

Modified Synchronous Reference Frame based Harmonic Extraction for Shunt Active Filter

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ABSTRACT

This paper presents the modified synchronous reference frame based Shunt Active Filter (SAF) for the instantaneous compensation of harmonic current present at the Point of Common Coupling. The harmonics generated by the non linear load are extracted using the positive frame and negative frame of the input signal using the modified synchronous reference frame theory with extended Multiple Reference Frame based PLL (EMRFPLL). Based on the harmonics extracted, pulse width modulation signals are generated using Artificial Neural Network based Space Vector Pulse width Modulation technique (ANNSVPWM). Using this switching technique the losses can be reduced and compensation can be done more accurately. The concept was verified using MATLAB / Simulink Simulation and the results confirm the THD at point of common coupling is below the required standards.

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1. INTRODUCTION

The number of electric utilities used for controlling and computing devices are increasing every day, with the advent of technology for control of motors using drives for power conversion there is an essential necessity to use power semi conductor devices in the electrical system. Switching ON and OFF the sinusoidal supply distorts the fundamental signal given to the electrical device. These devices have non linear load characteristics and these non linear load currents cause disturbance in other systems connected to the mains [1]. The harmonics which are generated due to the switching of nonlinear load leads to increased losses in the electrical system, poor power factor, increase in reactive power consumption and induces disturbance in electrically sensitive loads.

The harmonics can be compensated by providing passive filters, which compensates the harmonic of a particular order and the other harmonics remain in the system. By the provision of passive elements for filtering resonance problem occurs in an electrical system and the system becomes bulky [2]. In order to overcome these drawbacks active filters were introduced for dynamic compensation which eliminates harmonics of any order present in the system and resonance problem is avoided to keep the power quality indices below the required levels as specified by standard organizations such as IEEE 519.

Active filters are classified as series type, shunt type and Hybrid active filter. Shunt type active filters are used for the elimination of current harmonics present in the system. Hybrid active filter is a combination of shunt type and series type filter used for the elimination of both voltage and current harmonics present in the system.

SAF makes the source current sinusoidal irrespective of harmonic present in the non linear load and due to distorted source voltage conditions. The dynamic performance of shunt active filter is based on how

quickly the harmonic components are extracted from the load current. For the extraction of harmonics, methods such as Instantaneous Reactive power theory, PQ theory, symmetrical component theory, synchronous reference frame theory (SRF), Instantaneous active and reactive component theory [3], PI and Fuzzy logic based controller [4] are used for ideal source conditions and the SRF can be used for unbalanced source voltage condition in which speed of reference frame is not constant due to voltage harmonics and unbalance.

In this paper a modified SRF theory with EMRFPLL is used for the extraction of harmonics. This method minimizes the detection error of the phase angle to generate quick and precise reference signals [5]. The PWM signals for the Voltage Source Inverter (VSI) are generated by ANNSVPWM depending on the extracted harmonics as shown in Figure 1. The SAF produces current in opposite direction to the disturbances to cancel the harmonics and makes the source current sinusoidal and free from harmonics at PCC.

