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Active power compensation circuit for resonance mitigation and harmonic reduction in microgrid system

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Abstract

The nature and behavior of capacitors, transformers, inductors, active compensators, and non-linear loads can produce power resonance. Unfortunately, the presence of a resonance phenomenon can have a negative impact on system stability and lead to catastrophic power system failures. Therefore, even when using modern or conventional techniques to enhance total harmonic distortion (THD) or improve input power factor (IPF), it is necessary to avoid resonance. An active power compensation circuit (APCC) is proposed and designed to function with two categories of linear/non-linear loads. The APCC has been implemented and regulated using an adjusted pulse width modulation technique. The aim of the suggested APCC is to minimize AC side distortions, improve the IPF, and mitigate harmonics resonance at the same time. The simulation results demonstrate that the proposed APCC investigates the aim function of this study by absorbing harmonics, correcting IPF, and eliminating resonance problems under both transient and steady-state operating conditions. The supply voltage and current THD values for the first power circuit type are reduced by 96.7 % and 96.3 %, respectively, at α=30°. Meanwhile, for the second power circuit, the THD is reduced by 91.92 % and 90.4 %. Also, the IPF changed for the first and second power circuits from 0.72 and 0.86 to almost unity. These results demonstrated the effective performance of the APCC circuit and controller in reducing power harmonics, eliminating power resonance, and modifying power factors.

Keywords: harmonic resonance; total harmonic distortion; power factor; power quality; active power compensation circuit.

I. Introduction

Most electrical power system devices and components are inductive and non-linear load elements. Approximately 60 % of AC power supply distortion is caused by natural causes, while the remaining 40 % is caused by non-linear loads [1]. Three-phase rectifier and/or inverter structures can provide bidirectional energy flow. These structures are typically used in industrial applications, such as connecting renewable energy sources to the grid [2], electric vehicle applications [3], DC traction systems [4], high voltage DC systems [5][6], machine drives [7], and battery charging [8]. Non-linear elements cause distortions in voltage and current waveforms. This distortion causes a variety of issues, including poor input power factor (IPF), low efficiency, and improper operation of electrical equipment [9]. Harmonic distortion can be eliminated through the use of power capacitors and harmonic filters [10]. Wide and diverse, comprehensive techniques for improving power system performance have been implemented [11][12].

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However, owing to the characteristics of the FACTS devices' storage elements, power harmonic resonance may occur [13]. Power resonance is the phenomenon of resonance that occurs in electrical power systems, particularly AC circuits. In power systems, resonance can occur when the inductive and capacitive components' natural frequencies coincide, resulting in a significant increase in the voltage and current amplitudes within the circuit.

When resonance occurs in a power system, the system can become unstable, potentially leading to overvoltage, overcurrent, and damage to components. This can lead to power outages, equipment malfunctions, and even fires. Also, during resonance, a normal harmonic can be amplified by 10 to 25 times if resonance occurs at or near critical frequencies. This amplification increases voltage distortion to levels that exceed the acceptable limits and can lead to equipment failure or loss. Transmission line cables and transformers enable the spread of resonances from one network to another [14]. This is typically the result of IPF correction capacitors, harmonic filter circuits, parallel reactance, or control strategies that may be applied to drive the involved converters [15][16][17]. Engineers use various techniques, such as adding damping to the system, modifying the values of inductive and capacitive components, and avoiding loads with high harmonics to prevent resonance in power systems. In addition, power systems are often designed with a safety margin to prevent resonance from occurring. Overall, power resonance is a significant issue in the development and operation of electrical power systems, and it is essential to take the necessary precautions to prevent its occurrence to guarantee the safety and dependability of the system. Excessive surge current will cause irreversible damage to devices, and continuous surge current will also have a negative impact on the device's performance [18]. It is necessary to evaluate the resonance phenomenon in order to determine the strength of resonance, the risk of instability, and suitable methods for minimizing or preventing it [19]. Power electronics converters connected to microgrids are prevalent in renewable energy systems. Inductor-capacitor-inductor (LCL) filter resonance is affected by the microgrid state. Impedance fluctuations consequently have an impact on the stability of the system's controller function [20]. Resonance problems also cause significant inrush currents and erratic voltage regulation [21].

To comply with global harmonic standards [22][23], the LCL filter is used to minimize the injection of harmonics into the AC system. In order to address the issue of AC power supply distortions in industrial applications, both passive and active filters were employed. Passive power filters are used to mitigate harmonics by utilizing series/parallel connections. The elements of this type of filter must be returned when the load varies. While active power filters (APFs) are designed and controlled to eliminate AC power supply distortions under varying load conditions with the same power circuit [24], no retuning is necessary.

