International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 17, No. 2, June 2026, pp. 1221~1230
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v17.i2.pp1221-1230

Adaptive notch filter: An alternative synchronizer for effective performance of active power filter under challenging grid conditions

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Article Info

Article history:

Received Nov 13, 2025
Revised Feb 5, 2026
Accepted Apr 23, 2026

Keywords:

Adaptive notch filter
Distorted grid condition
Phase synchronization
Single-phase dq theory
Synchronous reference frame

ABSTRACT

Harmonic distortion issues on modern power systems are becoming highly significant due to the increasing integration of renewable energy sources, electric vehicles, and smart technologies. These distortions, mainly caused by the operation of power electronics devices, potentially degrade overall system quality, increase losses, and shorten equipment lifespan if they are not properly mitigated. Shunt active power filters (SAPFs) are found to be most effective against current harmonics issues, but their performance strictly depends on accurate grid synchronization. In this paper, an alternative method developed based on the adaptive notch filter (ANF) concept is proposed for reliable grid synchronization under challenging conditions. The proposed ANF-based synchronizer is modelled in MATLAB/Simulink and benchmarked against the existing self-tuning filter (STF) method under four cases involving sinusoidal, distorted, noisy, and distortion-with-noise grid conditions. Simulation findings demonstrate that the proposed method enables the connected SAPF to effectively mitigate harmonics by providing low total harmonic distortions (2.71% to 2.82%) and minimal phase deviation (0.2° to 0.5°), while maintaining the accuracy of fundamental current between 94.48% to 97.21%. As a result, the overall power factor of the system is raised to near unity, confirming the ability of the proposed ANF-based method to serve as a better alternative for SAPF synchronization.

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1. INTRODUCTION

Modern power systems have undergone rapid and transformative growth, where they have now become highly advanced with large integration of renewable energy sources, electric vehicles, and smart technologies. These technologies often require power electronics converters and inverters to connect to the operating grid, which potentially distort the ideal sinusoidal waveform of current and voltage, leading to significant harmonic issues. Without immediate mitigation, harmonics can cause a cascade of issues such as higher transmission losses, increased heating of devices, reduced equipment lifespan, and interference with sensitive electronics, thereby making harmonics management a critical challenge in modern power systems [1], [2]. Fortunately, researchers and industry experts are already actively working to deal with the issues of harmonics, where harmonic mitigation tools known as active power filters (APFs) have been developed.

Ongoing research shows that shunt-type active power filters (SAPFs) are most effective against harmonic currents in the power systems [3]-[5].

However, to effectively track and mitigate harmonic currents within the power systems, SAPFs depend strongly on advanced controllers. For instance, effective operation with the grid would require precise synchronization with the grid voltage, frequency, and phase [6]. Without a reliable synchronization feature in the controller, it is impossible for the SAPF to properly cancel harmonics, thereby compromising the stability and power quality of the system. In other words, to ensure accurate grid integration and optimal harmonics mitigation, synchronization is an important factor to be considered when designing the controller of SAPFs [7], [8]. Specifically on synchronization for APF applications, common methods that can be found in the literature include phase-locked loop (PLL) [7], [9], zero-crossing detector (ZCD) [7], [10], unit vector [8], [11], adaptive linear neuron (ADALINE) [12], [13], synchronous reference frame (SRF) [14], [15], and self-tuning filter (STF) [16]-[18] methods. These methods are reported to provide unique strengths and weaknesses in terms of accuracy, speed, and robustness under different grid conditions, where their respective features have already been critically contrasted in [7], [8].

