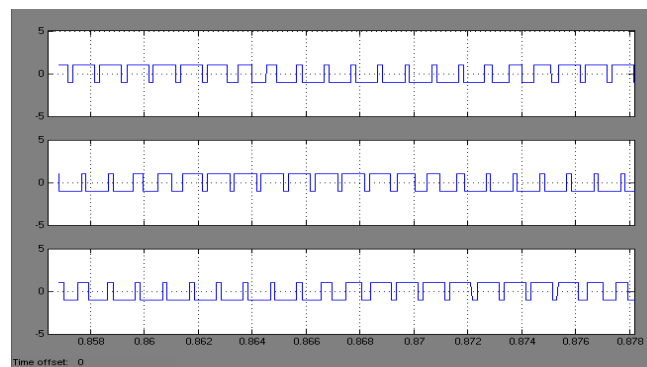


Figure 13. SVPWM Pulse Generation for VSI

### 5.4. Variable Frequency Drive with Active Power Filter

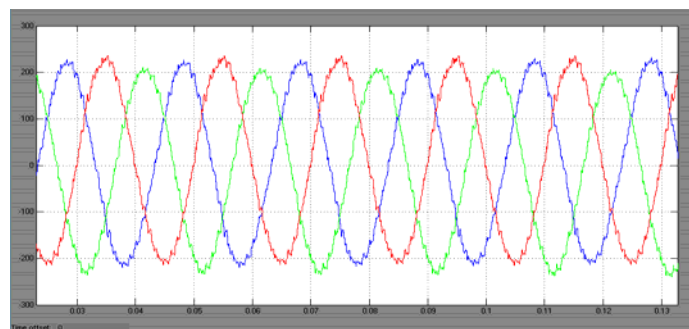


Figure 14. Output Current Waveform of VFD with Filter

In this Shunt Active Power Filter (SAPF) is connected to load side in order to reduce the output current harmonics. The current control scheme proposed for Shunt Active Power Filter (SAPF) is Synchronous Reference Frame theory and SVPWM technique is employed to generate pulse to SAPF by using MATLAB/SIMULINK. Figure 14 and Figure 15 shows output current waveform and FFT analysis of VFD with connecting active filter.

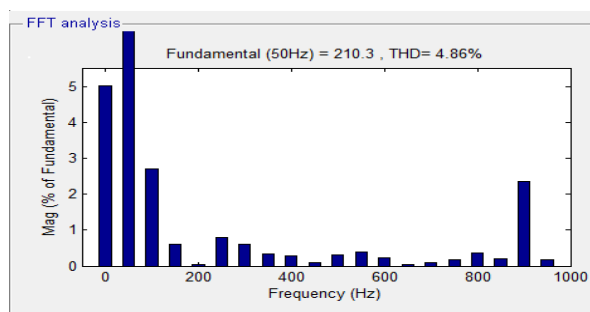


Figure 15. THD Level for VFD with Filter

## 6. Conclusion

This paper presents a novel Synchronous Reference Frame theory with SVPWM technique is used for controlling the injection of the compensating current. Shunt Active Power Filter is developed for harmonic reduction in VSI based Induction motor drive. From the simulation results it is observed that Total Harmonic Distortion (THD) is reduced from 12.12% to 4.86% using the proposed methodology in efficient manner.

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