In 2015 [25], the technique of harmonic resonance elimination pulse width modulation (PWM) was proposed and implemented on China's railways to eliminate resonances and maintain normal levels. In the same year [26], passive filters and APFs were connected in series to reduce harmonic currents and mitigate resonance caused by non-linear loads. The resonance of the power circuit, with harmonics dampened by a filter, depends on variations in non-linear load. In 2017 [27], three-phase power distribution systems employed shunt APF to eliminate resonance between the shunt capacitor and system inductor and reduce harmonic current resulting from an uncontrolled three-phase rectifier. The simulation and experimental outcomes fall within the acceptable range of results. In 2018 [8], an inductor-inductor-capacitor (LLC) circuit was designed to operate at a specific resonant frequency. This was done to minimize the losses of the insulated gate bipolar transistor (IGBT) in the LLC-resonant-converter and improve the efficiency of battery charging in electric vehicles. The system has been experimentally verified, and its overall efficiency has been increased to 93.7 %. Recently, in 2019 [28], a study was conducted on the impact of harmonics on the grid when coupled with PWM converters and LCL filters. It has been suggested that a modified converter current feedback controller can be used to suppress harmonic current components. In 2019 and 2021 [29][30], an APF was constructed to simultaneously enhance IPF, eliminate THD, and mitigate resonance effects caused by non-linear and linear loads. The standard LC filter was large and ineffective, while high-order PFs have resonance frequencies that may cause system instability. The literature proposes many methods to mitigate the resonance problem of power factor correction capacitors. Passive damping reduces power factor mitigation and increases power losses. Active damping may require more sensors to reach resonance elimination, which increases the cost and complexity of the filtering system [31][32][33][34].

Power harmonic resonance is a significant issue in power systems, and numerous papers have discussed its causes, effects, and mitigation techniques. To support the power quality (PQ) of the system, researchers are continuously devising techniques for detecting and reducing resonance in power systems. As an extension of the previous investigation, to completely comprehend the power quality improvement in grids due to non-linear loads, the active power compensation circuit (APCC) depicted in Figure 1 has been employed. The main aim of this study is to improve the power quality of the AC side system by reducing harmonics in the AC voltages and currents, improving the IPF, and eliminating the harmonics resonance if it is producing for any reason. The APCC system is controlled using a modified adjusted PWM (MAPWM) technique. The novelty of the proposed APCC and controller is to reduce harmonics, eliminate resonance issues, and provide instantaneous and accurate IPF with multiple linear/non-linear loads. The goal of this research is to enhance the system's quality as good as possible.

II. Materials and Methods

Typically, capacitors and inductors are utilized to generate resonance phenomena. The voltage or current resonance occurs when a capacitor and an inductor have the same reactance at a specific frequency. Utilizing a power electronics circuit, such as an active filter or STATCOM, with variable capacitive and inductive reactance effects for each harmonic component frequency, a harmonic resonance occurs at a specific frequency based on the operating conditions. The surge values of this resonance are considerable in comparison to the current and voltage ratings of a novel algorithmic power electronic circuit. Existence of power electronic switching devices, including Si IGBTs, SiC MOSFETs, and GaN FETs, that are exceptionally susceptible to unconstrained surge current and spike voltage. This precautionary condition must be avoided; otherwise, devices will operate outside of their secure operating range, causing catastrophic damage to power electronic circuits.

In addition, the effect of harmonic resonance destabilizes the system [15]. Based on this issue, the purpose of this paper is to demonstrate the ability of the APCC to eradicate harmonic resonance and compensate for reactive power, thereby contributing to the improvement of the utility's power quality. Consequently, the shape of the line current becomes nearly sinusoidal and in phase with the AC supply voltage without any resonance issues. After adjusting the controller to function as harmonic reduction, IPF correction, and resonance elimination, the three-phase APCC is run based on a controller proposed by [29][30]. On the basis of the proposed controller, a MAPWM is constructed. This is intended to operate and control the APCC. Figure 1 depicts the power circuit and controller of the proposed APCC. It is a three-phase inverter circuit connected to the AC side of the power system, specifically the microgrid, through an inductor (L_{ac}) and to the DC side through a capacitor (C_{dc}). The purpose of the capacitor is to store enough energy and maintain a nearly constant DC voltage link.

