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DSOGI-PLL and Moving Average Filter Based Control Method for Shunt Active Power Filter

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Abstract: The increasing penetration of nonlinear loads and power electronic converters in modern power systems has led to a significant rise in current harmonics and power quality problems. The shunt active power filter (SAPF) has emerged as an effective solution to mitigate these issues. However, the performance of SAPF systems largely depends on the accuracy of the reference current generation method and the effectiveness of the synchronization algorithm. In conventional synchronous reference frame (SRF–*dq*) based SAPF control methods, low-pass filters (LPFs) are commonly used to extract the fundamental component, while high-pass filters (HPFs) are employed to obtain harmonic components. Nevertheless, these filtering structures may introduce undesirable effects such as time delay and phase shift, which degrade the dynamic performance of the control system.In this study, an improved *dq*-based control strategy is proposed for SAPF applications by combining a Dual Second-Order Generalized Integrator Phase-Locked Loop (DSOGI-PLL) based synchronization technique with a Moving Average Filter (MAF) based harmonic extraction approach. In the proposed method, the DSOGI-PLL structure ensures accurate phase angle estimation even under distorted grid conditions, while the MAF structure enables the extraction of the fundamental current component without introducing the delay and phase shift problems associated with conventional LPF and HPF filters. The effectiveness of the proposed control method is evaluated through simulation studies under different operating conditions. In the case of sinusoidal grid voltage and nonlinear load, the total harmonic distortion (THD) of the source current is reduced from approximately 19.19% to 0.79%. Furthermore, under distorted grid voltage and nonlinear load conditions, the source current THD values decrease to the range of 1.55–1.89%. These results demonstrate that the proposed method significantly enhances harmonic mitigation performance and ensures compliance with the limits specified in the IEEE 519-2014 standard.

Keywords: Dual second-order generalized integrator (DSOGI), Harmonic mitigation, Moving average filter (MAF), Power quality, Shunt active power filter (SAPF)

Introduction

The increasing integration of power electronic converters and nonlinear loads in modern power systems has led to a significant rise in power quality problems such as current harmonics, voltage distortions, and reduced power factor (Özer et al., 2026). These undesirable effects may cause overheating in electrical equipment, malfunction of sensitive devices, additional power losses, and a decrease in overall system efficiency. Therefore, harmonic mitigation and power quality improvement have become critical issues in distribution networks (Sant, Patel et al. 2024).

Traditionally, passive filters composed of inductors and capacitors have been utilized to reduce harmonic components (Rath et al., 2024). Although passive filters offer a simple and low-cost solution, they suffer from several major drawbacks, including fixed compensation capability, bulky structure, and the possibility of resonance with grid impedance. Consequently, passive filters cannot always provide satisfactory performance under varying operating conditions (Sundaram & Venugopal 2016).

With the advancements in power electronics and digital control technologies, active power filters (APFs) have emerged as an effective solution for mitigating harmonics and improving power quality. Among the different types of active power filters, the shunt active power filter (SAPF) is widely employed to suppress current harmonics generated by nonlinear loads (Wu et al., 2024). The performance of SAPF systems largely depends on the accuracy of the reference current generation technique and the effectiveness of the synchronization algorithm(Sundaram & Venugopal 2016).

Various approaches have been proposed in the literature for reference current generation, including the instantaneous power theory (p–q theory) and the synchronous reference frame (SRF), also referred to as the *dq* theory (Özer & Karaca). However, the p–q theory may exhibit limited performance under unbalanced and distorted grid voltage conditions, as it may fail to generate an accurate reference current(Amini, Rastegar et al. 2024). In contrast, the SRF-based control approach has been widely adopted due to its simple structure and fast dynamic response.

Nevertheless, in conventional SRF-based control methods, low-pass filters (LPFs) are typically used to extract the fundamental component, whereas high-pass filters (HPFs) are employed to obtain harmonic components. The use of LPFs may introduce delays that slow down the dynamic response of the system (Çelik, Ahmed et al. 2022), whereas HPFs may cause phase shifts that adversely affect system stability and the accuracy of the reference current generation (Hmad et al., 2025).

