Performance improvement of harmonic detection algorithm in three phase three wire shunt active power filter under balance voltage condition

Zubairu Usman[1], Muhammad Hasbi Azmi[2], Siti Zaliha Mohammad Noor[3], Suleiman Musa[1]
[1]Department of Electrical and Electronics Engineering, College of Engineering, Kaduna Polytechnic, Kaduna, Nigeria
[2]School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia
[3]Solar Research Institute (SRI), College of Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia

Article Info

Article history:

Received Feb 3, 2024
Revised Nov 30, 2024
Accepted Dec 9, 2024

Keywords:

Active power filter
Band pass filter
D-Q theory
High pass filter
Low pass filter
Total harmonic distortion

ABSTRACT

Effective harmonic current identification is critical for shunt active power filters (SAPF) to provide accurate and sufficient compensation. This study proposes a modified synchronous reference frame fundamental (MSRFF) method for harmonic extraction in three-phase, three-wire systems. A band pass filter (BPF) was designed by combining low-pass and high-pass filters in the direct-quadrature (d-q) reference frame to improve filtering performance. Unlike traditional methods using phase-locked loops (PLL), this approach employs unit vector templates for synchronization and relies on direct current measurements from load currents. The band pass filter, with low cutoff frequencies, effectively isolates harmonic components in heavily contaminated systems, outperforming other filtering methods. System performance was evaluated using matrix laboratory (MATLAB) simulations, where total harmonic distortion (THD) values were reduced to 2.19% with a low pass filter, 0.99% with a conventional band pass filter, and 0.98% with the combined filter approach. The results demonstrate that the proposed strategy can accurately track and estimate harmonic signals, offering a robust solution for shunt active power filter applications.

Corresponding Author:

Siti Zaliha Mohammad Noor
Solar Research Institute (SRI), College of Engineering, Universiti Teknologi MARA
40450 Shah Alam, Selangor, Malaysia
Email: sitizaliha@uitm.edu.my

1. INTRODUCTION

Today in many cities, the growth of power quality problems due power electronic equipment such as programmable logic controller, electronic lightning, adjustable speed drive, together with other nonlinear loads has become an issue to power engineers. This leads to generation of harmonics and thereby causing changes in electrical nature of current and voltage of the power supply. Low power quality introduced harmonic currents and voltages into power system networks. Due to the non-linear load in the system, these harmonics are caused by fluctuations in impedance with applied voltage [1], [2]. This brings a significant economic loss due to the fact that some electrical equipment is sensitive to this power quality problem. Inadequate power quality within the system can lead to several issues, including inappropriate device function caused by balanced or unbalanced non-sinusoidal currents, which can overheat rotating machinery parts and neutral phase, as well as random tripping of protection devices [3]. Odd order harmonics, dominated by third, fifth, and seventh harmonic components, make up the harmonic spectrums of some common nonlinear loads, such as switching mode power supplies, uninterrupted power supplies, and fluorescent lamps. By compensating for these harmonic components, a significant portion of the harmonic currents can be eliminated [4]. Numerous devices for mitigating current harmonics have been designed to effectively reduce reactive power components, harmonic current, and the imbalance of nonlinear and variable loads. As a result, the load will receive supply of sinusoidal voltage and current with unity power factor. It has been demonstrated that shunt active power filters work well to balance reactive power sources and harmonic currents [5]–[7]. Its purpose is to inject an opposing but equal voltage or current distortion into the network system in order to cancel out the harmonic components on the ac side by drawing compensating current or voltage from the utility. It is connected to the load at point of common coupling (PCC) in parallel, as shown in Figure 1. The three primary components of the controller in a shunt active power filter (SAPF) design are detection, dc bus control, and current control, which is utilized to generate the switching pulse for the inverter [8].

The process of generating accurate system variables (information) for reference signal estimation begins with the detection of essential voltage/current signals. The wave that was disrupted yields a compensation signal that has both fundamental and harmonic contents. There are two ways to go about this: the frequency domain approach and the time domain approach. The Fourier analysis of the distorted (harmonics) voltage or current signals serves as the foundation for the frequency domain control strategy used to extract compensation commands. One of the disadvantages of this field is that it requires a lot of mathematical computation, which takes time to complete. Furthermore, a good and quick processor needs to be taken into consideration for better and more efficient performance. Time domain technique control strategies are simple to implement and don't require a lot of computation [9]. It relies on the instantaneous derivation of compensation commands in the form of distorted signals (voltage or current) that can take either of two forms.