The structure of the proposed controller (MAPWM) is illustrated in Figure 1. The required reference current is generated based on the phase load current ($i_{n\text{-}L}$), the fundamental value of the phase load current ($i_{n\text{-}L1}$), and the APCC current ($i_{n\text{-}APCC}$). Therefore, the reference current can be obtained as follows:

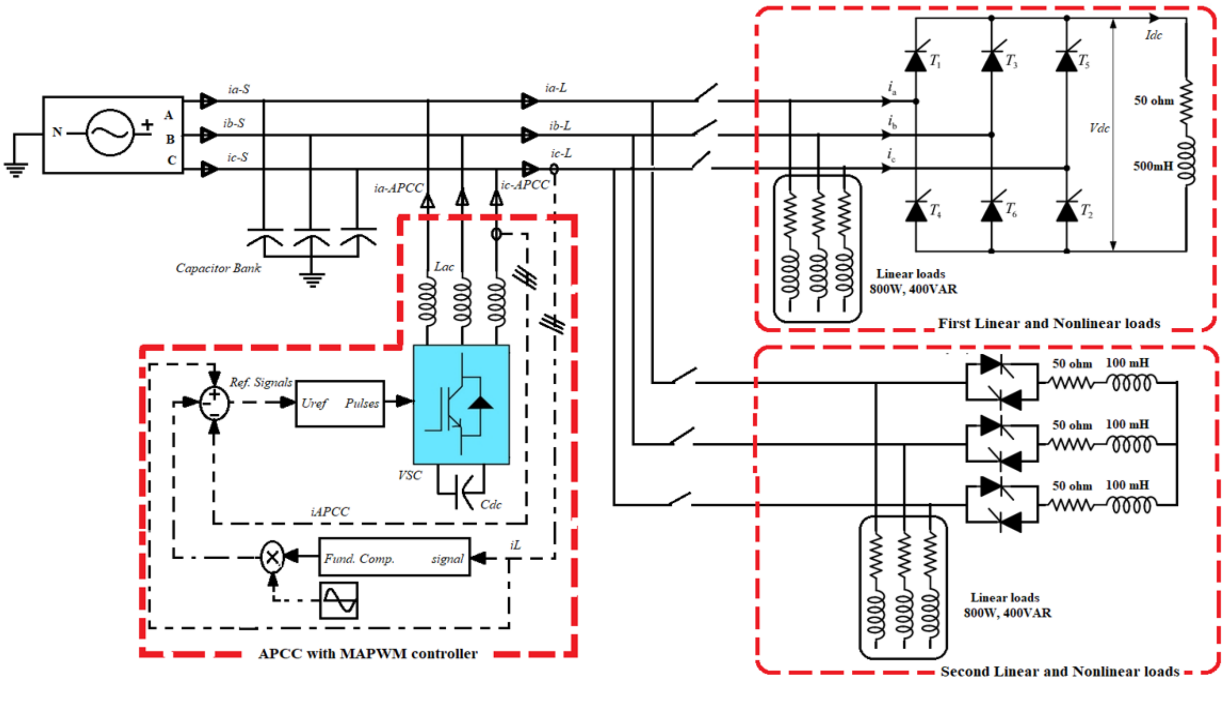


Figure 1. Proposed power circuits of an AC network, which consists of three-phase linear and non-linear loads with APCC.

$$Reference\ Signal\_n = i_{n-L} - i_{n-L1} - i_{n-APCC} \quad (1)$$

$$i_{n-L1} = I_{nL1} \text{x} \cos(\theta_{n1}) \text{ x } \sin(wt) \quad (2)$$

where (n) represents phases (a, b, and c), I_{nL1} is the real component of the fundamental load currents, and θ_{n1} is the corresponding phase angle relative to their related supply phase voltages. To obtain MAPWM digital signals of the APCC, the reference signal has been employed as modulating signals and is compared with triangle signals to get the PWM pulses that drive the APCC to minimize harmonics, eliminate resonance, reduce THD, and improve PF.

III. Results and Discussions

During the investigation of the harmonic resonance problem, various industrial power systems are modeled, validated, and tested. Two power circuits are selected, as shown in Figure 1. The first power circuit is a three-phase linear load with a three-phase AC/DC converter circuit, while the second power circuit involves a three-phase linear load with a three-phase AC/AC converter circuit. The APCC is dynamically controlled for various thyristor angle values. The phase voltage and frequency of the modeled system are 220 V and 50 Hz, respectively. The coupled inductor (L_{ac}) of the APCC is set to 5 mH, and the DC side capacitor (C_{dc}) is set to 125 μF. The switching frequency is chosen to be 3 kHz. The load parameters are illustrated in Figure 1.