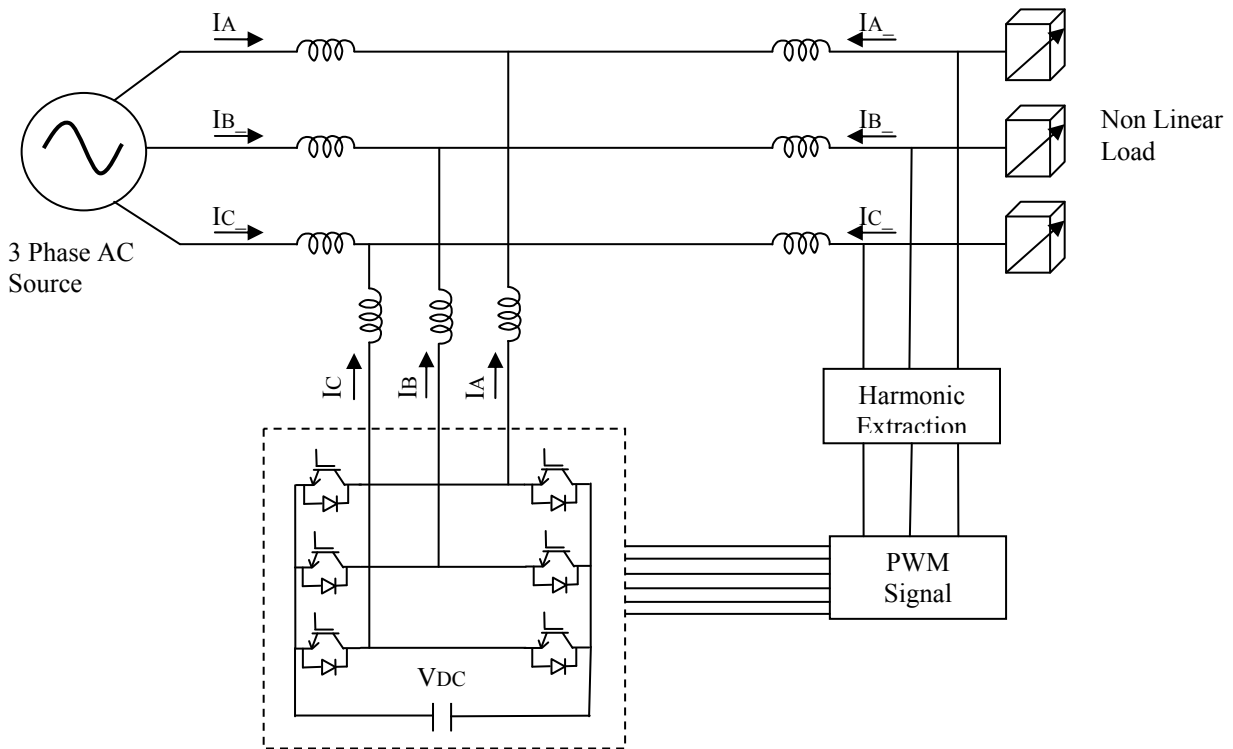


Figure 1. Block Diagram of Shunt Active Filter

2. MODIFIED SYNCHRONOUS REFERENCE FRAME BASED PLL

For the extraction of harmonics from the load current various algorithms have been proposed in the literature, the most popular is synchronous reference frame theory (SRF) and it has advantage of ease of execution, robust performance for ideal conditions when the load current is harmonically less distorted [6]. In unbalanced and distorted load conditions SRF method of harmonic current extraction is less effective. To trounce these drawbacks EMRFPLL has been proposed in this paper as shown in Figure 2. The load current and source voltage are measured by means of current and potential transformer. The measured three phase load current are converted in to two axis stationary coordinate system using Clarke transformation as shown in equations (1) to (3).

$$I_{\alpha} = \sqrt{\frac{2}{3}} \left(I_{A_L} - \frac{1}{2} I_{B_L} - \frac{1}{2} I_{C_L} \right) \tag{1}$$

$$I_{\beta} = \sqrt{\frac{2}{3}} \left(\frac{\sqrt{3}}{2} I_{B_L} - \frac{\sqrt{3}}{2} I_{C_L} \right) \tag{2}$$

