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DESIGN AND DEVELOPMENT OF ACTIVE POWER FILTER FOR HARMONIC MINIMIZATION USING SYNCHRONOUS REFERENCE FRAME (SRF)

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ABSTRACT

The research for the aimed towards avoiding the waveform of the current from distorted is make the researchers interested to do that.. The controllers used in an active power filter play an important role in determining the current waveform in electrical system will smooth with a minimum of the total harmonic distortion (THD). The main purpose of this paper is to propose the controller of an active power filter based on synchronous reference frame (SRF). A model of the proposed controller has been developed using MATLAB/SIMULINK. The results of the simulation shows that the effectiveness of the proposed controller toward in reducing THD at the acceptable.

Keywords: shunt active power filter, harmonics, total harmonic distortion, synchronous reference frame.

1. INTRODUCTION

In this modern technologies era, different types of loads are being used in different sectors like industries, offices or households. The use of the loads serve their own purposes in the specific fields. For example, induction motor is widely use in industries sector for power generation, computers are widely used across the industries, offices and households for other different purposes. The loads are classified into two categories: linear and non-linear load. Heater, capacitor and induction motor are some examples for linear load while computer, converter and lighting system are some examples for non-linear load [1-5].

Power supply produces a voltage and current waveform known as the fundamental waveform in the electrical system. The fundamental waveform from the power supply is in a clean sinusoidal shape. The use of linear load and non-linear load will produce different shape of waveform. When the linear load is used in the electrical system, it will produces a clean sinusoidal current waveform which is similar to the fundamental. Unlike the linear load, the presence of non-linear load in the electrical system will produces a non-sinusoidal current waveform. The production of non-sinusoidal current waveform happened because of the presence of harmonics in the electrical system [1-3].

Harmonic is a high frequency waveform generated by non-linear load. The frequency of harmonic is a few times of the frequency of the fundamental. The presence of harmonic in the electrical system will leads to distortion in both voltage and current waveform. Harmonics bring different types of problems into the electrical system [1-4]. There are two types of effects when harmonic is presences in the electrical system: instantaneous and long-term effect [1-2]. Instantaneous effect includes disturbance of controller in electronic systems, additional errors in induction disk electricity meters and disturbance in the relays used by electrical utilities. Harmonic currents also leads to vibration and noises in electromagnetic devices and interference on communication and control circuit. As of long term effects, harmonic causes heating in capacitor, heating in machines and transformers due to additional losses and heating in cables and equipment [1-4].

Due to the problems of harmonic, IEC has introduced the standard of 5% for the total harmonic distortion in the electrical system [1-5]. In order to reduce the harmonic content in the electrical system, various techniques have been developed. Passive filter and active power filter are commonly used in the electrical system for harmonic mitigation. Passive filter is the combination of inductor and capacitor. There are two types of passive filter: series type and shunt type. Series passive filter uses high series impedance to block the harmonic current while the shunt passive filter diverts the harmonic current into the low impedance shunt path [10]. Passive filter has some disadvantages such as bulky size, resonance problem and sensitive. Active power filter has been introduced to remove the disadvantages of the passive filter. It has smaller size, better filtering and offers better flexibility [5-6]. Active power filter is categorized into series topology, shunt topology and hybrid topology. Shunt topology is the most popular among the other topologies [9-10]. Active power filter will produce compensating current which has the same magnitude as the harmonic current but with different polarity into the electrical system [5-6].

2. SHUNT ACTIVE POWER FILTER

A. Circuit topology

Figure-1 shows the basic structure of the proposed three phase shunt active power filter. It is connected in parallel to the load. Figure-1 shows the standard three phase insulated-gate bipolar transistor (IGBT) based voltage source inverter (VSI) bridge, input AC inductor and a DC bus capacitor [3, 4, 5. 9, 10].

There are two types of inverter for the active power filter, which are voltage source inverter (VSI) with

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a DC bus capacitor and current source inverter (CSI) with a DC link inductor. Both VSI and CSI utilize the insulated-gate bipolar transistor (IGBT) with diodes differently. VSI uses IGBT with anti-parallel diode while CSI uses IGBT with series connected diodes for the reverse-blocking function. VSI is better than CSI in terms of efficiency, cost and size since CSI is expensive and bulky due to the DC link inductor [9-10]. The proposed shunt active power filter is control by synchronous reference frame (SRF) method.