Another critical issue in SRF-based SAPF control is the accurate estimation of the grid phase angle required for coordinate transformations. In grid-connected power electronic systems, phase-locked loop (PLL) structures are widely employed for synchronization purposes. Although the conventional SRF-PLL structure provides satisfactory performance under ideal grid conditions, its performance significantly deteriorates in the presence of harmonic distortion in grid voltages (Sevilmiş & Karaca 2019). To overcome these limitations, several advanced PLL structures have been proposed in recent years. Among them, the dual second-order generalized integrator based PLL (DSOGI-PLL) has attracted considerable attention due to its ability to provide more accurate phase and frequency estimation under distorted grid conditions (Sevilmiş & Karaca 2022).

In this study, an improved SAPF control strategy is proposed by combining a DSOGI-PLL-based synchronization technique with a moving average filter (MAF)-based harmonic extraction approach. In the proposed method, the DSOGI-PLL structure enables accurate phase angle estimation even under harmonic-contaminated grid conditions, while the MAF structure allows the fundamental current component to be extracted without introducing the delay and phase shift problems commonly associated with conventional LPF and HPF filters. Consequently, the proposed control strategy aims to enhance harmonic compensation performance and reduce the total harmonic distortion (THD) of the source current.

The effectiveness of the proposed method is evaluated through simulation studies conducted under different operating scenarios, including sinusoidal grid voltage with harmonic load and distorted grid voltage with nonlinear load conditions. The results obtained demonstrate that the proposed approach achieves lower THD values compared to conventional methods, thereby improving harmonic mitigation performance. Furthermore, the resulting THD values remain below the 5% limit specified in the IEEE 519-2014 standard, indicating that the proposed method provides an effective solution for improving power quality in distribution systems.

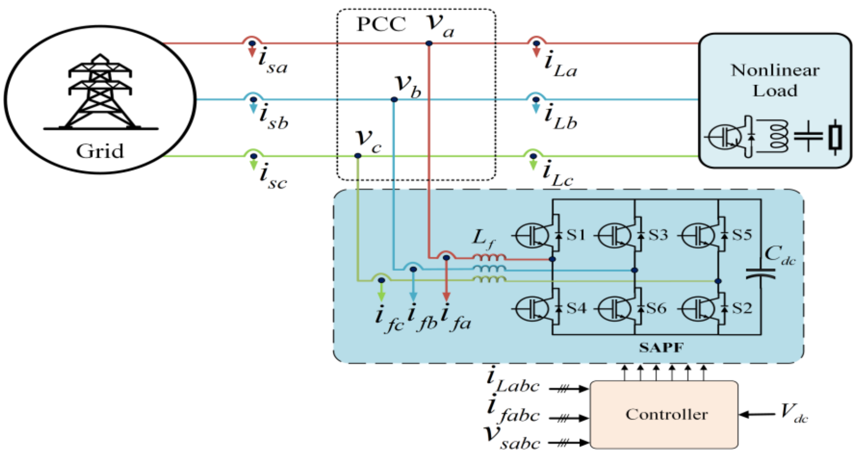

Figure 1. System configuration of the SAPF connected to the grid and nonlinear load.

Modeling of Shunt Active Power Filter

The schematic configuration of the SAPF system connected to the grid and nonlinear load is illustrated in Figure 1. The SAPF operates as a controlled current source that generates compensating currents with the same magnitude but opposite phase to the harmonic currents produced by the nonlinear load. By injecting these compensating currents at the point of common coupling (PCC), the harmonic components in the source current are effectively suppressed, allowing the source current to approach a sinusoidal waveform.

In this study, the SAPF structure consists of a voltage source inverter (VSI) connected in parallel with the distribution system, an interfacing inductor L_f, and a DC-link capacitor C_{dc}. The VSI is composed of six bidirectional semiconductor switches, which can be implemented using power electronic devices such as IGBTs, MOSFETs, or GTOs, depending on the power level of the application. The switching operation of the inverter is controlled by the signals generated from the control algorithm, enabling the SAPF to inject the required compensating currents into the system.

Improved *dq*-based control strategy for SAPF

In this study, an improved *dq*-based control strategy is proposed to enhance the harmonic compensation performance of SAPF under distorted grid conditions. The overall block diagram of the proposed control scheme is illustrated in Figure 2. The proposed structure combines a DSOGI-PLL-based synchronization unit with a moving average filter (MAF)-based fundamental component extraction method. While the DSOGI-PLL structure provides accurate phase angle estimation under distorted grid conditions, the MAF enables effective extraction of the fundamental current component in the *dq* reference frame. The main components and operating principles of the proposed control scheme are explained in detail in the following subsections.