For example, PLL, ZCD, and unit vector methods are known for their relatively simple and straightforward control structures, but their effectiveness is usually restricted to conditions where the grid is balanced, stable, and has a purely sinusoidal waveform. If the operating grid is having distortion or unbalance issues, these methods potentially lose synchronization accuracy and may become unreliable [7], [10], [11]. Meanwhile, the SRF method provides improved performance under dynamic conditions, but it usually depends on a heuristically tuned low-pass filter (LPF) to obtain accurate extraction of the fundamental component, which can be difficult when working under severe distortion [7], [11], [14]. Similarly, the ADALINE method also performs well when the electrical grid is balanced and sinusoidal, but usually degrades when subjected to harmonics and unbalance issues. Even if its learning rate is carefully tuned, but without a pre-filtering mechanism that can isolate the fundamental component, the ADALINE method often fails in distorted environments [7], [13]. Fortunately, with STF methods, effective grid alignment under highly distorted and unbalanced conditions can be achieved [16]-[18]. However, the performance of STF methods is sensitive to gain parameter tuning, where the tuning is often performed heuristically. It is also important to note that STF alone cannot generate the synchronization phase because it is basically a pre-filtering mechanism to eliminate unwanted distortions. To extract the desired phase, further processing is still required. As a result, STF is usually used in conjunction with other methods such as unit vector or SRF methods [15]-[18].

Recently, the adaptive notch filter (ANF) concept has been reported to show strong potential in isolating the fundamental component of grid signals, and this feature is highly beneficial to the operation of SAPFs [19]-[21]. Owing to its adaptive nature, a typical ANF can dynamically track frequency variations and effectively suppress unwanted harmonic components. Conceptually, this ability makes the ANF able to derive the desired synchronization phase internally [21], [22]. As a result, ANF is particularly advantageous in non-ideal grid environments where traditional filtering and synchronization methods often face challenges. Although there is existing research on using ANF as a synchronization unit, most studies are limited to balanced and distortion-free grid conditions [19]-[21]. Therefore, further investigation into its performance under distorted environments is essential to fully gauge its abilities.

To address this gap, this work presents a standalone ANF-based synchronizer module that ensures accurate alignment of the SAPF with the operating grid. The ANF-based synchronizer is designed to be easily adaptable to various control algorithms associated with the SAPFs. Next, to evaluate the effectiveness of the proposed ANF method, multiple test scenarios featuring challenging grid conditions and nonlinear rectifier loads are simulated in the MATLAB/Simulink platform. The results obtained have demonstrated that by utilizing the proposed ANF-based method, the associated SAPF achieves superior harmonics mitigation performance, which results in lower total harmonic distortion (THD), reduced phase error, and improved power factor as compared to the existing STF-based method. These findings highlight the proposed ANF-based method as a promising alternative for improving synchronization performance of SAPF that can contribute to improved power quality in modern electrical networks.

2. OVERALL CIRCUIT CONNECTION AND CONTROL ALGORITHMS

Figure 1 shows the overall circuit connection of a typical SAPF and the associated control stages in its controller. As shown, the SAPF is connected in parallel with the power system at the common point (PCC), positioned between the power source and the harmonic-producing load, resulting in the following current relationship by (1).

$$i_s = i_L - i_{mig} + i_{dc} = (i_F + i_H) - i_{mig} + i_{dc} = i_F + (i_H - i_{mig}) + i_{dc} \tag{1}$$

Where i_s is the source current, i_L is the load current comprising the fundamental i_F and harmonics i_H components, i_{mig} is the mitigation current generated by SAPF, and i_{dc} is the capacitor charging current. For effective harmonic mitigation, the SAPF must inject a mitigation current equal in magnitude and opposite in phase to the harmonic component of the load, such that $i_{mig} = i_H$. When this condition is met, the harmonic content in the source side is eliminated, and the resulting source current becomes (2).

$$i_s = i_F + i_{dc} \tag{2}$$

Meanwhile, in its controller, there are four main control stages involved, namely, harmonics extraction, dc-link voltage control, synchronization, and switching pulses generation. This work focuses specifically on the synchronization stage, where an alternative method based on the ANF concept is presented in the next section. For harmonic extraction, the direct-quadrature (dq) theory [23], [24] is employed. A proportional-integral (PI) controller [3], [4] is used for dc-link voltage regulation, while sinusoidal pulse-width modulation (SPWM) [11], [25] is applied for generating switching pulses. These three methods are selected as they are among the most commonly applied techniques in SAPF applications.