The creation of an active filter current reference in conventional current detection methods is typically predicated on the harmonic detection of load currents through the application of well-known time domain control strategies, such as synchronous detection method [10], instantaneous power theory (p-q theory) [11], synchronous reference frame (d-q theory) [12]–[14]. Due to its effectiveness and simplicity, the synchronous reference frame technique (d-q theory) has been the most frequently used in studies [15]–[17]. However, one problem that can be found to enhance the harmonic detection mechanism's performance in time domain correction is the filtering approach used in the d-q axis to assess the dynamics and accuracy of the reference current detection algorithm. The traditional method produces the reference signal by separating the fundamental from harmonic current signals using a numerical low pass filter (LPF) [18], [19]. This does not, however, totally remove the system's harmonic currents. Therefore, a strong filtering scheme in the control algorithm is required to ensure safe system operation by reducing the harmful unwanted harmonic current.

The LPF and high pass filter (HPF) are cascaded in this work to create a band pass filter, which enhances the performance of the shunt active power filter. This method bases the reference harmonic current's amplitude on the system's active power balance and is generated by the DC-link voltage controller. The desired cutoff frequencies are obtained by tuning the BPF's center frequency and bandwidth in order to lower the harmonic distortion (THD). This is how the paper is set up. The suggested harmonic detection technique control strategy is described in section 2. Section 3 provides specifics on harmonic extraction using BPF, and section 4 presents and discusses the outcomes of the simulation. Section 5 concludes with a summary of the work.

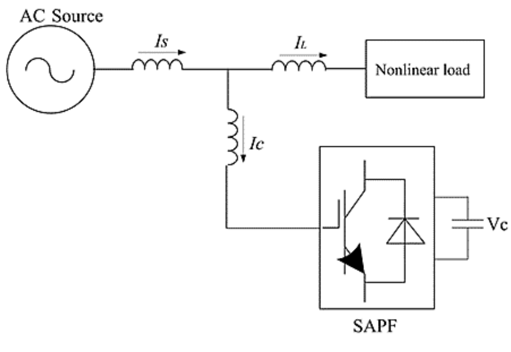

Figure 1. Shunt active power filter

2. HARMONIC CURRENT DETECTION TECHNIQUES

Time domain or frequency domain correction techniques can be used to achieve control strategies for the generation of compensation signals. Fourier analysis of the distorted voltage or current signals serves as the basis for the control strategy used in the frequency domain to extract compensating commands. In contrast, instantaneous derivation of compensation commands for time domain techniques is obtained in the form of distorted signals (voltage or current). This method is typically applied primarily to three-phase systems. When compared to frequency domain techniques, it has the advantage of simplicity and ease of implementation because it requires less mathematical computation.

2.1. Synchronous reference frame (SRF)

The reference harmonic current signals are extracted using this time domain correction technique. Block diagram for SRF-based harmonic current detection is shown in Figure 2. To implement the synchronous reference frame theory, a two-phase orthogonal coordinate system rotating at a predetermined speed is substituted for the three-phase coordinate system using the Clarke and Park transformation [20].

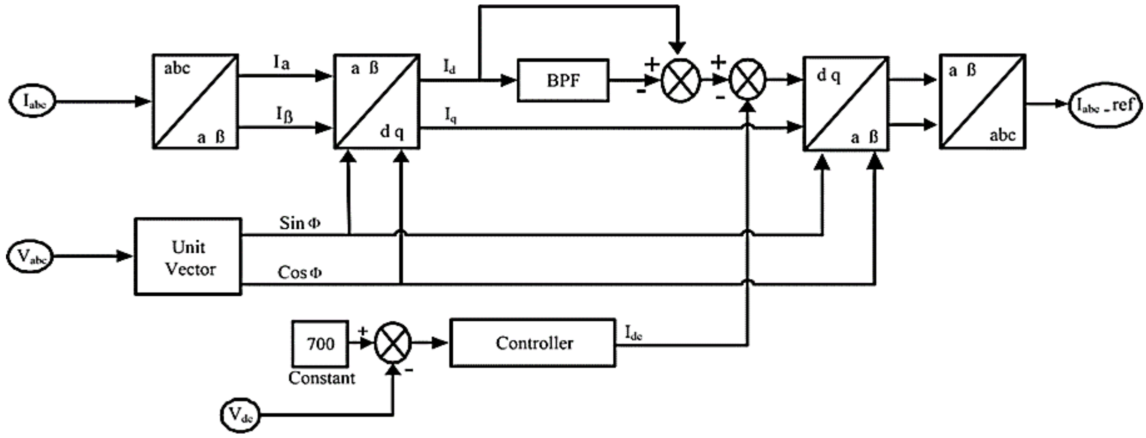

Figure 2. Block diagram of harmonic detection method

A step-by-step guide to completing this transition is provided below. First, as indicated by (1), the three-phase supply currents, ia, ib, and ic, are converted to a two-phase (α − β) stationary reference frame current, iα iβ.