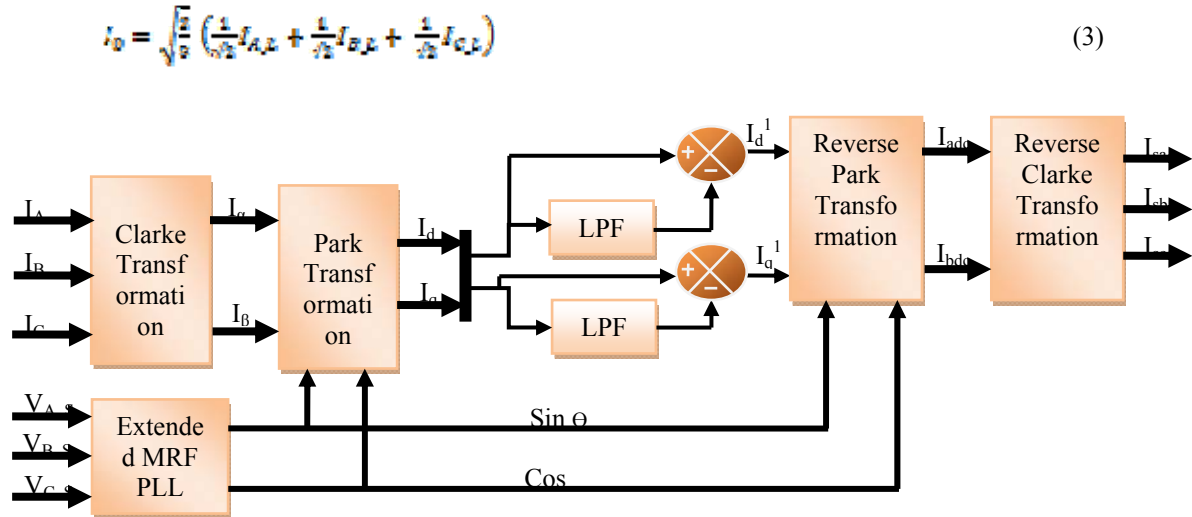


Figure 2. Block Diagram of Modified Synchronous Reference Frame based PLL

The reference frames in the stationary coordinate system are transformed to the synchronously rotating reference frame using equations (4) and (5). The currents I_d and I_q represent the direct and quadrature axis of the distorted load current.

$$I_d = I_a \cos \theta + I_b \sin \theta \quad (4)$$

$$I_q = -I_a \sin \theta + I_b \cos \theta \quad (5)$$

The two axes synchronously rotating reference frame is passed through a low pass filter to filter out the average component of the current and pass through the pulsating component of the current present in the load current [7]. The filtered harmonic current is transformed to stationary reference frame as given in equations (6) and (7)

$$I_{adc} = I_d^1 \cos \theta + I_q^1 \sin \theta \quad (6)$$

$$I_{bdc} = -I_d^1 \sin \theta + I_q^1 \cos \theta \quad (7)$$

The reference current in two axis is transformed in to three axes by reverse Clarke transformation as given in equations (8) to (10).

$$I_{sa} = \sqrt{\frac{2}{3}} \left(\frac{1}{\sqrt{2}} I_o + I_{adc} \right) \quad (8)$$

$$I_{sb} = \sqrt{\frac{2}{3}} \left(\frac{1}{\sqrt{2}} I_o - \frac{1}{2} I_{adc} + \frac{\sqrt{3}}{2} I_{bdc} \right) \quad (9)$$

$$I_{sc} = \sqrt{\frac{2}{3}} \left(\frac{1}{\sqrt{2}} I_o - \frac{1}{2} I_{adc} - \frac{\sqrt{3}}{2} I_{bdc} \right) \quad (10)$$

The current in the three phase coordinates represents the extracted harmonic content of the supply currents and the current to be injected to the VSI depends upon the difference between the harmonic content of the signal and the injected current of the active filter.

3. EXTENDED MRF PLL

The angle θ for the Park and Inverse park transformation is generated by the Phase Locked Loop (PLL) which synchronizes the output signal in frequency and phase with the input. In unbalanced and

distorted conditions to enable fast and accurate phase and frequency detection EMRFPLL is used for obtaining the instantaneous information of the phase angle and the magnitude of the signal [8]. The PLL detects the phase, filters out the unwanted signal and the oscillations are produced by the voltage controlled oscillator. The input voltages which are unbalanced are transformed into dq synchronous reference frame.

$$V_{abc}^+ = V_{abc} - V_{abc}^- \quad (11)$$

$$V_{abc}^- = V_{abc} - V_{abc}^+ \quad (12)$$

$$\begin{bmatrix} V_{\alpha}^+(t) \\ V_{\beta}^+(t) \end{bmatrix} = T_{\alpha\beta} \begin{bmatrix} V_a^+(t) \\ V_b^+(t) \\ V_c^+(t) \end{bmatrix} \quad (13)$$

$$T_{\alpha\beta} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} V_d^+(t) \\ V_q^+(t) \end{bmatrix} = T_{dq} \begin{bmatrix} V_{\alpha}^+(t) \\ V_{\beta}^+(t) \end{bmatrix} \quad (15)$$

$$T_{dq} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \quad (16)$$

The feedback loop regulates the dq reference frame. The positive sequence and negative sequence of the harmonics are present at the input. In EMRFPLL has two synchronous reference frames rotating in opposite directions at the equivalent angular speed. The fundamental positive and negative sequence components are separated from the fundamental frequency [9]. The error caused by the negative sequence component is eliminated. V_d gives an estimation of the amplitude of the positive sequence component and V_q gives information of the negative sequence component, both rotating in opposite directions at the equivalent angular speed of the input signal. When the frequencies are locked the negative sequence component input voltage appears as disturbance input to the PLL oscillating at twice the fundamental frequency.