A. Input phase voltage and current

The two typical power circuits are modeled using the MATLAB program, and the simulation results are displayed. The input phase voltage (VA), current ($i_{a\text{-}S}$), and their FFT spectra at a firing angle (α = 30°) with and without the use of APCC for the two circuits are illustrated in Figure 2, Figure 3, Figure 4, and Figure 5. Due to the nature of the loads, different resonance categories can be observed in Figure 2(a) and Figure 4(a). The FFT analysis confirms that the resonance effect will be completely eliminated once the APCC is connected. Additionally, these figures demonstrate that the APCC reduces distortion in the input supply voltage and current to stay within standards and

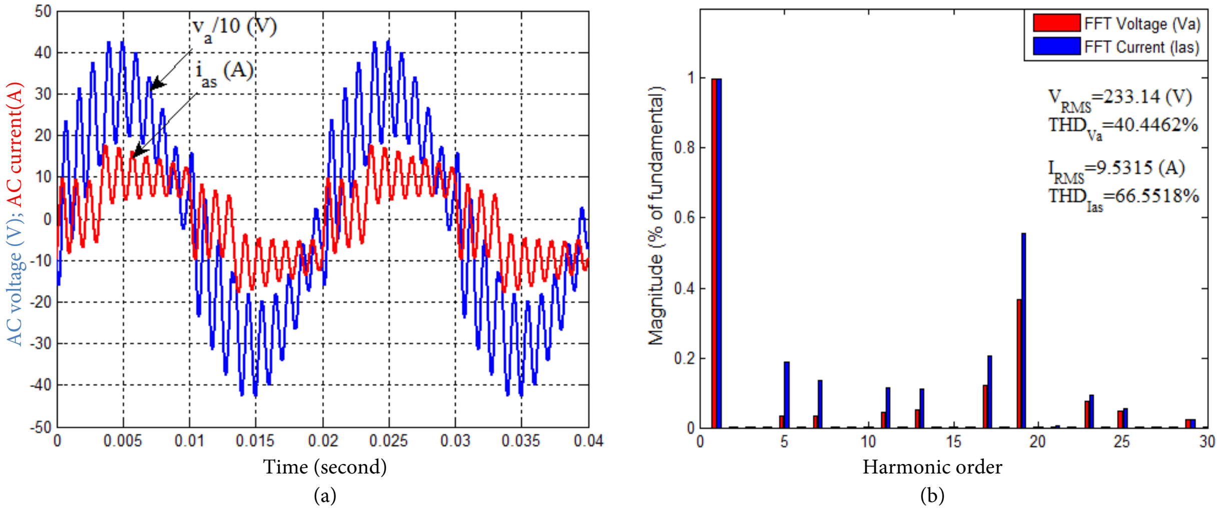


Figure 2. (a) Input phase current and voltage of the first power circuit; (b) FFT analyzer without APCC at α=30°.

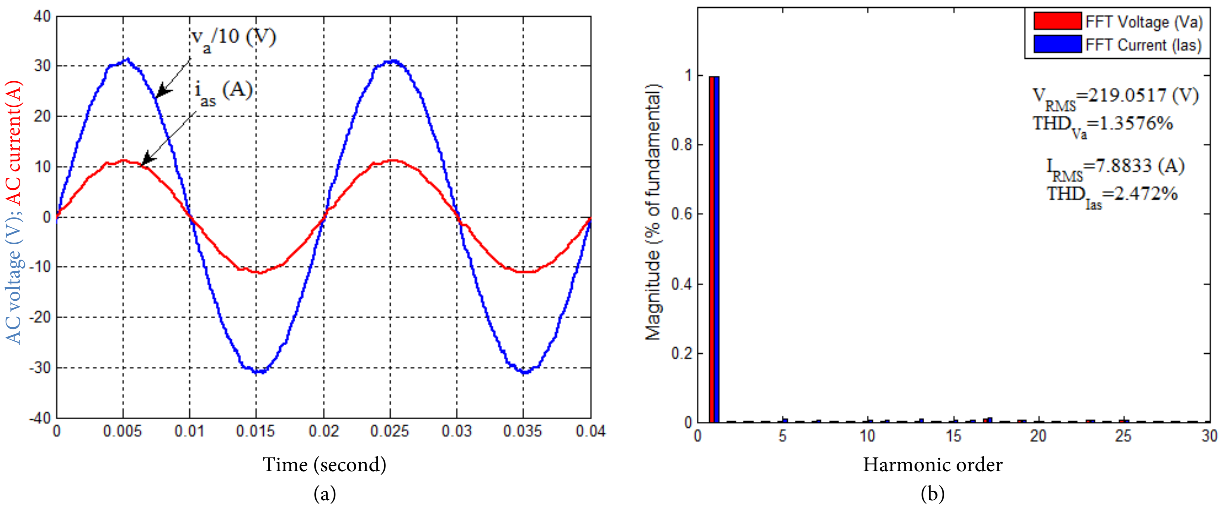


Figure 3. (a) Input phase current and voltage of the first power circuit; (b) FFT analyzer with APCC at α=30°.