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

In the second step, the α − β plane is switched to the d-q reference frame, and the unit vector is used to generate the sine and cosine signals needed to synchronize with the supply's voltages and current [21]. Both AC and DC components make up the obtained d-q currents. The harmonic component of current is represented by the AC component, while the fundamental component is fixed as the DC part. As illustrated in Figure 3, this harmonic component can be extracted with ease by applying cascaded 2nd order low pass and high pass filters. For d-q reference frame, current expression is as (2).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin(\theta) & -cos(\theta) \\ cos(\theta) & sin(\theta) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2}$$

Where θ represents the voltage signal's phase angle.

Step three involves using the band pass filter created by cascading LPF and HPF to remove the AC signal in order to detect the harmonics.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d & i_d \\ \bar{i}_q & i_q \end{bmatrix} \tag{3}$$

In step four, iα and iβ are thus obtained as follows:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \sin(\theta) & -cos(\theta) \\ cos(\theta) & sin(\theta) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{4}$$

The iα-ref and iβ-ref reference current signals are provided by.

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta) & -cos(\theta) \\ cos(\theta) & sin(\theta) \end{bmatrix} \begin{bmatrix} \tilde{i_d} + i_{dc} \\ \tilde{i_q} \end{bmatrix} \quad (5)$$

Lastly, step five uses the inverse transformation to provide the ABC reference frame, from which the current is obtained as (6).

$$\begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} \quad (6)$$

The necessary PWM switching pulses for the inverter are produced by comparing the extracted harmonic reference current with the filter or inverter currents.

3. BAND-PASS FILTER DESIGN

As shown in Figure 3, the design utilized two second-order low-pass and high-pass filters to create a band pass filter (BPF) capable of effectively isolating and reducing undesired current harmonics in the system. These harmonics, which remained present in the line and contributed to the reactive power component, were targeted to improve overall filtering efficiency. The low pass filter was designed to suppress high-frequency noise, while the high pass filter eliminated low-frequency disturbances, allowing the BPF to focus on the harmonic frequency range of interest. By combining these filters, the system achieved a more refined harmonic isolation process, ensuring greater stability and accuracy in compensating reactive power. This design approach not only improved the harmonic suppression but also enhanced the overall performance of the shunt active power filter in high-contamination environments.

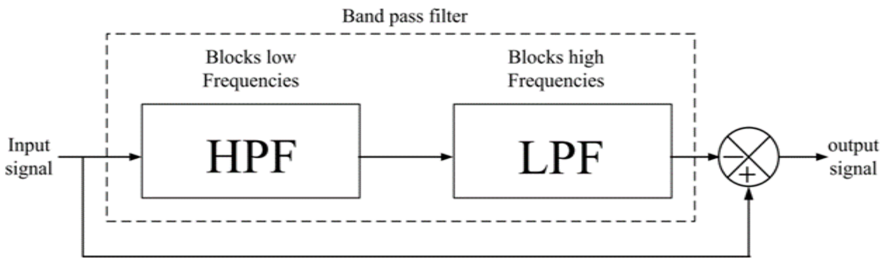

Figure 3. Cascaded LPF and HPF to form band pass filter

Overall harmonic compensation is achieved in the fundamental dq-frame due to the transposition of the fundamental frequency signal to a DC component. A band of the chosen harmonic current spectrum results from removing it and all other harmonics from the load current using the LPF and HPF. Characteristic harmonics, which are generated by semiconductor converter devices operating in steady state under ideal conditions, are expressed as follows [22]:

$$h = np \pm 1 \quad (7)$$

where n is an integer between 1, 2, 3, and h is the order of harmonics. p is the quantity of pulses in a cycle.

The fundamental d-q-frame has an intriguing property in that it has characteristic harmonics with orders ±6n-1 fold to ±6n orders, despite the fact that it does not allow for specific selective compensation of harmonic current [23]. This has the benefit of utilizing a single selective controller to simultaneously compensate for two harmonic orders. The order of the characteristic or dominant harmonics for a three-phase bridge rectifier, with p = 6 pulses per line frequency cycle, is H = n·6 ± 1 = 5, 7, 11, 13, 17, 19, 23, 25, 35, 37.

The BPF was adjusted for attenuation, bandwidth, and center frequency at the necessary harmonic frequency using lower cut off frequencies and a pass band (BW) of 10 Hz. This resulted in improved THD performance. This method effectively attenuates the more dangerous harmonic components of the distorted load current, which are not sufficiently reduced by other controllers, almost entirely. The primary factor affecting the accuracy and dynamics of the harmonic (distortions) detection mechanism is the numerical filter. One must choose a compromise between the two when choosing a filter's features. These depend on the filter's cutoff frequency and order [24].