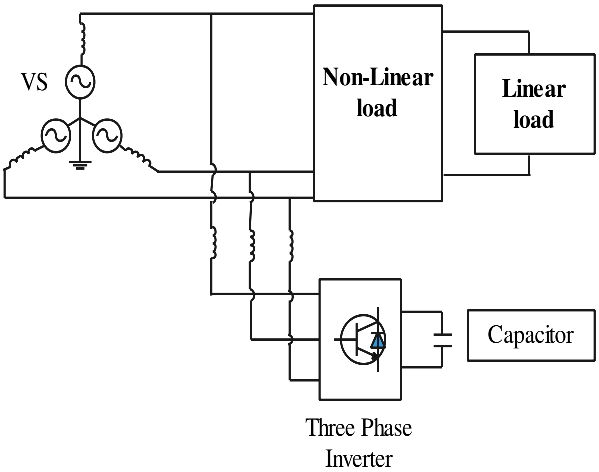

Figure-1. Basic structure of shunt active power filter.

B. Principle of synchronous reference frame (SRF)

Synchronous reference frame method is uses to generate the reference current for harmonic mitigation. It is a method based on the transformation of vectors from stationary reference frame (a-b-c reference frame) into d-q reference frame (also known as synchronous reference frame), where d is the rotating direct axis and q is the quadrature axis reference frame.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{pmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{pmatrix} cos\omega_s t & -sin\omega_s t \\ sin\omega_s t & cos\omega_s t \end{pmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2}$$

The measured load current is transform from stationary reference frame into α-β reference frame using (1) and further transform into d-q reference frame using (2). After the transformation into the d-q reference frame, the load currents from the line frequency component are changes into DC quantities while a shift of frequency by ω occurred to the harmonic components. The usage of high pass filter in the d-q frame will leads to a cutoff at the line frequency which will allow the extraction of the DC components. (3) and (4) are used to obtain the harmonic component.

$$i_{dh} = I_{ld} - I_d^{dc} \tag{3}$$

$$i_{qh} = I_{lq} - I_q^{dc} \tag{4}$$

The desired reference current is obtained after proper filtering in the d-q reference frame. The reference currents are transform back to α-β reference frame using (5) and further inverse transform back to stationary reference frame using (6).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{pmatrix} cos\ \omega_s t & -\sin\omega_s t \\ \sin\omega_s t & \cos\omega_s t \end{pmatrix} \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} i_{ac}^* \\ i_{bc}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{pmatrix} \begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} \tag{6}$$

The reference current generated by synchronous reference frame method is derived directly from the load current. Hence, it is not influenced by the unbalance or distorted voltage. During the transformation, phase lock loop (PLL) circuit is used to generate reference phase angle so that the reference current generated rotates synchronously with the fundamental currents [5, 9].

C. Principle of phase lock loop (PLL)

The phase angle of the fundamental component is important during the transformation of measured variables into synchronous reference frame. Hence, phase lock loop circuit is used to obtain the phase angle of the positive sequence fundamental component of voltage. Both Clarke and Park's transformation are used to identify the phase angle. The positive sequence of the voltage is measured and transform into the into α-β reference frame using Clarke transformation and further transform into d-q reference frame using Park's transformation. The synchronous reference frame phase voltages appear as DC quantities where the phase voltage in q axis is set to zero. A proportional integrator (PI) controller is used to regulate the error between the reference signal and feedback signal. The error compensation signal of the PI controller is added to the feed forward fundamental frequency to obtain fundamental frequency information ω. Phase angle θ is obtained by inverse Park's transformation into α-β reference frame and further inverse transform using Clarke's inverse transformation into stationary reference frame. The vector phase lock loop is closed and the phase angle for reference current transformation is locked to the fundamental phase angle.

3. MODEL DESIGN AND SIMULATION

MATLAB/Simulink is used to model and simulate the proposed shunt active power filter. The parameters of simulations are shown in Table-1.

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Table-1. Design and circuit specifications.

Three phase supply		
Source voltage	**V_a, V_b, V_c**	**$230V_{rms}$**
Frequency	f	50Hz
Line inductance	L_{sa}, L_{sb}, L_{sc}	2.8mH
Three phase linear load		
Resistor	R	10Ω
Inductor	L	1mH
Capacitor	C	100µF
Three phase bridge diode (non-linear load)		
Snubber resistance	R_s	10Ω
Snubber capacitance	C_s	1nF
Tuned fifth harmonic passive filter		
Inductor	L	2.02mH
Capacitor	C	200µF
Tuned seventh harmonic passive filter		
Inductor	L	2.07mH
Capacitor	C	100µF
Shunt active power filter		
DC bus capacitor	C	2200µF
AC side inductor	L_{fa}	1mH
AC side capacitor	C_{fa}	2.5µF