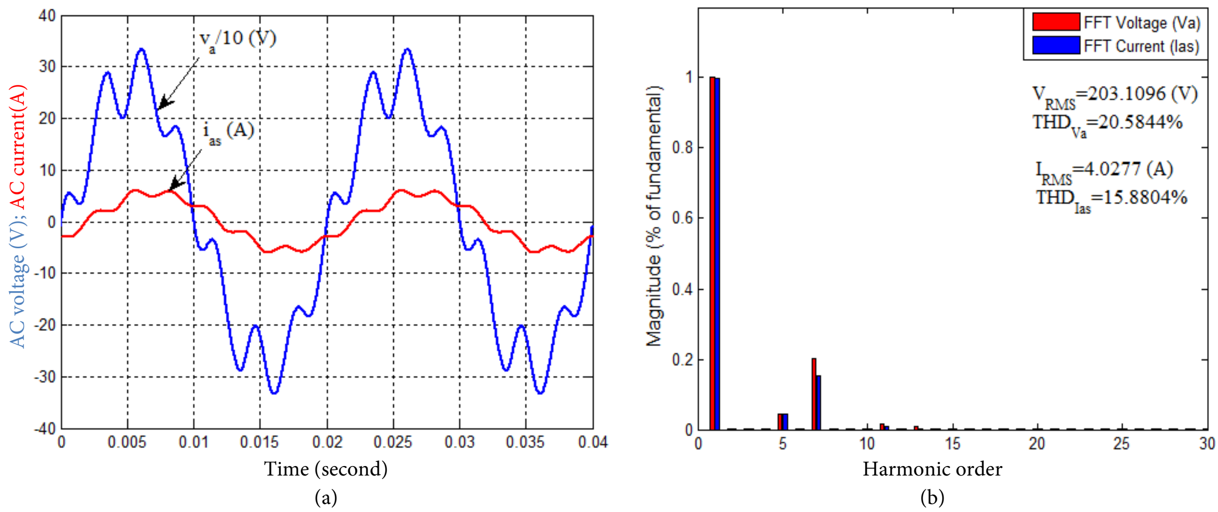


Figure 4. (a) Input phase current and voltage of the second power circuit; (b) FFT analyzer without APCC at *α*=30°.

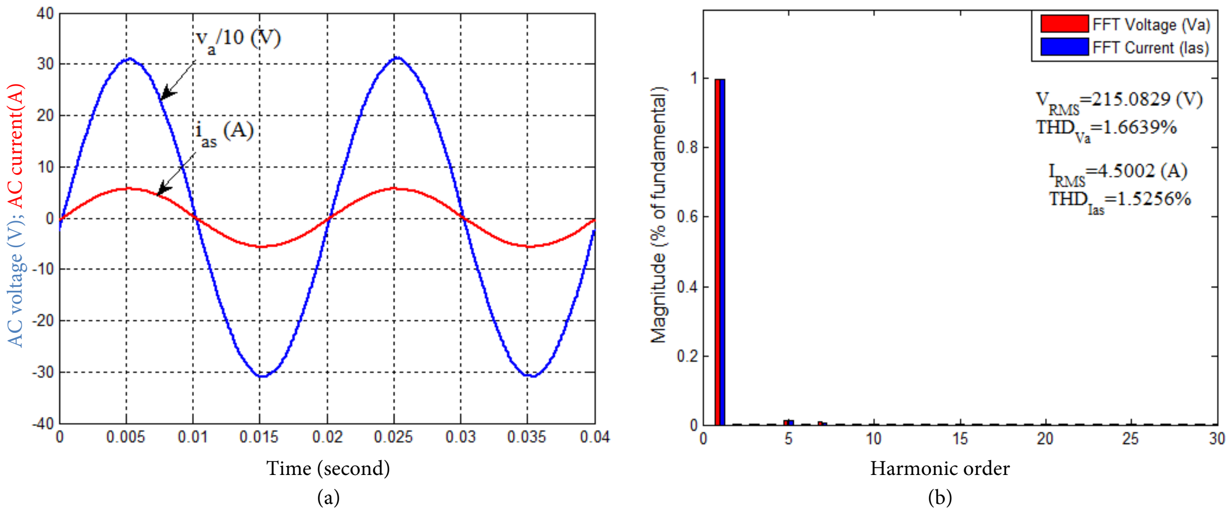


Figure 5. (a) Input phase current and voltage of the second power circuit; (b) FFT analyzer with APCC at *α*=30°.

improves the IPF near unity. Before connecting the APCC, the THD values of the input phase voltage (THD_*va*) and current (THD_*ia*) for the first power circuit were 40.5 % and 66.6 %, respectively. After connecting the APCC, the THD_*va* and THD_*ia* values were reduced to 1.4 % and 2.5 %. Similarly, for the second power circuit, the THD_*va* and THD_*ia* values without APCC were 15.9 % and 20.6 %. Meanwhile, the THD_*va* and THD_*ia* values with the APCC were 1.5% and 1.7 %, respectively. Comparing these results with other studies [29][30][35] is still good and proves the effectiveness of the suggested circuit.