However, a higher order filter with a low cutoff frequency improves harmonic attenuation at the expense of a slower response when the load varies. Simulation studies showed that, at the expense of response speed, the cascaded filters used in Figure 3 produced better results. As a result, it is important to determine the trade-off between accuracy and speed (time response).

The filter parameters are found using the expressions found in (8)–(12) of [25].

$$BW = f_2 - f_1 \tag{8}$$

$$Q = \frac{f_0}{BW} \tag{9}$$

$$\propto = \frac{1}{Q} \tag{10}$$

High pass filter cutoff frequency:

$$f_1 = \sqrt{\left(\frac{BW}{2}\right)^2 + f_0^2} - \frac{BW}{2} \tag{11}$$

Low pass filter cutoff frequency:

$$f_2 = \sqrt{\left(\frac{BW}{2}\right)^2 + f_0^2} + \frac{BW}{2} \tag{12}$$

where BW is bandwidth, Q is a quality factor, $\propto$ is attenuation, f_1 is low cutoff frequency, f_2 is high cutoff frequency, and f_0 is the center frequency.

4. RESULTS AND ANALYSIS

The performance of the suggested shunt active power filter was examined using MATLAB/Simulink simulation. Table 1 shows the design parameters that were used in this simulation study. The test system consists of a three-phase voltage supply with an uncontrolled rectifier resistor-inductor (RL) load. The analysis was done using LPF, traditional BPF, and finally an LPF and HPF combination. Based on Table 2's results, the combined LPF and HPF filters (BPF), as shown in Figure 3, perform better in terms of THD. Better performance is achieved with a smaller bandwidth. To filter the signal, the BPF is tuned at the desired harmonic frequency using low cutoff frequencies and a pass band (BW) of 10 Hz. The (19) and (20) determine the appropriate BPF cut-off frequencies. It was possible to separate the fundamental from harmonic components of the measured system load, demonstrating the efficacy of this configuration in mitigating harmonic currents as shown in Table 2.

The filter inductor (L) is used to connect the shunt APF to the non-linear load system in order to compensate for harmonics. The simulation results' signal waveforms are shown in Figures 4 through 10. The non-linear load's current signal is displayed in Figure 4 prior to compensation. Before compensation, the distorted line current causes a non-linear load that results in a total harmonic distortion (THD) of 25.60%. This outcome unequivocally demonstrates that the presence of a non-linear load distorts the supply current.

Table 1. Design parameters for simulation study

System parameters	Values	System parameters	Values
Frequency	50 Hz	DC Voltage	700 V
Supply voltage	220 V	Capacitor (Cdc)	3000 μF
Filter inductor	3 mH	Low pass filter (LPF)	20 Hz
Load impedance (R_L, L_L)	40 Ω, 2 mH	High pass filter (HPF)	10 Hz
Source impedance (Rs, Ls)	0.15 Ω, 0.03 mH	Center frequency (fo)	14.14 Hz
Line impedance (Rr, Lr)	1 Ω, 1 mH	Bandwidth (BW)	10

Table 2. THDs for the three filters with SAPF

Filter type	THD%	t_d
LPF	2.19	0.145
LPF	2.2	0.2
LPF	3.74	0.5
Conventional BPF	0.99	0.170
LPF and BPF (BPF)	0.98	0.165

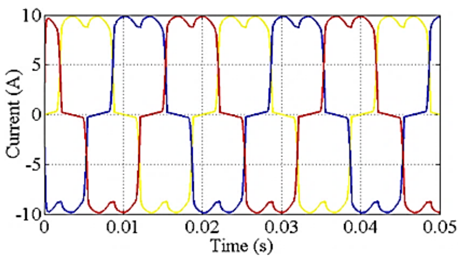

Figure 4. Source current before compensation

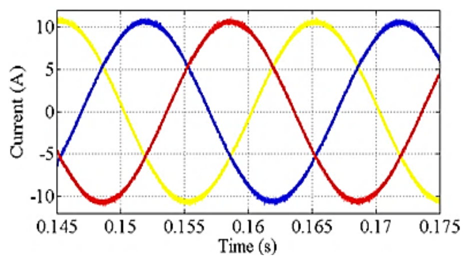

Figure 5. Source current before compensation

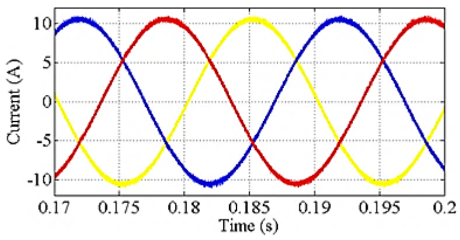

Figure 6. Source current after compensation (SAPF with conventional BPF)