The first model being simulated is the linear load model. Linear load is first connected into the electrical system and simulated to show that linear load does not yield any total harmonic distortion since there is no harmonic produced by the linear load. The second model simulated is the non-linear load model. The linear load is replaced with a non-linear load to indicate the total harmonic distortion in the electrical system before installing filters. Next, tuned fifth harmonic passive filter is connected into the electrical system. Then, tuned fifth harmonic passive filter is replaced with tuned seventh harmonic passive filter. After this simulation, both tuned fifth and seventh harmonic passive filter are connected into the electrical system. The simulation is carried on by removing the both passive filters and replaced with shunt active power filter based on synchronous reference frame. Then, tuned fifth harmonic passive filter is connected into the electrical system together with shunt active power filter based on synchronous reference frame. The tuned fifth harmonic passive filter is replaced with tuned seventh harmonic passive filter. Lastly, both passive filters are connected together with shunt active power filter based on synchronous reference frame.

4. SIMULATION RESULTS AND DISCUSSION

The results from the simulation carried out using MATLAB/Simulink are shown in this section. Figure-2 and Figure-3 show the current waveforms obtained at supply end and THD_I at supply end when linear load is connected in the electrical system.

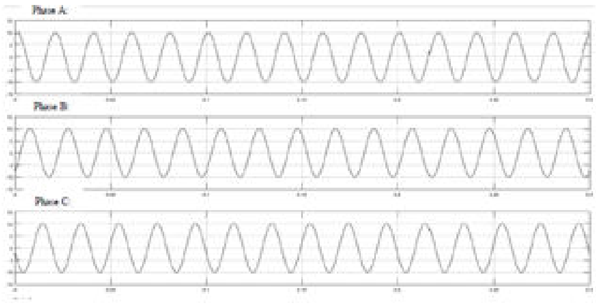

Figure-2. Current waveforms at supply end (linear load).

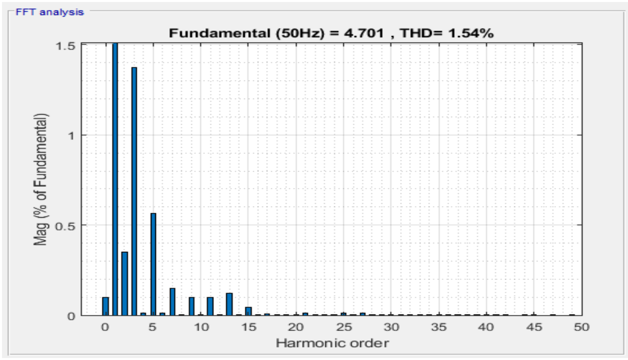

Figure-3. THD_I at supply end (linear load).

When a linear load is used in the electrical system, the current waveforms are in a pure sinusoidal form. There are no distortion in the current waveforms since there are no harmonic content in the electrical system as the total harmonic distortion is 1.54%. The linear load is then replaced with non-linear load.

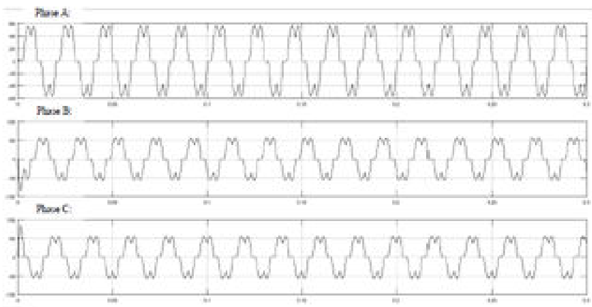

Figure-4. Current waveforms at supply end (non-linear load).

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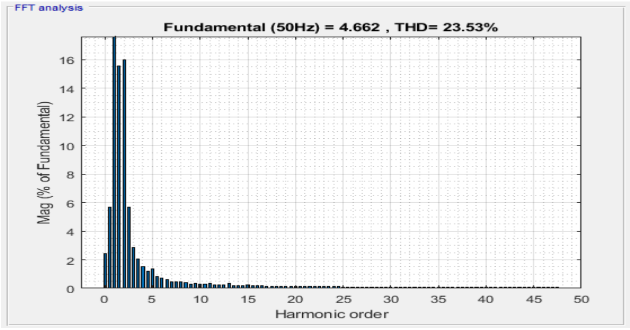

Figure-5. THD_I at supply end (non-linear load).

Based on Figure-4, when the linear load is replaced with non-linear load, the current waveforms at supply are distorted. The electrical system yields a total harmonic distortion of 23.53% as shown in Figurte-5. Tuned fifth harmonic passive filter is connected into the electrical system to block fifth harmonic content in the electrical system.