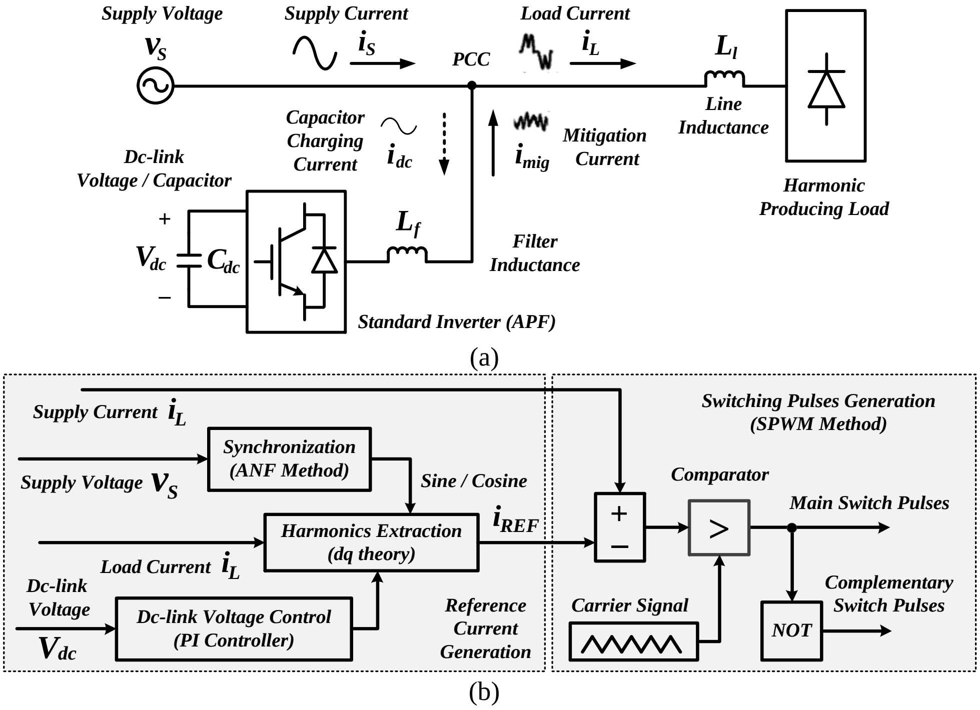

Figure 1. Main components in the SAPF system: (a) circuit configuration and (b) control processes

3. SYNCHRONIZER BASED ON ADAPTIVE NOTCH FILTER (ANF)

One important factor that determines the reliability of grid-connected systems is having an accurate phase synchronization feature. In this regard, an adaptive notch filter (ANF) is reported to provide the ability to isolate specific frequency components from a measured signal. The ANF is developed based on the concept of a notch filter, where the desired frequency components are suppressed within a narrow band, while all the other frequency components are allowed to pass through without much attenuation. With this ability, the notch filter can be tuned to effectively track and isolate the targeted sinusoidal component, particularly the fundamental frequency of the operating power systems [19]-[22]. As a result, this ability has more commonly been applied for harmonic or signal separation, rather than emphasizing the fundamental role of ANF in grid synchronization. Moreover, earlier studies have mainly focused on balanced and ideal grid conditions. Hence, in this work, the ANF concept is explicitly presented as a standalone synchronization mechanism for SAPF, demonstrating its ability to perform reliable phase synchronization independently under distorted and noisy grid conditions. Mathematically, any periodic signal can be approximated as a sum of sinusoidal components, expressed in typical time-domain form as (3).

$$v(t) = \sum_{n=1,2,3\dots}^{N} A_n \sin(\omega_n t + \theta_n) \tag{3}$$

Where A_n is the magnitude, ω_n is the angular frequency, and θ_n is the phase of the n-th component, with $n = 1,2,3 \dots$, to a maximum number N. To obtain these parameters, previous efforts have led to the derivation of the following differential equations, which are now widely used as the foundation of the ANF structure, as illustrated in Figure 2.