$$\text{LPF}(s) = \left[\frac{\omega_p}{s} + \omega_p \right] \quad (17)$$

$$V_{d1}^+(s) = \frac{\omega_p}{s + \omega_p} [V_d^+ + V_q^+(s)] \quad (18)$$

$$V_{q1}^+(s) = \frac{\omega_p}{s + \omega_p} [V_d^+ \cdot \phi_s(s) + V_q^+(s)] \quad (19)$$

$$\text{PI}(s) = [K_p + K_i]/s \quad (20)$$

4. ARTIFICIAL NEURAL NETWORK BASED SPACE VECTOR PWM

PWM signals are used for modulating the time duration of the pulses to provide a compensation current in opposition the current harmonics present at PCC [10]. The ANNSVPWM measures the amplitude and angle of the reference frame to generate the gating pulses. The measured harmonic component of the current is fed as input to the ANNSVPWM which acts as a feed forward neural network for non linear mapping system. The input is converted in to direct axis and quadrature axis components V_d and V_q . The magnitude and angle are separated by Cartesian to polar conversion of the two axis components [11]. The ANN is used to calculate the time periods for the angular position of the different sectors in the reference frame. The computational burden of customary SVPWM to check the look up table for calculating the time delays is reduced by using ANNSVPWM [12]. The neural network is trained using equations 15 – 21 and the ANN model is generated and placed using simulink. The turn on time for the three phase inputs are given by the following equations.

The time of application of the different sectors is found using voltage second principle. The sector is detected by comparing the angle with predefined values. The neural network takes α^* as reference voltage position. Multilayer neurons are used in the first and second layer and the number of nodes, the weights are set in the training stage as shown in Table 1.

$$T_{A-ON} = \begin{cases} \frac{T_o}{4} = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=1,6 \\ \frac{T_o}{2} + t_b = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=2 \\ \frac{T_o}{2} + t_o + t_b = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=3 \\ \frac{T_o}{2} + t_a = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=5 \end{cases} \quad (21)$$

$$T_{A-ON} = \frac{T_s}{4} + f(V^*)g_A(\alpha^*) \quad (22)$$

$f(V^*) \rightarrow$ Voltage amplitude scale factor

$g(\alpha^*) \rightarrow$ Turn on Signal at Unit Voltage

$$g_A(\alpha^*) = \begin{cases} K \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=1,6 \\ K \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=2 \\ K \left[\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=3,4 \\ K \left[\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=5 \end{cases} \quad (23)$$

$$T_{B-ON} = \begin{cases} \frac{T_o}{2} + T_a = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=5,6 \\ \frac{T_o}{4} = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=2,3 \\ \frac{T_o}{2} + T_b = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=4 \\ \frac{T_o}{2} + T_a + T_b = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=5,6 \end{cases} \quad (24)$$

$$g_B(\alpha^*) = \begin{cases} K \left[\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=1 \\ K \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=2,3 \\ K \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=4 \\ K \left[\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=5,6 \end{cases} \quad (25)$$

$$T_{C-ON} = \begin{cases} \frac{T_o}{2} + T_a + T_b = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=1,2 \\ \frac{T_o}{2} + T_a = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=3 \\ \frac{T_o}{4} = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=4,5 \\ \frac{T_o}{2} + T_b = \frac{T_s}{4} + K.V.* \left[-\sin\left(\frac{\pi}{3} - \alpha^*\right) - \sin(\alpha^*) \right]; S=6 \end{cases} \quad (26)$$

$$g_c(\alpha^*) = \begin{cases} K \left[\sin \left(\frac{\pi}{3} - \alpha^* \right) - \sin(\alpha^*) \right]; S=1,2 \\ K \left[\sin \left(\frac{\pi}{3} - \alpha^* \right) - \sin(\alpha^*) \right]; S=3 \\ K \left[-\sin \left(\frac{\pi}{3} - \alpha^* \right) - \sin(\alpha^*) \right]; S=4,5 \\ K \left[-\sin \left(\frac{\pi}{3} - \alpha^* \right) - \sin(\alpha^*) \right]; S=6 \end{cases} \quad (27)$$