B. Harmonics and input power factor

To check the suggested APCC and its controller, the two typical power circuits with and without the APCC system are tested at firing angles from 5° to 90° (different conditions). Figure 6 and Figure 7 show the waveforms of the effective IPF and THD of the supply phase voltage and current without and with the APCC at various firing angle values. These findings demonstrate that after connecting the APCC, the AC distortion (THD) outcomes improve, and the effective IPF remains close to unity. This implies that the proposed system and controller can operate effectively under different load levels and generate nearly identical outcomes. Compared with others [36][37] that used passive elements to reduce harmonics and correct power factor, the finding results at different loads remain good.

C. Apparent, real, reactive, and distortion powers

The active (P), reactive (Q), apparent (S), and distortion (D) powers for the non-sinusoidal case are calculated as:

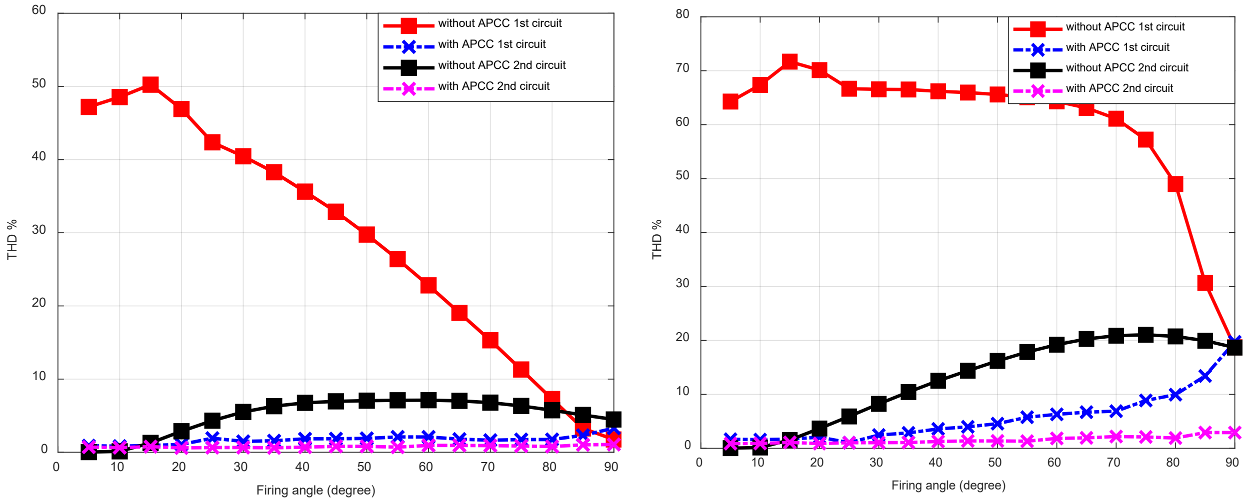
$$P = V_1 I_1 \cos(\theta_1) + \sum_{h=2}^{\infty} V_h I_h \cos(\theta_h) \quad (3)$$

$$Q = V_1 I_1 \sin(\theta_1) + \sum_{h=2}^{\infty} V_h I_h \sin(\theta_h) \quad (4)$$

$$S = V_1 I_1 + V_h I_h \quad (5)$$

$$D = \sqrt{S^2 - P^2 - Q^2} \quad (6)$$

where V_1, I_1, V_h, I_h, and θ are the fundamental voltage component, fundamental current component, voltage harmonics component, current harmonics component, and phase angle of the supply current (I) with respect to the supply voltage (V), respectively. The AC distortion power (D) displayed in Figure 8 and Figure 9 for the two power circuits illustrates the success of using the APCC by eliminating harmonics, and this



(a) (b)

Figure 6. THD of the supply phase: (a) voltage and (b) current of the first (1st) and second (2nd) power circuits without and with the APCC.