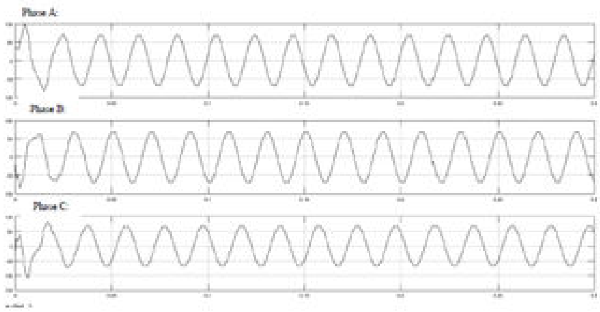

Figure-6. Current waveforms at supply end with tuned fifth harmonic passive filter.

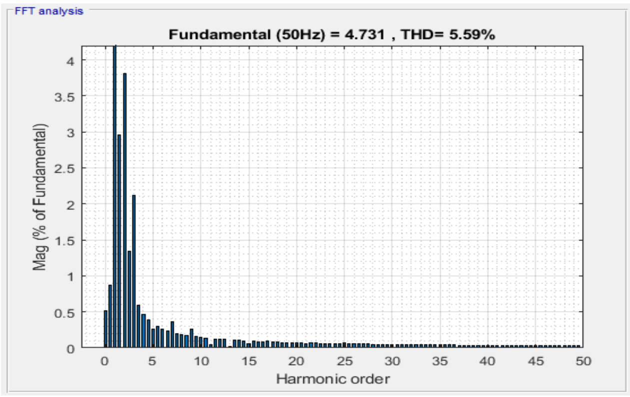

Figure-7. THD_I at supply end with tuned fifth harmonic passive filter.

Connecting the tuned fifth harmonic passive filter into the electrical system reduces the distortion in current waveforms shown in Figure-6. The total harmonic distortion also reduces to 5.59%. The tuned fifth harmonic passive filter is replaced with tuned seventh harmonic passive filter.

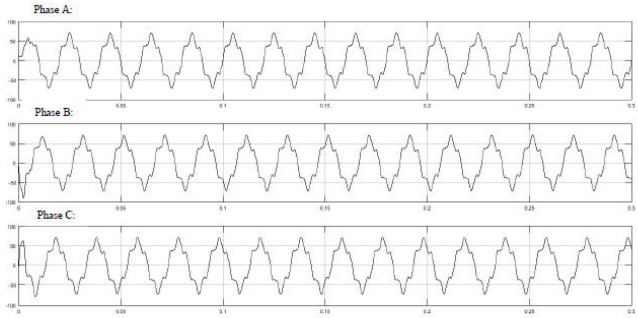

Figure-8. Current waveforms at supply end with tuned seventh harmonic passive filter.

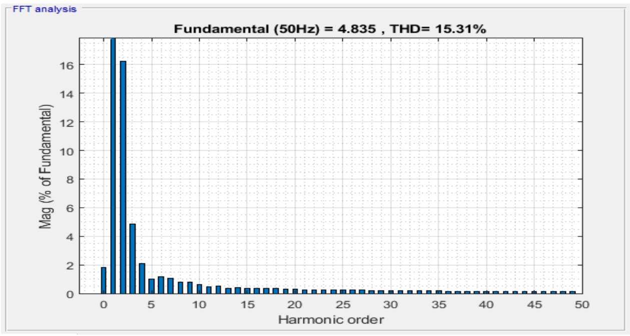

Figure-9. THD_I at supply end with tuned seventh harmonic passive filter

Based on the total harmonic distortion shown in Figure-9, the performance of the tuned seventh harmonic passive filter is poorer compare to tuned fifth harmonic passive filter even though it shows reduction in terms of total harmonic distortion compare to the electrical system where no filters are present. The tuned fifth harmonic passive filter is then added into the electrical system together with tuned seventh harmonic passive filter.

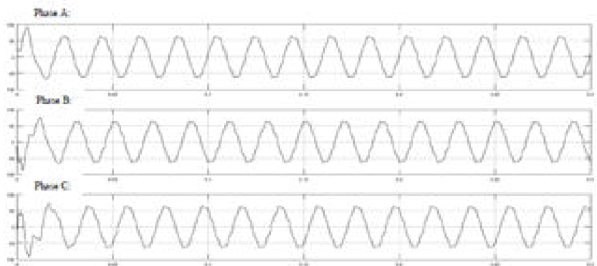

Figure-10. Current waveforms at supply end with tuned fifth and tuned seventh harmonic passive filter.