Table 1. ANN based SVPWM Training

1st Layer	12 Neuron (Log Sig)	Input Layer
2 nd layer	12 Neuron (Log Sig)	Hidden layer
3 rd Layer	3 Neuron (Purelin)	Output layer
	Training Error	0.53 %
	Training Epoch	98430

5. RESULT AND DISCUSSION

The simulation of the proposed system is validated by means of Matlab / Simulink for a Source voltage of 300 V, with a source inductor of 200 micro heny DC ink voltage of 400 V, load rating of 5 KW non linear load. The input to the system is a three phase pure sinusoidal signal as shown in Figure 3.

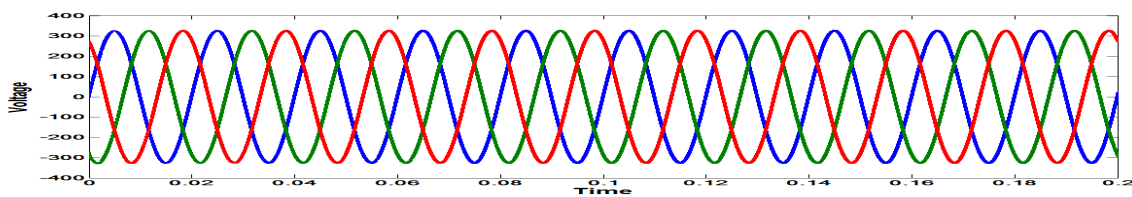


Figure 3. Source Voltage

The load current due the non linear load is distorted as shown in Figure 4. The input voltage to the system is sinusoidal whereas the current wave form of the three phases are non sinusoidal and consequently the reactive power consumed by the load is increased, the power factor of the system is reduced [13]. This leads to poor efficiency to the various loads connected to the power system.

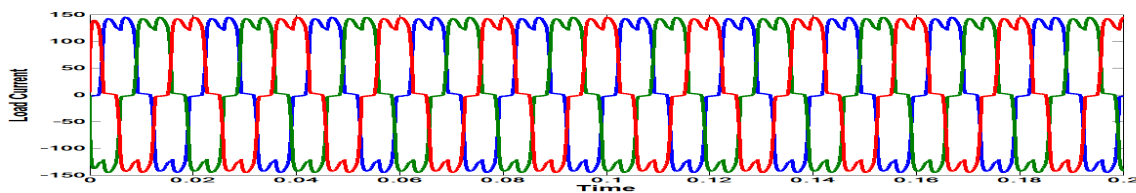


Figure 4. Load current

The deformed load current implicates the same in the source current. In order to avoid this drawback shunt active filter is connected at the point of common coupling [14]. The non sinusoidal load current is measured and the harmonic content of the load current is extracted and the compensation current is generated by using ANNSVPWM technique. The compensation current of three phases to be injected into the system to cancel the harmonics out of phase is shown in Figure 5.

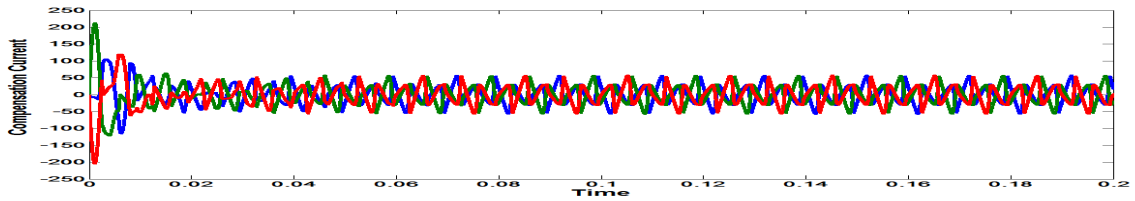


Figure 5. Compensation Current

The compensation current is injected at the point of common coupling and the harmonics present in the load current are eliminated and the source current is made sinusoidal in shape as shown in Figure 6.