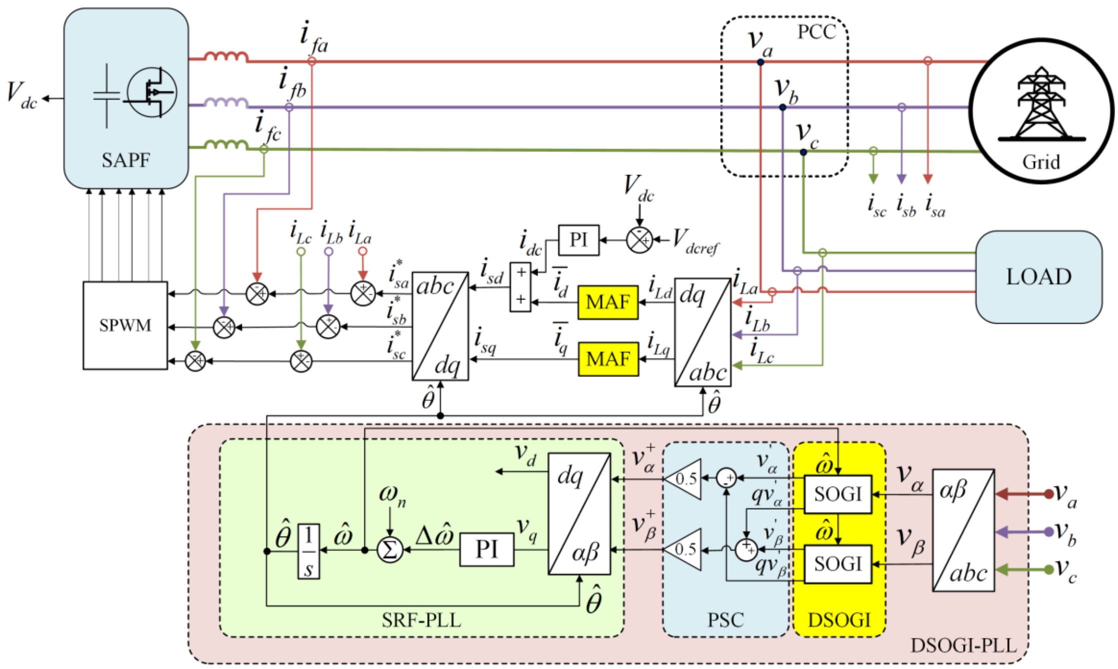

Figure 2. Block diagram of the proposed *dq*-based control strategy for SAPF.

DSOGI-PLL Configuration

Figure 2 shows the overall block diagram of the proposed *dq*-based control strategy for SAPF. In this control scheme, the DSOGI-PLL unit is used to obtain the grid phase angle, which is required for the coordinate transformations. Within the DSOGI-PLL structure, two second-order generalized integrators (SOGIs) are employed to suppress unwanted harmonic components present in the v_α and v_β signals. Each SOGI produces both a filtered version of the input signal and its corresponding quadrature (90° phaseshifted) component. In this context, qv'_α and qv'_β represent the quadrature components of v'_α and v'_β respectively. The transfer functions of the SOGI can be expressed as given in Rodriguez et al. (2006).

$$R(s) = \frac{v'_{\alpha,\beta}}{v_{\alpha,\beta}} = \frac{k\hat{\omega}s}{s^2 + k\hat{\omega}s + \hat{\omega}^2} \tag{1}$$

$$Q(s) = \frac{qv'_{\alpha,\beta}}{v_{\alpha,\beta}} = \frac{k\hat{\omega}^2}{s^2 + k\hat{\omega}s + \hat{\omega}^2} \tag{2}$$

In this expression, the parameters k and $\hat{\omega}$ correspond to the damping coefficient and the estimated angular frequency, respectively. As illustrated in Fig. 5, the outputs of the SOGI blocks are forwarded to the positive sequence calculator (PSC) to obtain the positive sequence components of the v_α and v_β signals, denoted as v_α^+ and v_β^+. The PSC module is implemented based on the instantaneous symmetrical component theory, and its operation follows the formulation presented in (Golestan, Monfared et al. 2012).

$$\begin{bmatrix} v_\alpha^+ \\ v_\beta^+ \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & -q \\ q & 1 \end{bmatrix}\begin{bmatrix} v'_\alpha \\ v'_\beta \end{bmatrix} \tag{3}$$

The extracted signals v_α^+ and v_β^+ are subsequently processed by a conventional SRF-PLL to estimate the phase angle, amplitude, and frequency of the input voltages. The estimated frequency is then fed back to the SOGI blocks, allowing the DSOGI-PLL structure to adapt to variations in the grid frequency.