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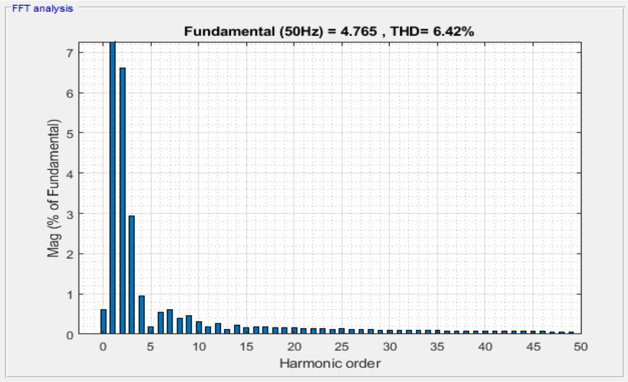

Figure-11. THD_I at supply end with tuned fifth and tuned seventh harmonic passive filter.

When both tuned passive filters are used, the electrical system yields a total harmonic distortion of 6.42% as shown in Figure-11. The distortion in current waveforms also become lesser when comparing Figure-10 with Figure-4. The tuned passive filters are removed while the shunt active power filter based on synchronous reference frame is connected into the electrical system.

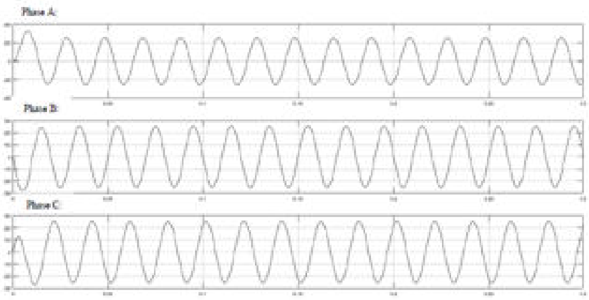

Figure-12. Current waveforms at supply end with shunt active power filter based on synchronous reference frame.

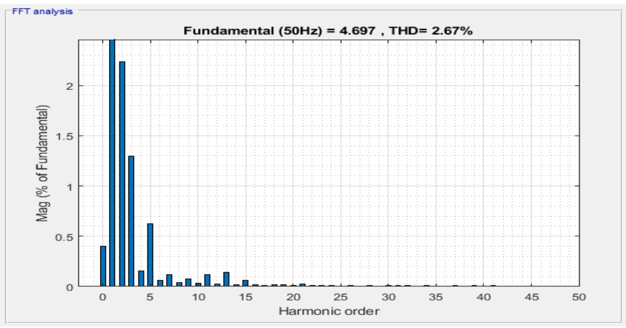

Figure-13. THD_I at supply end with shunt active power filter based on synchronous reference frame.

The proposed shunt active power filter based on synchronous reference frame managed to reduce the total harmonic distortion to 2.67%. The current waveforms shown in Figure-12 are in a sinusoidal shape. Tuned fifth harmonic passive filter is added into the electrical system.

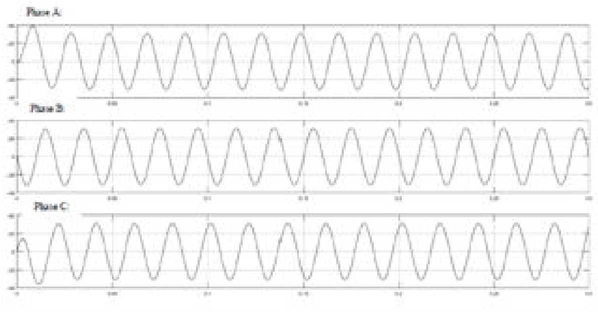

Figure-14. Current waveforms at supply end with shunt active power filter based on synchronous reference frame and tuned fifth harmonic passive filter.

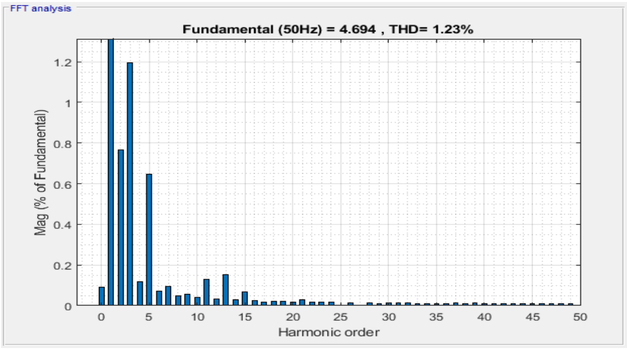

Figure-15. THD_I at supply end with shunt active power filter based on synchronous reference frame and tuned fifth harmonic passive filter.

When the tuned fifth harmonic passive filter is connected together with the shunt active power filter based on synchronous reference frame, the total harmonic distortion is further reduced to 1.23%. The tuned fifth harmonic passive filter is replaced with tuned seventh harmonic passive filter.