$$y'' = 2K_a \omega e(t) - \omega^2 y \tag{4}$$

$$e(t) = v(t) - y' \tag{5}$$

$$\omega' = -K_b \omega y e(t) \tag{6}$$

Note that $v(t)$ is the input voltage signal, ω is the angular frequency, $e(t)$ is the error signal, K_a and K_b are the two gain parameters control the accuracy and convergence speed. These gain values are finalized using a simulation-based tuning approach where initial ranges are obtained from related studies and then adjusted through repeated simulations to achieve satisfactory performance. With proper tuning, the solution containing sine and cosine functions at the fundamental frequency ω_1 will be generated according to (7).

$$\begin{bmatrix} y \\ y' \end{bmatrix} = \begin{bmatrix} -\frac{A_1}{\omega_1}\cos(\omega_1 t + \theta_1) \\ A_1 \sin(\omega_1 t + \theta_1) \end{bmatrix}, \; A_1 = \sqrt{(y')^2 + (\omega_1 y)^2} \tag{7}$$

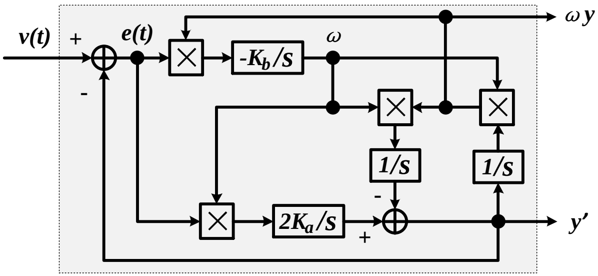

Figure 2. Conceptual structure of ANF-based synchronizer

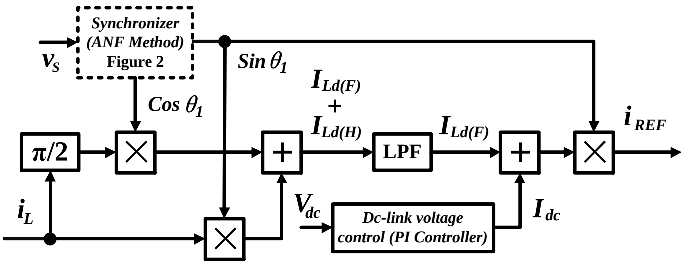

Figure 3. Connection of the ANF-based synchronizer with the dq-theory method

In most cases, these sine and cosine signals serve as main components for achieving accurate synchronization with the operating grid. Once obtained, both signals can be directly utilized in the harmonic's extraction stage, where a dq-theory method is employed in this work. To further illustrate the integration between the ANF-based synchronizer and the dq-theory method, Figure 3 presents the overall connection and signal flow between the two components. In essence, these sine and cosine signals are used to construct the rotating reference frame required by the dq transformation, enabling precise decoupling of the fundamental and harmonic components. Technically, the load current i_L is directly transformed into the corresponding d-frame I_{Ld} using the (8).

$$I_{Ld} = (i_L \angle \theta)(\sin \theta_1) + i_L \angle (\theta - 90^\circ)(\cos \theta_1) \tag{8}$$

Where $i_L \angle \theta$ and $i_L \angle (\theta - 90^{\circ})$ represent two orthogonal periodic signals of the load current, while $sin\,\theta_1$ and $cos\,\theta_1$ are the two synchronization signals delivered by the ANF method. Note that for harmonics extraction purposes, as reported in [24], [25], the q-frame representation is not needed and thus is removed for simplification. In the d-frame, the load current I_{Ld} will contain the fundamental $I_{Ld(F)}$ and harmonic $I_{Ld(H)}$ components according to expression (9), and a low-pass filter with a cut-off frequency of 15 Hz is applied to isolate only the fundamental component [23], [25].

$$I_{Ld} = I_{Ld(F)} + I_{Ld(H)} \quad (9)$$

Finally, together with the charging current I_{dc}, the reference current i_{REF} can be generated according to expression (10). From a mathematical standpoint, because the sine and cosine signals are directly extracted from the grid voltage and then used to compute the reference current, the resulting reference current is inherently synchronized with the grid. This ensures proper alignment in both phase and frequency, which is critical for accurate control in grid-connected systems. In a similar manner, these synchronization signals can also be adapted for use with other harmonic extraction techniques, demonstrating the flexibility of the ANF as an independent synchronizer module.