MAF Structure

The LPFs employed for filtering i_{Ld} and i_{Lq} present two major drawbacks: they introduce phase delay and are not capable of effectively attenuating harmonic components generated by nonlinear and unbalanced loads. To overcome these limitations, a moving average filter (MAF) is adopted in this study instead of conventional LPFs, as illustrated in Figure 2. Due to its simple structure and ease of implementation, the MAF has recently gained considerable attention in power electronic control applications (Özer, Sevilmiş et al. 2022).

Under specific conditions, the moving average filter (MAF) can exhibit a behavior similar to that of an ideal low-pass filter (LPF). The transfer functions of the MAF in the *s*-domain and *z*-domain can be represented as follows (Golestan, Ramezani et al. 2013).

$$\mathrm{MAF}(s) = \frac{1 - e^{-T_\omega s}}{T_\omega s} \tag{4}$$

$$\mathrm{MAF}(z) = \frac{1}{N}\frac{1 - z^{-N}}{1 - z^{-1}} \tag{5}$$

In these expressions, T_ω and N represent the window length of the MAF and the filter order, respectively. The filter order N is defined as $f_s T_\omega$, where f_s denotes the sampling frequency. Based on (5), the digital implementation of the MAF can be derived, and its block diagram is presented in Figure 3. Owing to its simple structure, the MAF enables an efficient and straightforward implementation in SAPF control schemes based on the *dq*-theory.

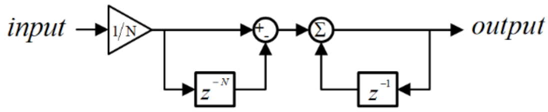

Figure 3. Block diagram of MAF for digital implementation.

***dq*-Based Reference Current Generation**

The synchronous reference frame (*dq*) method is widely used in shunt active power filter (SAPF) applications due to its simple structure and fast dynamic response. In this method, the three-phase load currents are transformed into a rotating reference frame where the fundamental component appears as a DC value while harmonic components appear as oscillating quantities.The three-phase load currents i_{La}, i_{Lb}, and i_{Lc} are transformed into the synchronous reference frame using the Park transformation as

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\hat{\theta} & \cos(\hat{\theta}-\frac{2\pi}{3}) & \cos(\hat{\theta}+\frac{2\pi}{3}) \\ \sin\hat{\theta} & -\sin(\hat{\theta}-\frac{2\pi}{3}) & -\sin(\hat{\theta}+\frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (6)$$

where $\hat{\theta}$ represents the grid phase angle obtained from the DSOGI-PLL synchronization unit.

The obtained *dq*-axis currents contain both fundamental and harmonic components. To extract the fundamental component of the load currents, a moving average filter (MAF) is applied to the *dq*-axis currents. The filtered signals are expressed as

$$\overline{i_d} = MAF(i_{Ld}) \quad (7)$$

$$\overline{i_q} = MAF(i_{Lq}) \quad (8)$$

These filtered components represent the fundamental components of the load current in the synchronous reference frame. In addition to harmonic compensation, the DC-link voltage of the voltage source inverter must be maintained at a constant level to ensure proper operation of the SAPF. For this purpose, the measured DC-link voltage V_{dc} is compared with the reference value V_{dcref}, and the resulting error signal V_{dcer} is processed through a PI controller to generate the active current component i_{loss}:

$$i_{dc(n)} = i_{dc(n-1)} + K_{pd(n)}(V_{dcer(n)} - V_{dcer(n-1)}) + K_{id(n)}V_{dcer(n)} \quad (9)$$

The reference current components in the *dq* frame are then obtained as

$$i_{sd} = \overline{i_d} + i_{dc} \quad (10)$$

$$i_{sq} = \overline{i_q} \quad (11)$$

After calculating the reference currents in the *dq* frame, the three-phase reference source currents are obtained using the inverse Park transformation

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \begin{bmatrix} \cos\hat{\theta} & -\sin\hat{\theta} \\ \cos(\hat{\theta}-\frac{2\pi}{3}) & -\sin(\hat{\theta}-\frac{2\pi}{3}) \\ \cos(\hat{\theta}+\frac{2\pi}{3}) & -\sin(\hat{\theta}+\frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \quad (12)$$

In order to determine the compensating current required from SAPF, the reference source currents are subtracted from the measured load currents. In this way, the reference filter currents that must be injected by the SAPF are obtained. These reference currents are then compared with the measured filter currents, and the resulting error signals are used to generate the PWM switching pulses for the voltage source inverter.