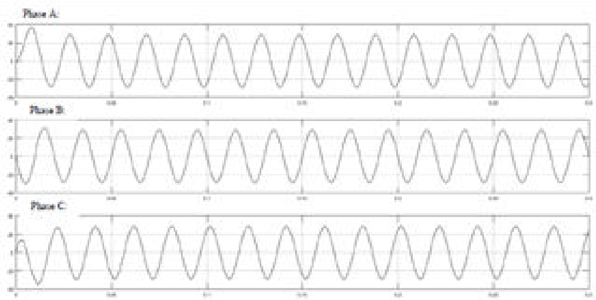

Figure-16. Current waveforms at supply end with shunt active power filter based on synchronous reference frame and tuned seventh harmonic passive filter.

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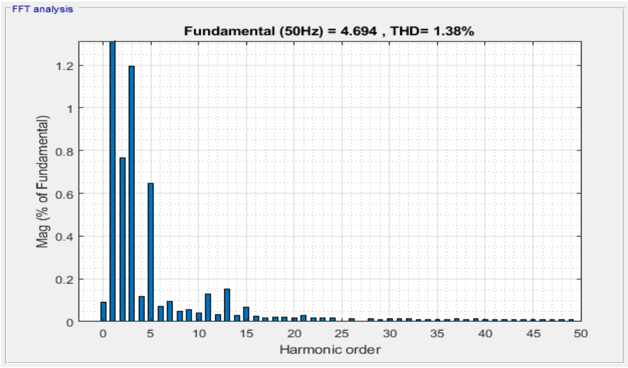

Figure-17. THD_I at supply end with shunt active power filter based on synchronous reference frame and tuned seventh harmonic passive filter.

Replacing the tuned fifth harmonic passive filter with tuned seventh harmonic passive filter yields a poorer performance in terms of harmonic minimization since the tuned seventh harmonic passive filter has poorer performance compare to tuned fifth harmonic passive filter when they are used alone in previous simulations. The shunt active power filter based on synchronous reference frame is connected together with tuned fifth and tuned seventh harmonic passive filter into the electrical system.

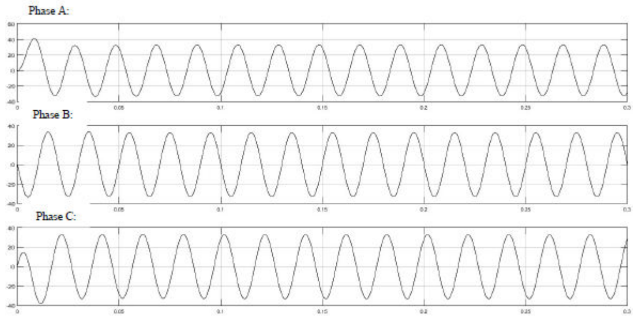

Figure-18. Current waveforms at supply end with shunt active power filter based on synchronous reference frame, tuned fifth and tuned seventh harmonic passive filter

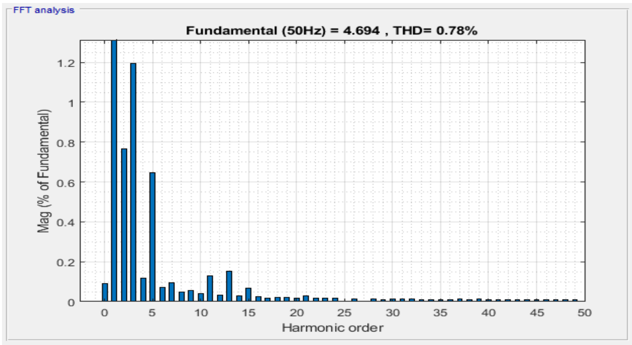

Figure-19. THD_I at supply end with shunt active power filter based on synchronous reference frame, tuned fifth and tuned seventh harmonic passive filter.

When both passive filters are connected into the electrical system together with shunt active power filter based on synchronous reference frame, the total harmonic distortion reached the lowest value among all simulations which is 0.78%. The current waveforms obtained in Figure-18 also identical to Figure-2, where linear load is used. The results are concluded in Table-2.

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Table-2. Overall results.