$$i_{REF} = (I_{Ld(F)} + I_{dc})\, sin\,\theta_1 \quad (10)$$

4. RESULTS AND DISCUSSION

The single-phase power system containing the SAPF circuits, the related control approaches, and the newly introduced STF-based synchronizer has been designed and simulated in the MATLAB/Simulink environment. Main simulation parameters applied in this study are summarized in Table 1 for reference. To provide a comprehensive evaluation of the proposed method, four test scenarios are considered in this study: Case A (sinusoidal supply), Case B (distorted supply), Case C (sinusoidal supply with noise), and Case D (distorted supply with noise). In Case A, the supply voltage is a sinusoidal waveform with a fundamental value (rms) of 230 V at 50 Hz. Next, in Case B, harmonic distortion with THD of 19.92% is added, highlighting the presence of significant harmonic content. Furthermore, to simulate additional challenging conditions, noise disturbance featuring a signal-to-noise ratio (SNR) of 19.83 dB is added to the sinusoidal supply for Case C. Lastly, in Case D, both harmonic distortion and noise profile are combined to create a particularly challenging test environment. Meanwhile, for the load setup, an uncontrolled bridge rectifier connected with a series resistor-inductor (RL load) is applied.

Table 1. Main simulation parameters applied in this study

System parameters	Details
Supply voltage	Fundamental = 230 V (rms), 50 Hz
Harmonics content (THD = 19.92 %)	3rd harmonic = 15.21 %, 5th harmonic = 10.86 % 7th harmonic = 6.52 %, 9th harmonic = 2.17 %
Noise content (SNR = 19.83 dB)	2204 Hz component = 6.52 %, 3104 Hz component = 3.91 % 4722 Hz component = 4.34 %, 6102 Hz component = 5.21 %
Choke inductance/filter inductance	3 mH / 5 mH
Load-Bridge rectifier connected with a series resistor-inductor (RL)	R = 12 Ω, L = 150 mH
Dc-link capacitor/DC-link voltage	4700 μF / 420 V
Switching frequency	5 kHz
ANF gain	K_a = 0.04, K_b= 1000
STF gain [18, 25]	K = 20
PI gain	K_p = 0.5, K_i = 4

For benchmarking purposes, the previously established method based on the self-tuning filter (STF) concept, whose control structure and mathematical formulation are thoroughly detailed in [17], [18], [23], [25], is re-implemented and evaluated under the same test conditions. Note that since the STF concept is already well-documented in the existing literature, it is not discussed in this work to avoid redundancy. In this work, two main verification processes are considered to evaluate the effectiveness of the proposed ANF-based synchronizer: (1) assessing the phase tracking performance of the synchronizer, and (2) evaluating the overall mitigation performance of the SAPF when utilizing the proposed method. The phase tracking results are illustrated in Figure 4, while the overall performance metrics are summarized in Table 2, with key findings graphically presented in Figure 5. In addition, to visually analyze voltage and current distortions, harmonic mitigation, and power quality improvement, the system conditions before and after SAPF operation are shown in Figure 6, demonstrating the effectiveness of the connected SAPF in enhancing power system performance under challenging grid conditions, complying with the IEEE 519 standard [26].