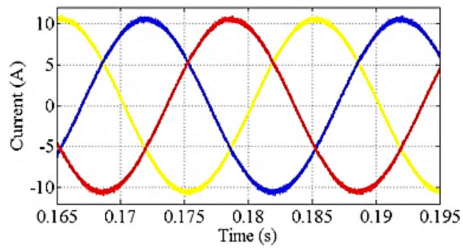

Figure 7. Source current after compensation (SAPF with combined LPF and HPF)

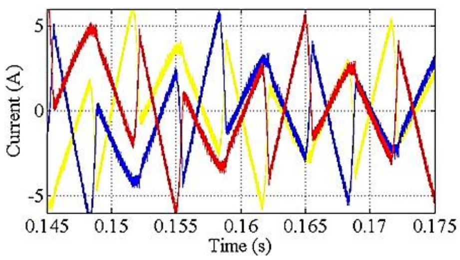

Figure 8. Compensation current (SAPF with LPF)

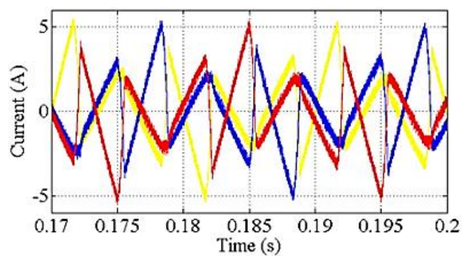

Figure 9. Compensation current (SAPF with conventional BPF)

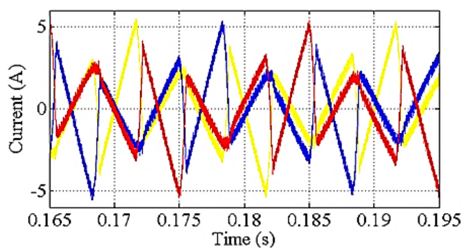

Figure 10. Compensation current (SAPF with combined LPF and HPF)

In order to eliminate current harmonics, a shunt active power filter was applied, which resulted in a reduction in the THD of the distorted load current from 25.60% to 2.19%, 0.99%, and 0.98% (as shown in Table 2) based on an FFT analysis of the source current before and after compensation using three different filtering schemes. Source current waveforms following compensation are shown in Figures 5-7, respectively, for each filter configuration. With the application of a shunt active power filter, it is evident from these results that the source current is now sinusoidal. Current compensation is shown in Figures 8-10. While the THD is high, the LPF filter outperformed the two BPF configurations in terms of delay time. But a 4th order BPF which exhibits a corresponding delay response is generated when 2nd order LPF and 2nd order HPF are combined. This clearly yields a better result in terms of THD. Yusuf *et al.* [26] explained a low pass filter was used for filtering of the harmonics content and the THD was found to be 2.2% with a t_d of 0.2. Again, from [27] 3.74% THD was observed when a band pass filter was used with dq theory with a t_d of 0.5. Table 2 displays the results that these analyses produced. When compared to the other filtering schemes, the combined LPF and HPF (BPF) exhibit better performance with a THD of 0.98%. This verified that the suggested filtering scheme effectively addressed the system's harmonic distortions. However, the major constraint in this research is tuning of the filter devices which makes it very difficult to achieve and consumes a lot of time. A complete simulation diagram of the shunt active power filter is shown in Figure 11.