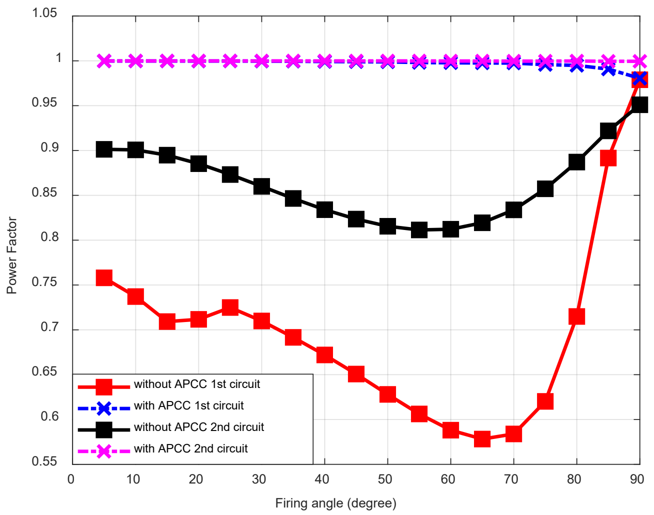
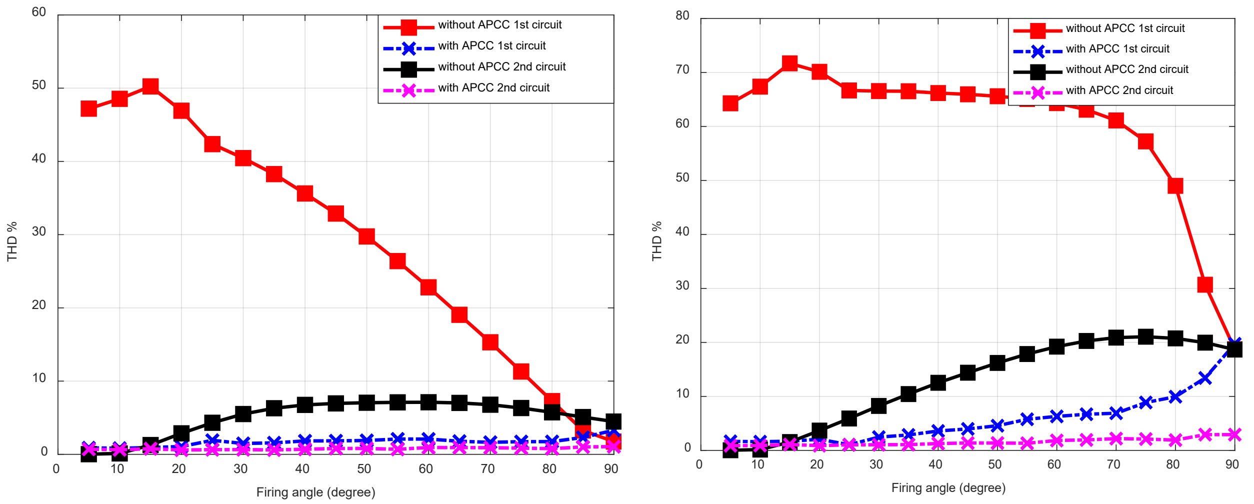


Figure 7. The effective IPF results without and with APCC of the (a) first and (b) second power circuits.



(a) (b)

Figure 8. Apparent, real, reactive, and distortion powers of the first circuit (a) without and (b) with the APCC.

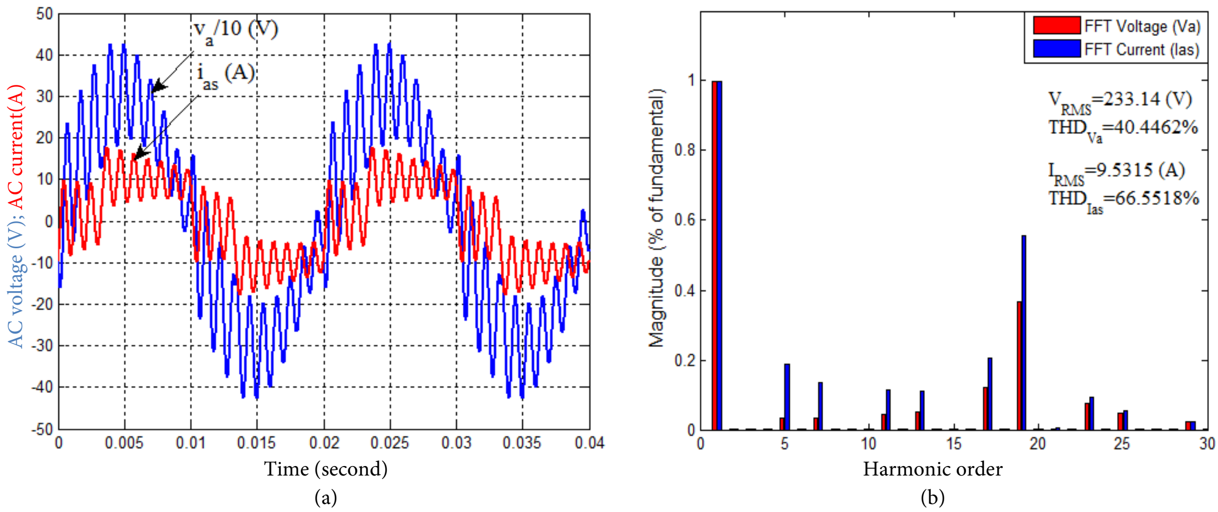


Figure 9. Apparent, real, reactive, and distortion powers of the second circuit (a) without and (b) with the APCC.