Filter	THD_I before filter installation (%)	THD_I after filter installation (%)	THD_I reduced (%)
Tuned fifth harmonic passive filter	24.92	5.92	19
Tuned seventh harmonic passive filter	24.92	18.62	6.3
Tuned fifth and tuned seventh harmonic passive filter	24.92	6.58	18.34
Shunt active power filter based on synchronous reference frame	24.92	2.66	22.26
Shunt active power filter based on synchronous reference frame and tuned fifth harmonic passive filter	24.92	1.23	23.69
Shunt active power filter based on synchronous reference frame and tuned seventh harmonic passive filter	24.92	1.38	23.54
Shunt active power filter based on synchronous reference frame, tuned fifth and tuned seventh harmonic passive filter	24.92	0.78	24.14

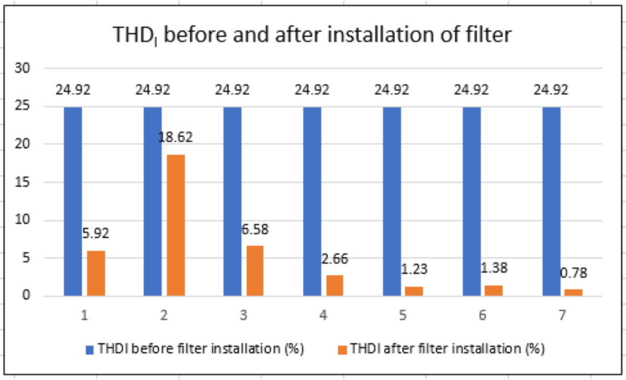

Figure-20. Graph of THD_I before and after installation of filter.

Based on Table-2, the proposed shunt active power filter based on synchronous reference frame managed to reduce the total harmonic distortion to 2.66%, which is below the 5% standard specified by IEC. Shunt active power filter based on synchronous reference frame is able to reduce 22.26% of total harmonic distortion in the electrical system, where the combination of tuned fifth and tuned seventh harmonic passive filter cannot achieve.

5. CONCLUSIONS

From the results observed, the proposed shunt active power filter based on synchronous reference frame can be used to mitigate the harmonic in a three phase three wire electrical system when non-linear load is present. The results also prove that the proposed shunt active power filter based on synchronous reference frame has better performance in terms of harmonic reduction compare to passive filter since shunt active power filter based on synchronous reference frame alone is sufficient to reduce the harmonic content to the level below 5% as specified by IEC.

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APPENDIX

The following figures are the simulation model designed using MATLAB/Simulink.

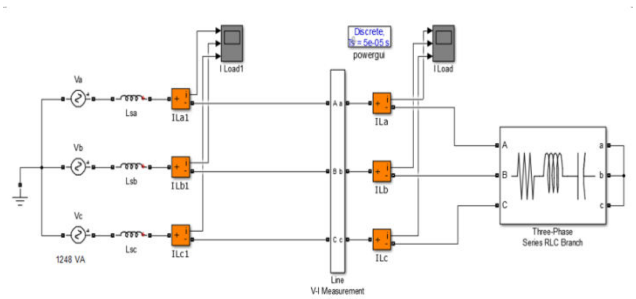

Figure-21. Linear load model.

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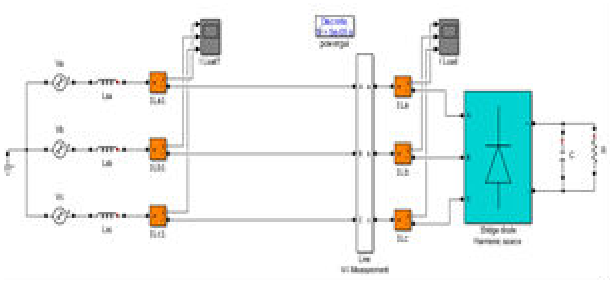

Figure-22. Non-linear load model.

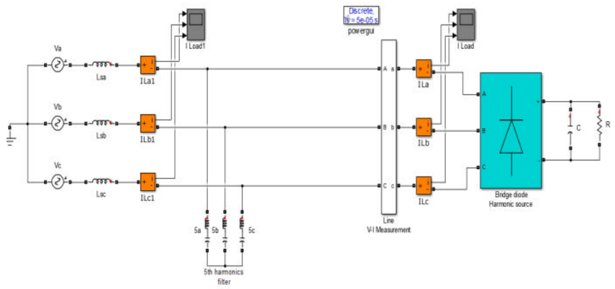

Figure-23. Non-linear load model with tuned fifth harmonic passive filter.

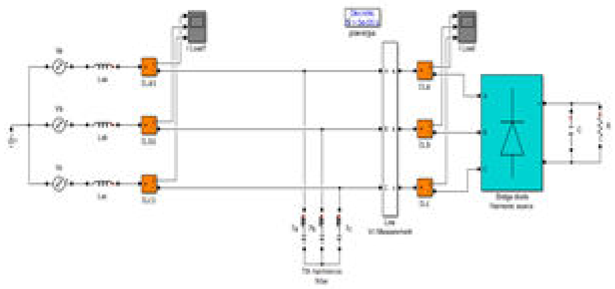

Figure-24. Non-linear load model with tuned seventh harmonic passive filter.