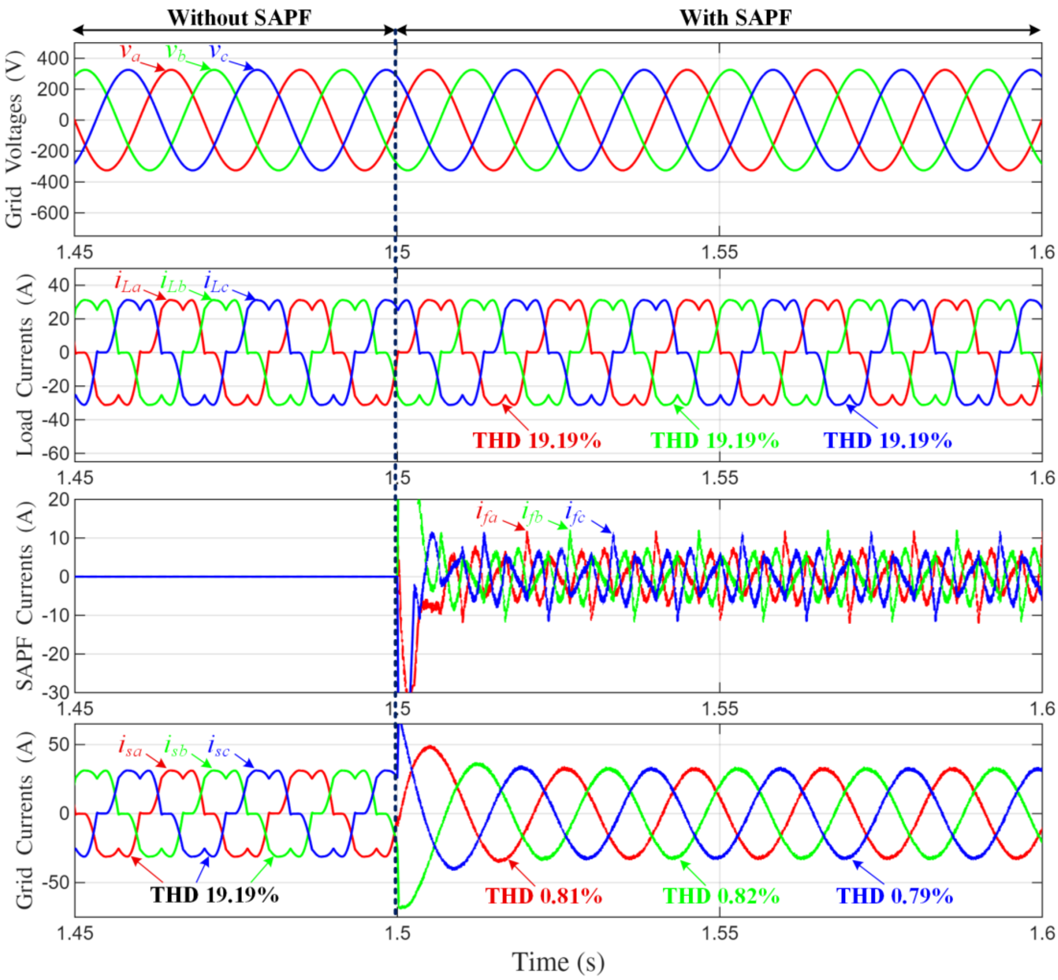

Figure 4. Grid voltages (v_a, v_b, v_c), load currents (i_{La}, i_{Lb}, i_{Lc}) SAPF compensating currents (i_{fa}, i_{fb}, i_{fc}) and grid currents (i_{sa}, i_{sb}, i_{sc}) under sinusoidal grid voltage and nonlinear load conditions.