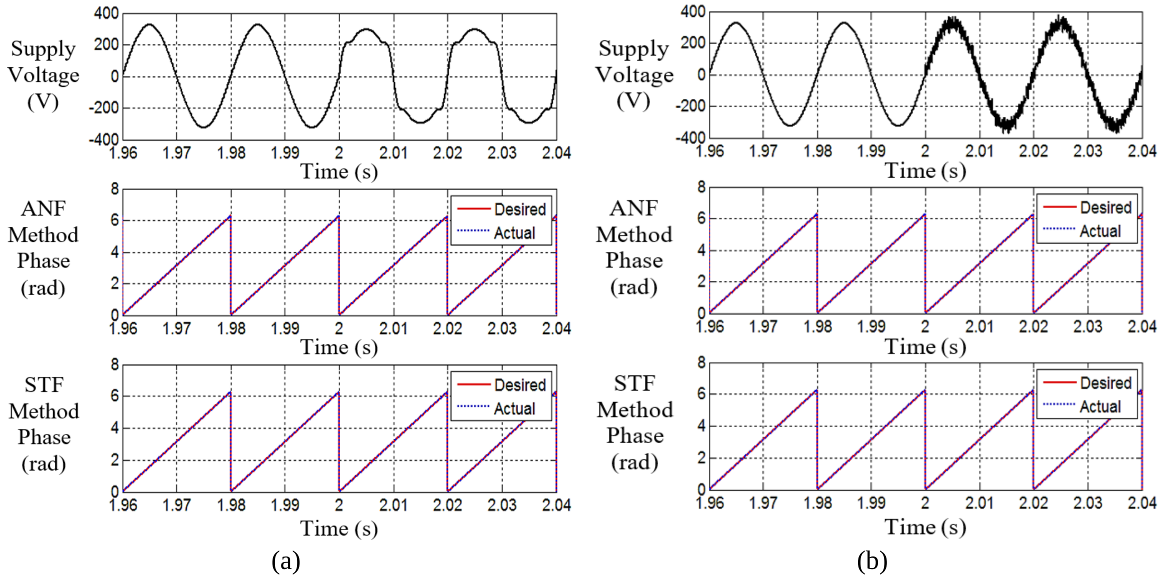

Figure 4. Comparison of phase (rad) obtained from the ANF-based and STF-based synchronizers when subjected to a supply voltage with (a) 19.92% harmonic content and (b) 19.83 dB noise level

Table 2. Evaluation of key metrics for SAPF integrated with the proposed ANF-based synchronizer against the existing STF-based synchronizer

Test Case	THD (%)	Phase (°)	Power factor	Fundamental rms current (A)	Accuracy of fundamental current (%)
Before the activation of SAPF					
Case A	35.36	-19.3	0.8898	15.06	N/A
Case B	40.14	-13.1	0.9038	16.18	N/A
Case C	35.06	-18.9	0.8928	15.07	N/A
Case D	40.04	-12.9	0.9049	16.19	N/A
SAPF integrated with the proposed ANF-based synchronizer					
Case A	2.82	0.2	0.9996	14.23	94.48
Case B	2.71	0.4	0.9996	16.63	97.21
Case C	2.75	0.2	0.9996	14.27	94.69
Case D	2.78	0.5	0.9996	16.65	97.15
SAPF integrated with the existing STF-based synchronizer [18], [25]					
Case A	3.01	0.4	0.9995	14.23	94.48
Case B	3.04	0.8	0.9994	16.63	97.21
Case C	2.96	0.4	0.9995	14.27	94.69
Case D	3.25	0.8	0.9994	16.65	97.15

First, to evaluate the phase-tracking performance, two test conditions are applied: harmonic distortion with a THD of 19.92%, and additive noise with an SNR of 19.83dB. These conditions are used to examine how well each method maintains accurate phase estimation when confronted with complex signal disruptions. The corresponding phase outputs obtained from both methods are shown in Figure 4. Do note that the input voltage is set to become distorted and noisy starting from t = 2 s onwards. From Figure 4, it can be observed that the existing STF-based synchronizer exhibits highly stable and reliable performance across all tested conditions, overcoming the impact of distortion and noise, as expected. Nevertheless, the proposed ANF-based synchronizer is also found to achieve nearly the same performance, maintaining precise phase tracking even under significant signal degradation. This close agreement highlights the reliability of the proposed ANF-based method and its potential to serve as an alternative for the purpose of synchronization.