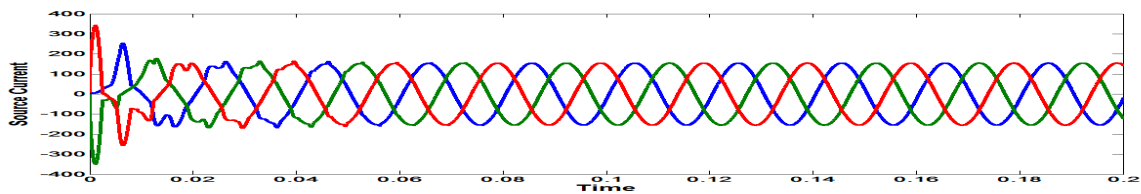


Figure 6. Source Current

In Figure 7 the comparison of source current to load current is shown for one phase of the three phase system. The load current which is non sinusoid is made sinusoidal in shape.

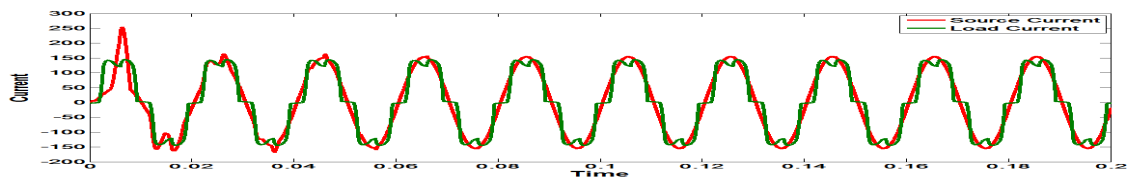


Figure 7. Source Current Vs Load Current

The comparison of power factors of a conventional SRF PLL with a EMRFPLL (Figure 8) shown that by using the proposed technique the overall power factor of the system is improved.

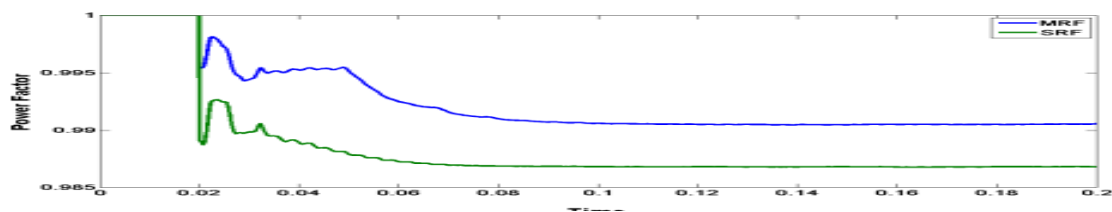


Figure 8. Comparison of PF with conventional PLL and EMRFPLL

The objective of the proposed work is to reduce the THD below the standards specified by professional bodies for power quality standards. Comparison of THD for conventional vs proposed system is shown in Table 2, and comparison of PF for conventional vs proposed system is shown in Table 3.

Table 2. Comparison of THD for Conventional vs Proposed System

Phase	Conventional SRF PLL		Modified SRF with EMRFPLL	
	Before Compensation	After compensation	Before Compensation	After compensation
R Phase	24.55 %	0.86 %	25.57 %	0.82 %
Y Phase	25.04 %	0.85 %	24.66 %	0.83 %
B Phase	24.78 %	0.85%	24.93 %	0.83%

Table 3. Comparison of PF for Conventional vs Proposed System

PF	Conventional SRF PLL		Modified SRF with EMRFPLL	
	Before Compensation	After compensation	Before Compensation	After compensation
PF Values	0.72	0.9857	0.72	0.996

6. CONCLUSION

A novel control technique for detection of harmonics by EMRFPLL is proposed for a three phase three wire system in this paper. The extracted harmonics from the three phase load currents are given to a modified ANNSVPWM to generate the compensating currents for the distortions. The system is modelled and simulated using Matlab / Simulink and the measured harmonic levels as given in table shows the THD of EMRFPLL is superior compared to conventional PLL [15]-[17]. The EMRFPLL is used to track the phase and frequency information and generate accurate values of angle for the transformation in SRF theory. The proposed results are used to validate the effectiveness of the control technique.

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