Results and Discussion

To evaluate the performance of the DSOGI-PLL and MAF-based SAPF control method, simulation studies are carried out in the MATLAB/Simulink environment under both sinusoidal and distorted grid voltage conditions with a nonlinear load. The system is modeled using a discrete-time approach with a sampling time of 1e-5 s. The grid voltage is set to 400 V (line-to-line) with a frequency of 50 Hz, while the interfacing inductor and DC-link capacitor are selected as 2 mH and 2500 μF, respectively.

Fig. 4 illustrates the grid voltages v_a, v_b, v_c, the nonlinear load currents i_{La}, i_{Lb}, i_{Lc}, the compensating currents generated by the SAPF i_{fa}, i_{fb}, i_{fc}, and the source currents drawn from the grid i_{sa}, i_{sb}, i_{sc}. In addition, the figure presents a comparison between the operating conditions when the SAPF is disabled and when it is activated. First, the performance of the system is evaluated under sinusoidal grid voltage and nonlinear load conditions. When the grid voltages v_a, v_b, v_c, shown in Figure 4 are examined, it can be observed that the three phases are balanced and have a sinusoidal waveform. Due to the nonlinear load, the load currents i_{La}, i_{Lb}, i_{Lc}, contain significant harmonic components, resulting in noticeably distorted current waveforms. Under these conditions, the THD of the load currents is approximately 19.19%.

When the source currents i_{sa}, i_{sb}, i_{sc}.are examined, it is observed that the harmonic components generated by the nonlinear load are directly transferred to the grid current when the SAPF is not operating. As a result, the source currents exhibit highly distorted waveforms, and the THD value reaches approximately 19.19%. When the SAPF is enabled using the proposed DSOGI-PLL and MAF-based control strategy, the filter produces compensating currents i_{sa}, i_{sb}, i_{sc}.that are injected at the PCC to cancel the harmonic components of the load current. This compensation significantly improves the waveform quality of the source currents, making them nearly sinusoidal. Consequently, the THD of the source currents decreases from 19.19% to 0.81%, 0.82%, and 0.79%, respectively. These results confirm that the proposed control approach provides effective harmonic suppression under sinusoidal grid voltage conditions.