Next, the performance of the proposed ANF-based synchronizer is examined across the four considered scenarios to determine its impact on SAPF mitigation, and its performance is directly contrasted against the existing STF-based synchronizer. As presented in Table 2 and Figure 5, it is obvious that there is a significant reduction in the THD values, phase difference, and improvement in the power factor after activating SAPF (as compared to the uncompensated condition), which confirms the effectiveness of both methods in managing the mitigation operation of SAPF. Nevertheless, from a closer comparison, the proposed ANF-based synchronizer can be observed to consistently provide superior performance across all the test scenarios. For instance, the THD values recorded with the proposed ANF-based synchronizer are between 2.71% and 2.82%, meanwhile, the existing STF-based synchronizer displays slightly higher THD values between 2.96% and 3.25%. A lower THD indicates that the proposed ANF-based synchronizer is more effective in minimizing the impact of harmonics and can provide a sinusoidal current waveform of better quality, thus contributing to improved system operation and reduced power losses.

Figure 5. Performance comparison under various power supply conditions for the SAPF integrated with the proposed ANF-based synchronizer, the existing STF-based synchronizer, and without any SAPF connected (None), in terms of (a) THD (%), (b) phase angle (°), and (c) power factor

Besides that, the phase tracking accuracy of the proposed ANF-based synchronizer is also found to have improved. For instance, the phase deviation for the proposed ANF-based method is recorded in the smaller range of 0.2°– 0.5°, as compared to the existing STF method, which shows a slightly larger range of 0.4°– 0.8°. This improvement is supported by the selective tracking ability of the ANF, which isolates the fundamental frequency while allowing other components to pass largely unaffected, thereby granting a more accurate phase estimation. As a result, the smaller phase deviation shows that the proposed ANF-based synchronizer is providing a more precise alignment of the mitigating current with the reference grid voltage, which is crucial for achieving optimal reactive power compensation. By balancing convergence and stability, the selected gain parameters help to reduce excessive fluctuations and high-frequency disturbances, thus resulting in a more reliable phase tracking. Consequently, as a combined result of the lower THD and reduced phase difference, the power factor recorded with the proposed ANF-based method is improved to approximately 0.9996, which is higher than the existing STF-based method (0.9994 – 0.9995). This improvement confirms that the proposed ANF-based synchronizer provides more efficient reactive power compensation. As a result, the mitigated source current becomes nearly in-phase with the corresponding supply voltage, indicating highly effective mitigation performance.

Furthermore, Table 2 shows that the accuracy of the fundamental current for both synchronization methods remain nearly identical, i.e., ranging between 94.48% to 97.21%. Meanwhile, from Figure 6, SAPF utilizing either synchronization method has effectively mitigated harmonics even under significant distortion and noise, with the source current waveforms becoming more sinusoidal and nearly in-phase with the supply voltage. Once again, this confirms that both synchronization methods have successfully achieved the intended harmonics mitigation and reactive power correction. In other words, the proposed ANF-based synchronizer can provide improved mitigation performance without compromising accuracy. Note that the ANF-based method is also considered to have a simpler control structure, where it can generate the synchronization phase independently, without requiring additional auxiliary processes, unlike STF, which primarily functions only as a pre-filter. These features collectively establish the proposed ANF-based method as a potential alternative for SAPF synchronization, ultimately delivering a more reliable harmonics mitigation.