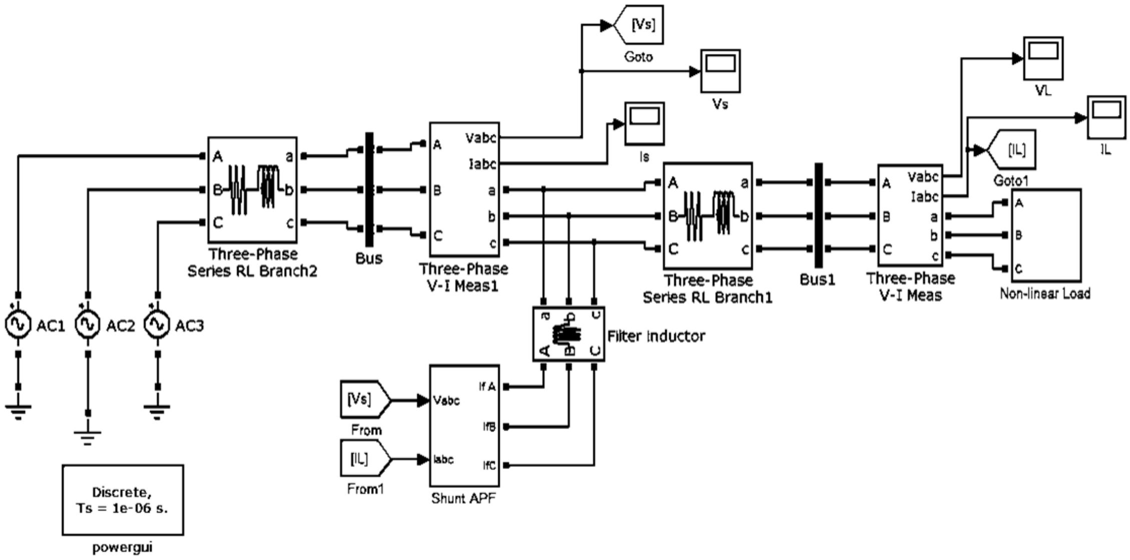

Figure 11. Complete topology of the SAPF

5. CONCLUSION

Harmonic current mitigation in the fundamental d-q frame is presented in this study. By transposing fundamental frequency to dc-signal (i.e., rotating the reference frame at fundamental frequency), this technique achieves overall harmonic compensation. By employing LPF and HPF to isolate the DC and all other harmonic currents from the load current, a specific harmonic current spectrum band is produced. When the voltage source inverter switches on, this harmonic spectrum acts as a reference signal. However, a band of chosen harmonics was found. Fundamental d-q-frame, unlike harmonic d-q-frame, does not permit specific selective harmonic current compensation. This setup is straightforward and doesn't involve a lot of computation when tuning to a particular harmonic for compensation. Although there is a noticeable delay because of the numerical filters, the configuration yields better THD results. This delay can be addressed in the future by using a filter less system for separations of harmonics in the d-q frame using mathematical theory or principle. Also tuning problems can be eliminated when artificial intelligence (AI) is used in the process to reduce time wastage. The results of the simulation demonstrate how well this approach works to mitigate unwanted low order harmonics that are still present in the system even after an LPF has been used. With this filter configuration, the THD decreased from 25.60% to 0.98%.

ACKNOWLEDGEMENTS

The authors would like to express a great appreciation to the Solar Research Institute (SRI), Universiti Teknologi MARA (UiTM), and College of Engineering, UiTM Shah Alam, Selangor, Malaysia for knowledge, facilities, and financial support.

REFERENCES

[1] A. Kumar, "Power quality issues and harmonics performance analysis for non-linear load in power distribution system," in *2022 19th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE)*, IEEE, 2022, pp. 1–5, doi: 10.1109/CCE56709.2022.9975948.

[2] A. N. Skamyin, I. V Dobush, and I. A. Gurevich, "Influence of nonlinear load on the measurement of harmonic impedance of the power supply system," in *2023 5th International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE)*, IEEE, 2023, pp. 1–5. doi: 10.1109/REEPE57272.2023.10086795.