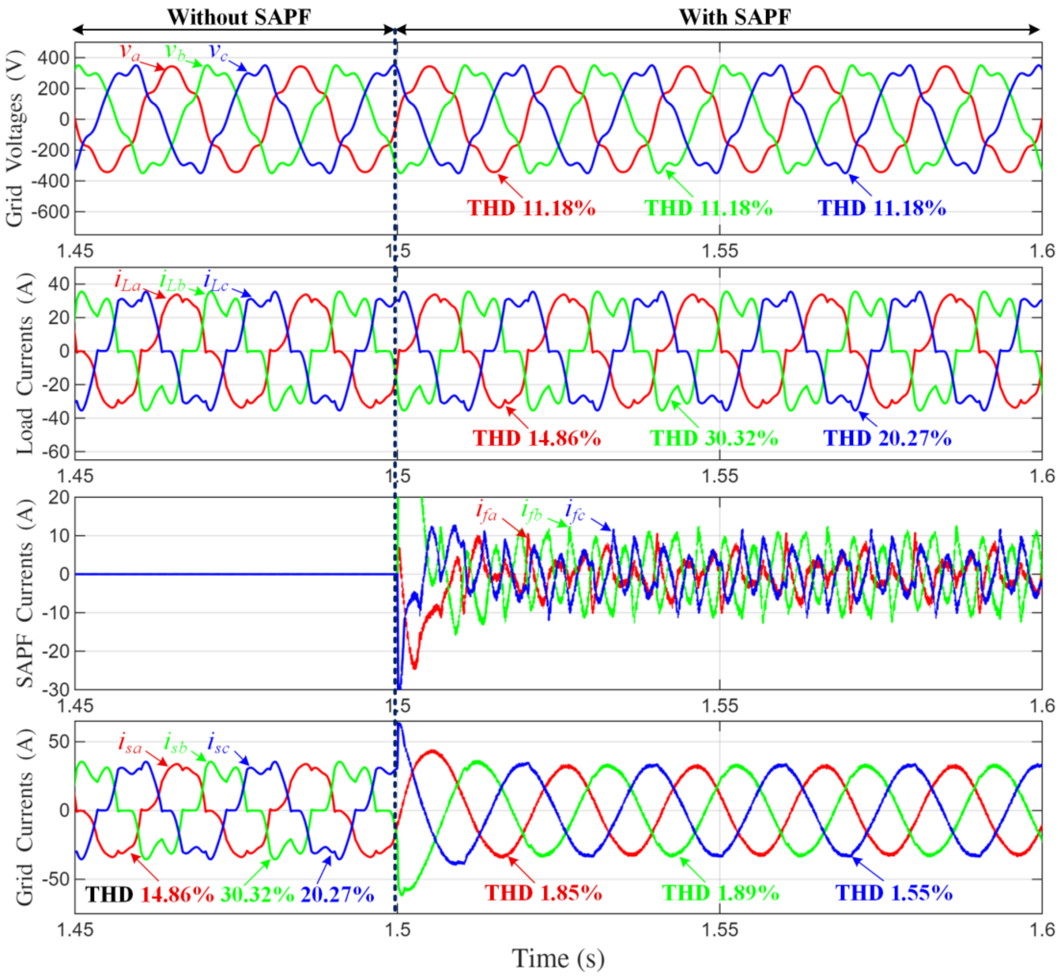

Figure 5. Grid voltages (v_a, v_b, v_c), load currents (i_{La}, i_{Lb}, i_{Lc}) SAPF compensating currents (i_{fa}, i_{fb}, i_{fc}) and grid currents (i_{sa}, i_{sb}, i_{sc}) under distorted grid voltage and nonlinear load conditions.

To further evaluate the performance of the proposed DSOGI-PLL and MAF-based SAPF control strategy under more challenging operating conditions, simulation studies are conducted for the case of distorted grid voltage and nonlinear load. Fig. 5 illustrates the grid voltages v_a, v_b, v_c,, the load currents i_{La}, i_{Lb}, i_{Lc}, the compensating currents generated by the SAPF i_{fa}, i_{fb}, i_{fc}, , and the source currents i_{sa}, i_{sb}, i_{sc}.

Under distorted grid voltage conditions, both the grid voltages v_a, v_b, v_c, and load currents i_{La}, i_{Lb}, i_{Lc}, contain significant harmonic components. When the SAPF is not in operation, these harmonics propagate directly to the source currents, causing considerable waveform distortion. After the activation of the SAPF with the proposed DSOGI-PLL and MAF-based control method, the filter injects appropriate compensating currents to mitigate the harmonic components present in the system. As a result, the source currents become considerably smoother and closer to sinusoidal waveforms despite the presence of grid voltage distortion. The THD values of the source currents are reduced to 1.85%, 1.89%, and 1.55%, respectively. This outcome demonstrates that the proposed control method maintains strong harmonic mitigation capability even under distorted grid voltage and nonlinear load conditions.

This outcome demonstrates that the proposed control method maintains strong harmonic mitigation capability even under distorted grid voltage and nonlinear load conditions. Overall, these results clearly demonstrate the effectiveness, robustness, and practical applicability of the proposed DSOGI-PLL and MAF-based control strategy. Furthermore, the achieved THD values satisfy the requirements of the IEEE 519-2014 standard, indicating that the proposed method provides a reliable solution for power quality improvement.

Conclusion

In this study, an improved *dq*-based control strategy is proposed for shunt active power filter (SAPF) applications by combining a DSOGI-PLL-based synchronization method with a moving average filter (MAF)-based harmonic extraction approach. In the proposed method, the DSOGI-PLL structure provides accurate phase angle estimation under harmonic-contaminated grid conditions, while the MAF structure enables the extraction of the fundamental current component without introducing the delay and phase shift problems commonly associated with conventional LPF and HPF filters.

The performance of the proposed control strategy is evaluated through simulation studies conducted under different operating conditions. Under sinusoidal grid voltage and nonlinear load conditions, the THD of the source current, which is approximately 19.19% when the SAPF is not in operation, is reduced to 0.79% using the proposed method. Under distorted grid voltage and nonlinear load conditions, the TDD values of the source currents are reduced to 1.85%, 1.89%, and 1.55%, respectively.

The obtained results demonstrate that the proposed DSOGI-PLL and MAF-based control strategy provides high harmonic mitigation performance under both sinusoidal and distorted grid conditions. Furthermore, the resulting TDD values remain below the limits specified in the IEEE 519-2014 standard. Therefore, the proposed method can be considered an effective solution for improving power quality in SAPF applications.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest.

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