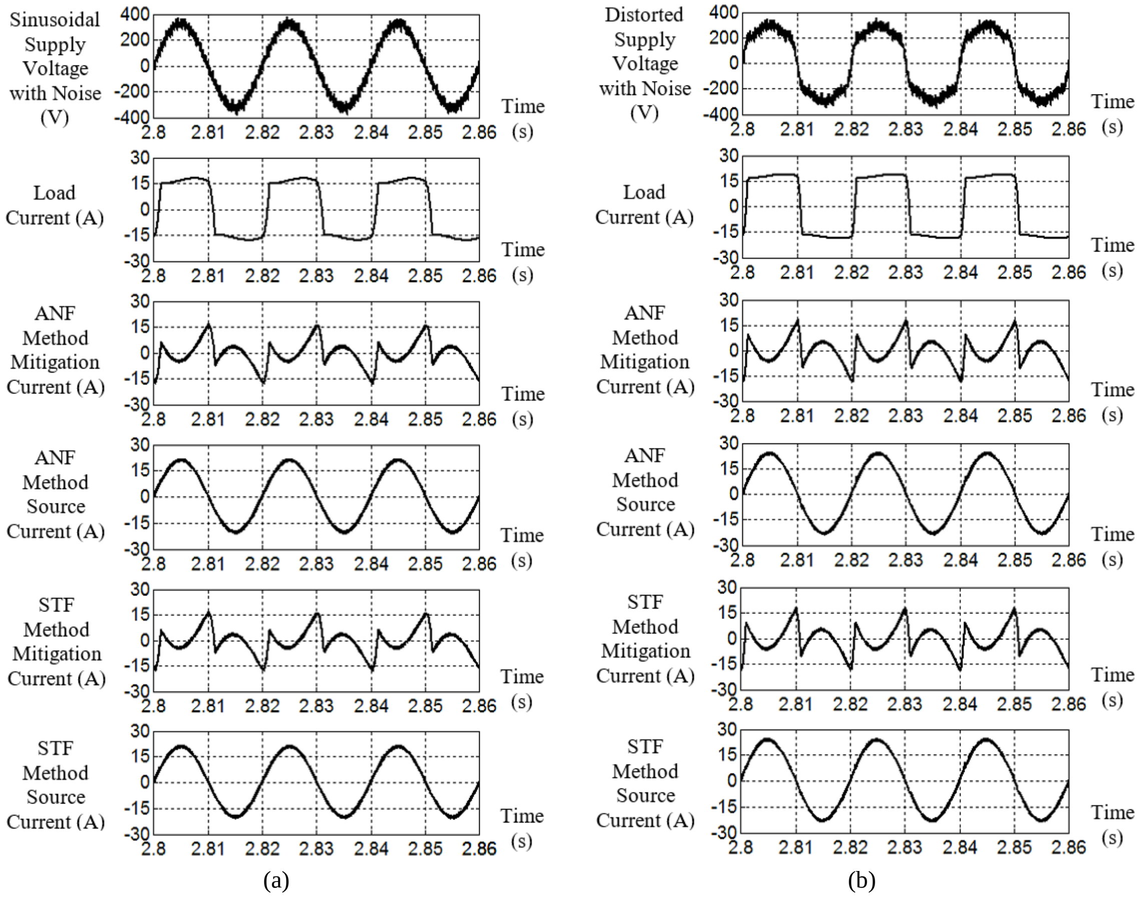

Figure 6. Simulation waveforms obtained showing the behavior of SAPF utilizing the proposed ANF-based synchronizer and the existing STF-based synchronizer under (a) Case C and (b) Case D supply conditions

5. CONCLUSION

This study has demonstrated a newly proposed ANF-based synchronizer for single-phase SAPF, where its performance is benchmarked against the existing STF-based method under ideal, distorted, noisy and distorted-with-noise grid conditions. Simulation results confirm its effectiveness by achieving lower THD values (2.71–2.82%) and phase deviation (0.2°–0.5°), and almost unity (0.9996) power factor, while maintaining accuracy of fundamental current between 94.48% and 97.21%. Unlike the existing STF-based method, the proposed ANF-based synchronizer can generate the desired synchronization phase independently, ensuring reliable operation without additional processing. With accurate phase tracking and reliable harmonics mitigation performance, the proposed ANF-based synchronizer has proven to be a promising alternative for SAPF applications in modern electrical systems. Note that this study is limited to single-phase simulation, and the performance under practical conditions such as dynamic grid variations and real-world disturbances, has not yet been verified. Hence, future work can focus on extending the ANF-based synchronizer to three-phase systems, conducting experimental validations, and exploring adaptive tuning strategies to further enhance its reliability under highly nonlinear and dynamic grid conditions.

FUNDING INFORMATION

This research was supported by Ministry of Higher Education, Malaysia (MoHE), through Fundamental Research Grant Scheme (FRGS/1/2024/TK08/UTAR/02/4).

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Kenny Sau Kang Chu	✓	✓	✓		✓	✓		✓	✓					
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [YH], upon reasonable request.

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