[3] P. Ramya, K. Sahithya, T. Vamsi, and B. Pangedaiah, "Improvement in the power quality by using dynamic voltage restorer," in *2022 IEEE 2nd Mysore Sub Section International Conference (MysuruCon)*, IEEE, 2022, pp. 1–6, doi: 10.1109/MysuruCon55714.2022.9972594.
[4] C. Laurano, S. Toscani, and M. Zanoni, "A simple method for compensating harmonic distortion in current transformers: Experimental validation," *Sensors*, vol. 21, no. 9, p. 2907, 2021, doi: 10.3390/s21092907.
[5] T. J. Abirami, N. L. Surasmi, B. R. Vinod, and G. Shiny, "Synchronous reference frame theory based shunt active filter for harmonic and unbalance compensation," in *2023 International Conference on Control, Communication and Computing (ICCC)*, IEEE, 2023, pp. 1–6, doi: 10.1109/ICCC57789.2023.10165198.
[6] A. Govind, K. Jayaswal, V. K. Tayal, and P. Kumar, "Simulation and real time implementation of shunt active power filter for power quality enhancement using adaptive neural network topology," *Electric Power Systems Research*, vol. 228, p. 110042, 2024, doi: 10.1016/j.epsr.2023.110042.
[7] M. Pichan, H. Hafezi, H. Basnet, and T. Roinila, "Comprehensive design and experimental verification of shunt active power filter," in *IECON 2022–48th Annual Conference of the IEEE Industrial Electronics Society*, IEEE, 2022, pp. 1–6, doi: 10.1109/IECON49645.2022.9968974.
[8] O. F. Benaouda, M. Mezaache, H. Djeghloud, and A. Bendiabdellah, "Study of the performance of fault-tolerant multi-level inverter included in shunt active power filter," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 13, no. 3, pp. 2471–2481, 2023, doi: 10.11591/ijece.v13i3.pp2471-2481.
[9] L. B. Leene and T. G. Constandinou, "Time domain processing techniques using ring oscillator-based filter structures," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 64, no. 12, pp. 3003–3012, 2017, doi: 10.1109/TCSI.2017.2715885.
[10] E. Sundaram and M. Venugopal, "On design and implementation of three phase three level shunt active power filter for harmonic reduction using synchronous reference frame theory," *International Journal of Electrical Power & Energy Systems*, vol. 81, pp. 40–47, 2016, doi: 10.1016/j.ijepes.2016.02.008.
[11] K. Yadav, G. Mehta, and V. K. Yadav, "Power quality improvement with harmonic reduction using PQ theory-based shunt active power filter," in *Smart Energy and Advancement in Power Technologies: Select Proceedings of ICSEAPT 2021, Volume 2*, Springer, 2022, pp. 1–16, doi: 10.1007/978-981-19-4975-3_1.
[12] D. Tsvetanov, N. Djagarov, Z. Grozdev, and J. Djagarova, "Synchronous reference frame theory control for current harmonics suppression in ship power system using shunt active power filter," in *2022 International Conference Automatics and Informatics (ICAI)*, IEEE, 2022, pp. 120–128, doi: 10.1109/ICAI55857.2022.9960096.
[13] D. Prasad, N. Kumar, and R. Sharma, "Shunt active power filter based on synchronous reference frame theory connected to SPV for power quality enrichment," in *Machine Learning, Advances in Computing, Renewable Energy and Communication: Proceedings of MARC 2020*, Springer, 2022, pp. 281–292, doi: 10.1007/978-981-16-2354-7_26.
[14] E. A. Al-Ammar *et al.*, "Synchronous reference frame theory based intelligent controller for current THD reduction," *Journal of Electrical Engineering & Technology*, vol. 16, pp. 2917–2936, 2021, doi: 10.1007/s42835-021-00824-3.
[15] S. F. Al-Gahtani *et al.*, "A new technique implemented in synchronous reference frame for DVR control under severe sag and swell conditions," *IEEE Access*, vol. 10, pp. 25565–25579, 2022, doi: 10.1109/ACCESS.2022.3151919.
[16] M. Calar and K. Kayisli, "Synchronous reference frame control of transformer based DC mA current sensor," in *2023 11th International Conference on Smart Grid (icSmartGrid)*, IEEE, 2023, pp. 1–5.
[17] S. Ahmad, S. Mekhilef, and H. Mokhlis, "DQ-axis synchronous reference frame based PQ control of grid connected AC microgrid," in *2020 IEEE International Conference on Computing, Power and Communication Technologies (GUCON)*, IEEE, 2020, pp. 842–847, doi: 10.1109/GUCON48875.2020.9231080.
[18] F. Rong, J. Yu, and A. Luo, "Reference current computation method based on adaptive low-pass filter for active power filter," in *2010 International Conference on Measuring Technology and Mechatronics Automation*, IEEE, 2010, pp. 996–999, doi: 10.1109/ICMTMA.2010.26.
[19] R. Cardoso and H. A. Grundling, "Reference generation for harmonics cancellation, displacement power factor correction and unbalance compensation under unknown fundamental frequency," in *31st Annual Conference of IEEE Industrial Electronics Society, 2005. IECON 2005*, IEEE, 2005, pp. 6-pp. doi: 10.1109/IECON.2005.1568905.
[20] Y. Zou, L. Zhang, Y. Xing, Z. Zhang, H. Zhao, and H. Ge, "Generalized Clarke transformation and enhanced dual-loop control scheme for three-phase PWM converters under the unbalanced utility grid," *IEEE Transactions on Power Electronics*, vol. 37, no. 8, pp. 8935–8947, 2022, doi: 10.1109/TPEL.2022.3153476.
[21] S. Yang, W. Zheng, F. Chen, and Z. Shao, "A novel synchronous reference frame transformation technique for background harmonics elimination and its application," in *2019 IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2)*, IEEE, 2019, pp. 933–938, doi: 10.1109/EI247390.2019.9061893.
[22] N. Shah, "Harmonics in power systems causes, effects and control," *Power Engineering Journal*, pp. 1–23, 2013.
[23] A. G. Prasad, K. Dheeraj, and A. N. Kumar, "Comparison of control algorithms for shunt active filter for harmonic mitigation," *International Journal of Engineering Research & Technology*, vol. 1, no. 5, pp. 1–6, 2012.
[24] D. Wang, L. Zhang, C. Wang, S. Liu, and Q. Liu, "A harmonic detection strategy based on FBD power theory," in *2019 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, IEEE, 2019, pp. 1–5, doi: 10.1109/APPEEC45492.2019.8994402.
[25] P. Mattavelli, "A closed-loop selective harmonic compensation for active filters," *IEEE Transactions on Industry Applications*, vol. 37, no. 1, pp. 81–89, 2001, doi: 10.1109/28.903130.
[26] S. D. Yusuf, A. Z. Loko, J. Abdullahi, and A. A. Abdulhamid, "Performance analysis of three-phase shunt active power filter for harmonic mitigation," *Asian Journal of Research and Reviews in Physics*, vol. 6, no. 3, pp. 7–24, 2022, doi: 10.9734/ajr2p/2022/v6i3118.
[27] A. Mostefa, K. Belalia, T. Lantri, H. M. Boulouiha, and A. Allali, "A four-line active shunt filter to enhance the power quality in a microgrid," *International Journal of Renewable Energy Development*, vol. 12, no. 3, 2023, doi: 10.14710/ijred.2023.50270.