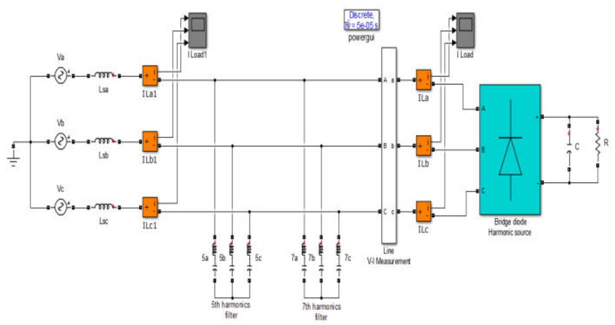

Figure-25. Non-linear load model with tuned fifth and tuned seventh harmonic passive filter.

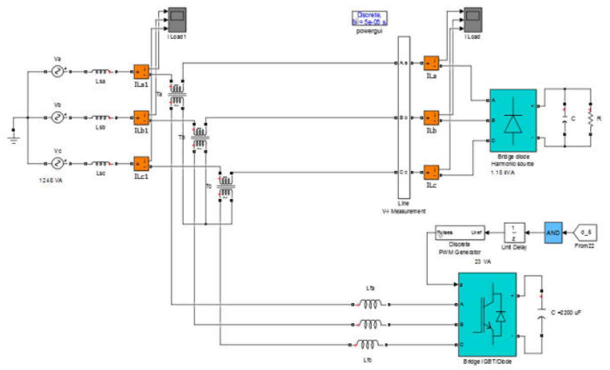

Figure-26. Non-linear load model with shunt active power filter based on synchronous reference frame.

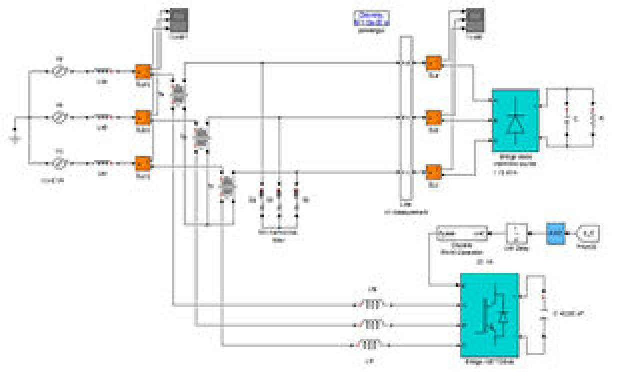

Figure-27. Non-linear load model with shunt active power filter based on synchronous reference frame and tuned fifth harmonic passive filter.

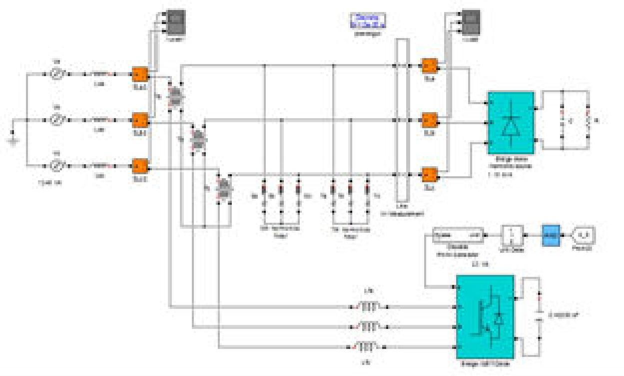

Figure-28. Non-linear load model with shunt active power filter based on synchronous reference frame and tuned seventh harmonic passive filter.

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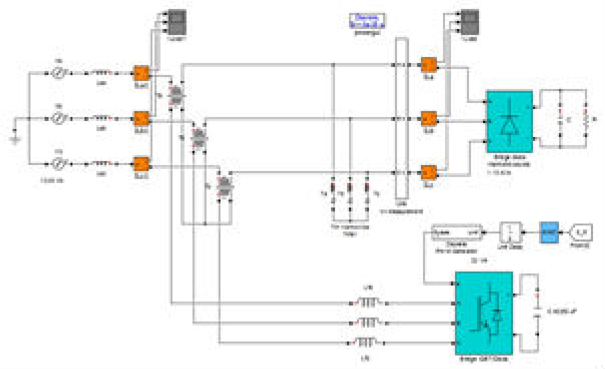

Figure-29. Non-linear load model with shunt active power filter based on synchronous reference frame, tuned fifth and tuned seventh harmonic passive filter.

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