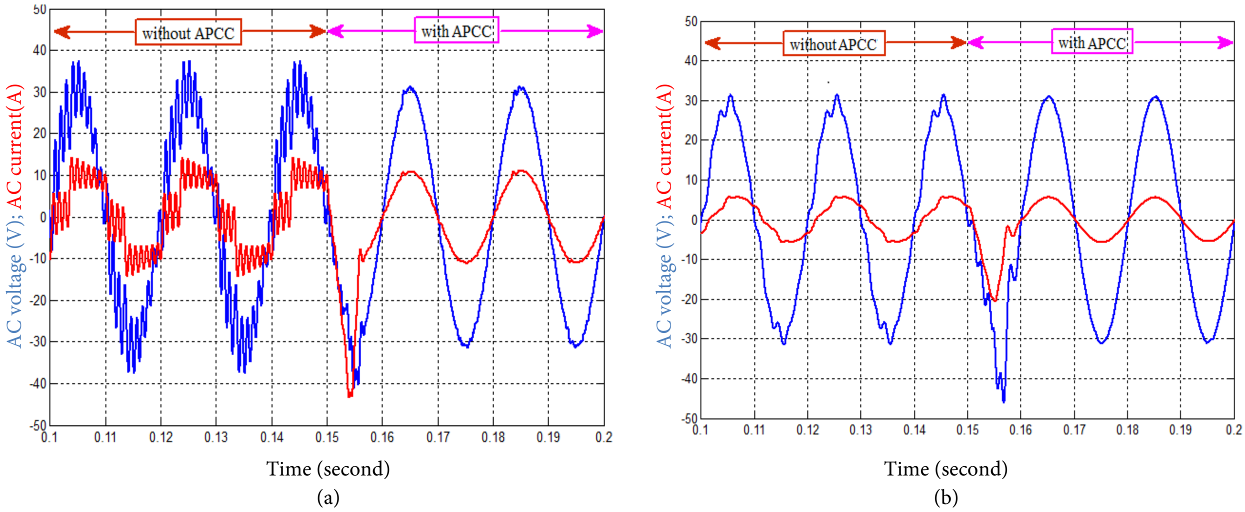


Figure 10. Steady-state and dynamic results of the phase supply voltage and current without and with the APCC of (a) the first and (b) the second load power circuits.

supports the THD results. Additionally, the reactive power supplied by the AC source, as seen in Figure 8 and Figure 9 for the two power circuits, has almost disappeared. The reactive power data support the actions of the APCC and prove the findings and results of the IPF. The total amount of (S) and (P) is utilized after connecting the APCC. This is due to the reduction of (Q) and (D) components on the AC side of both typical power circuits, as depicted in Figures 8 and 9. In this study, the power quality for different power circuits and different load conditions is good with acceptable levels, unlike the passive power filters that are tuned for specific load conditions and harmonic [38].

D. Steady-state and dynamic results

Figure 10 demonstrates the steady state and dynamic capabilities of the APCC in mitigating harmonic resonance and enhancing IPF for the two power circuits. The figure illustrates the efficacy of APCC in obtaining the desired result under steady-state and dynamic conditions for such systems. According to the overall findings, the system's originality and novelty are that it has the possibility to minimize THD under different operating settings, improve power factor, and prevent power resonance if it occurs for any reason.

IV. Conclusion

The main objective of this research is to provide an illustration of a unique power quality improvement circuit that can be suitable for both linear and non-linear loads. The main objective of the suggested APCC circuit and MAPWM controller is to completely eliminate resonance phenomena, improve IPF, and minimize THD in various operating conditions. The APCC system incorporates features such as active filtering, power factor compensation, and resonance elimination. Enhancements have been made to improve cost-effectiveness, maintenance, power quality, efficiency, and power density. The appliance has been tested using various industrial power systems and load conditions. The THD results of the AC voltage and current of the first circuit are improved by 96.55 % and 96.25 %, respectively. Meanwhile, for the second circuit, the THD values improved by 91.75 % and 90.57 %. In addition, the IPF stays around unity for all operating conditions for the two power circuits. The simulation results indicate that the suggested APCC is effectively designed and built in both transient and steady states. For future studies, the system will be tested experimentally, and the APCC will be used in other linear and non-linear industrial applications to check its validity.

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Declarations

Author contribution

Rakan Antar designed, developed the theory, performed the computations, verified the analytical method. **Rakan Antar** investigated the idea by modeling the system under supervision of **Basil Saied**. All authors wrote the manuscript, discussed the results, commented on the manuscript, contributed with the designed system, implemented the research, and writing the final manuscript.

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Competing interest

There are no conflicts to declare.

Additional information

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