BIOGRAPHIES OF AUTHORS

Zubairu Usman is a dedicated electrical engineering student at Kaduna Polytechnic, affiliated with Ahmadu Bello University. He holds a diploma in Electrical/Electronic Engineering and has gained practical experience through internships at companies like the Nigerian National Petroleum Company Limited and Kaduna Refining and Petrochemical Company. Zubairu has also held leadership positions in student organizations, showcasing his leadership abilities. He is committed to continuous learning, holding certificates in data science, project management, CAD software, and SOLIDWORKS. Zubairu is an active member of professional bodies like the Nigerian Society of Engineers and the Institute of Electrical and Electronics Engineering. At 28, he is known for his strong work ethic and enthusiasm for learning, aiming to make significant contributions to the field of electrical engineering. He can be contacted at email: zubairuusman84@gmail.com.

Muhammad Hasbi Azmi obtained a Foundation in Engineering in 2018 and a bachelor of engineering (Hons) in Electrical Engineering in 2022 with first-class honour from Universiti Teknologi MARA (UiTM), Malaysia. He is currently pursuing Ph.D. in Electrical Engineering after being offered to enroll in the fast-track doctoral programme at Universiti Teknologi MARA (UiTM). His current research interests include the field of renewable energy, power quality, optimization, artificial intelligence, and power electronics. He can be contacted at email: mhasbiazmi@gmail.com.

Ts. Dr. Siti Zaliha Binti Mohammad Noor obtained Bachelor of Electrical Engineering (Hons) in 2005, M.Sc. Power Electronics in 2008 and Ph.D. in Electrical Engineering in 2018 from Universiti Teknologi MARA (UiTM), Malaysia. She is currently a Senior Lecturer at the Faculty of Electrical Engineering, UiTM. She has authored and co-authored over 40 technical papers in indexed international journals and conferences. Her research interests are renewable energy, power electronics, modeling and simulation, signal processing and embedded controller applications. She is a Certified Energy Manager, Certified Professional in Measurement and Verification CPMV), and Qualified Person (QP) SEDA Malaysia Grid-Connected Solar Photovoltaic Systems Design. She is also attached to industry collaborations as the Subject Matter Expert (SME) for the photovoltaic (PV) system and energy audit. She also received a gold award in the e-Content Development Competition (e-ConDev2018) and a silver award in the Educational, Design, Games, Invention, and Innovation Competition 2022 (EDGII2022) for the course renewable energy -friends of the world as an educator and developer of the course. Currently, more than 1200 students join the course worldwide for free. She can be contacted at email: sitizaliha@uitm.edu.my.

Suleiman Musa obtained his National Diploma in Electrical and Electronic Engineering Technology Kaduna Polytechnic in 1994 and graduated at Upper Credit. He then joined the service of the Polytechnic in 1995 as an assistant technician. In 1998 He obtained his Higher National Diploma (power and machine option) at Upper Credit from the Department of Electrical and Electronic Engineering Technology Kaduna Polytechnic. Furthermore, he obtained the Post Higher National Diploma in Electronics and Telecommunication Engineering at Upper Credit from the same Department of Electrical and Electronic Engineering Technology in 2002. He proceeded to Bayero University Kano where he obtained a master's degree in Electrical Engineering in 2008. In 2017 He obtained a Ph.D. degree in Electrical Power System from the Universiti Putra Malaysia. He can be contacted at email: sumusa115@gmail.com.