

Improving the PQ Harmonic Detection Method for Active Power Filters in Single-Phase Power Systems

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ABSTRACT

This study proposes an enhanced instantaneous power (PQ) theory for harmonic detection in single-phase active power filters (APFs). The method eliminates harmonic currents, improves the power factor for nonlinear loads, and supports distorted voltage sources while maintaining filter performance. Real-time OPAL-RT simulations show that the THD of the source current was reduced from 18.11% to 0.16%, outperforming the traditional PQ method and meeting IEEE 519-2022. The power factor was corrected to unity. The improved PQ method also reduced computation time by up to 42.76% compared to the combined PQ method, with lower computational complexity, making it well suited for microcontroller-based real-time control in resource-constrained APF applications.

Keywords: Computation Time Reduction, Instantaneous Power Theory, Active Power Filter, Harmonic Detection

1. INTRODUCTION

Recently, electrical technology has advanced rapidly, leading to the widespread use of power electronic devices in the development of household appliances, public utilities, and industrial systems. Most electrical devices used today are nonlinear in nature. These include electric

vehicle charging systems, electric rail systems, electric motor drive systems, fluorescent lamps, computer equipment, and power electronic circuits. Such nonlinear devices generate harmonics into the distribution systems, which adversely affect both electricity producers and consumers [1-3]. These effects include power losses in transmission lines [4], excessive heating of electrical equipment [5], malfunctioning of protective devices [6], reduced lifespan of electrical components [7], capacitor bank overloads [8], and may lead to power system failures and blackouts in severe cases [9].

Addressing these issues is essential alongside the development of modern technology. Harmonic currents are the primary cause of these power quality problems. Therefore, the harmonic current elimination can directly improve power quality. One of the effective solutions is the use of an active power filter (APF). APF offers several advantages, such as the ability to handle harmonics of all orders, compact sizing, elimination of the harmonic in the various load conditions, and good flexibility of harmonic elimination [10-13]. However, the efficiency of the APF depends on several control systems, consisting of harmonic detection for calculating the reference current, compensating current control for tracking the reference current and injecting it into the point of common coupling (PCC), and regulation of the DC bus voltage. These control systems require high-performance computational resources to achieve high harmonic elimination performance. Consequently, the microcontroller-based real-time control systems used in APFs are associated with high costs due to the requirement of the extremely fast computational time of the control system. Therefore, reducing computation burden, subsequently the computation time, in control system is important for the development of APF. This study introduces an improved harmonic detection method for APF that lowers computation time burden while providing fast and accurate reference current calculation performance.

Harmonic detection has been developed from the past to the present, with the primary objective of accurately calculating the reference current of fluctuating power system conditions. It can be categorized into two main groups, including the traditional methods and combined methods. The traditional methods are used for ideal sinusoidal voltage sources to accurately calculate the

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reference current of the considered load. The commonly known traditional method for its simplicity and ability to directly compute active and reactive power is the instantaneous power theory (PQ). This method was introduced by Akagi [14]. The combined method group is designed for distorted sinusoidal voltage sources and changing load conditions, such as the PQ combined with sliding-window Fourier analysis (SWFA) [15], the PQ combined with positive sequence voltage detector (PSVD) [16], and the PQ combined with PSVD and SWFA [17]. Although these methods achieved high accuracy for the reference current calculation of fluctuating power system conditions, they required long computation time and high sampling rate on a digital signal processor. To overcome this limitation, the PQ method is improved to reduce computation time and accommodate distorted sinusoidal voltage sources and changing load conditions.

Existing PQ-based combined methods typically require multiple calculation stages to extract the fundamental voltage, resulting in considerable computational burden for real-time implementation on embedded controllers [15-18]. In addition, phase-locked loop (PLL) enhancement techniques previously developed to improve harmonic voltage issues introduce additional processing layers that further increase computation time [17]. These limitations indicate that current approaches do not simultaneously address both computational efficiency and robustness under distorted voltage conditions. This motivates the development of a simplified yet accurate harmonic detection method tailored for real-time harmonic detection. Therefore, the improved PQ method was developed using a PLL that calculates the angle synchronized with the fundamental phase angle of the voltage source under fluctuating power system conditions. The PLL is modified with SWFA to completely separate the fundamental component from the harmonic components in the phase detector process instead of using an LPF in the traditional PLL [19]. Additionally, the improved PQ method simplifies the computation of the reference current compared to the traditional PQ method. These enhancements directly contribute to the accuracy and speed of harmonic detection. This proposed method aligns with the objectives of this study and offers the following main advantages:

- The major contribution in the improved PQ method is the modified PLL for phase angle detection and the modified process of traditional PQ to achieve reduced computation time and accommodate distorted sinusoidal voltage sources and load variation.

- The improved PQ method can provide a fast and accurate calculation of the reference current under fluctuating power system conditions.

- The improved PQ harmonic detection method is demonstrated to have high performance of harmonic elimination and power factor correction in a single-phase system using real-time simulation with the OPAL-RT hardware. Furthermore, the percentage of total harmonic distortion (%THD) is following the IEEE standard 519-

2022 [20].

- The improved PQ method can be further applied to other electrical systems, indicating its broader applicability. The results confirm that the development of harmonic detection strategies can reduce the need of high-performance microcontrollers. As a result, the production cost of APF will decrease in the future, enabling broader adoption.

The presentation of this work begins with an explanation of the power system under consideration, which exhibits nonlinear load behavior. Section 3 introduces the harmonic detection methods, including the traditional PQ method, the combined PQ method, and the improved PQ method. Section 4 presents the real-time simulation with the OPAL-RT hardware. Section 5 discusses the testing and analysis results obtained using OPAL-RT hardware. The final section provides conclusions and highlights the new knowledge gained from this study.

2. CONSIDERED SYSTEM

The considered single-phase system in this study is designed to simulate the non-linear characteristic of loads that cause harmonics in the power distribution system. This behavior is consistent with modern electrical equipment commonly in use, including electric trains of rail systems, home electric vehicle chargers, computers, adapters, LEDs, and other electrical devices. This considered system consists of a single-phase voltage source connected to a full-wave controlled rectifier. The rectifier converts the AC signal into a DC signal before delivering power to the load, as illustrated in Fig. 1.

The study examined the amount of harmonic currents produced in a power distribution system as a function of load fluctuations. Load conditions were set from 0.5 kW to 1.0 kW, with resistance changing from 200 ohms to 100 ohms, respectively. The results revealed that the %THDi at the source increased from 7.01% to 15.61%, while the PF decreased from 0.88 to 0.87, respectively. In addition, the system was configured with voltage source variations in both magnitude and waveform distortion to test the capability of harmonic detection. In this work, the voltage source was defined under both ideal and non-ideal conditions. The non-ideal condition characterized a 20% reduction in magnitude and a distorted voltage waveform with a %THDv of 10% and served as the basis for evaluating the performance of the proposed harmonic detection method. The results of this situation revealed that the %THDi at the source increased from 10.37% to 18.11%, while the PF decreased from 0.78 to 0.76, respectively.

3. HARMONIC DETECTION METHODS

Harmonic detection is one of the key processes for improving power quality with APFs. This process is implemented to calculate the reference current for APFs. Any error or deviation in this calculation can cause the

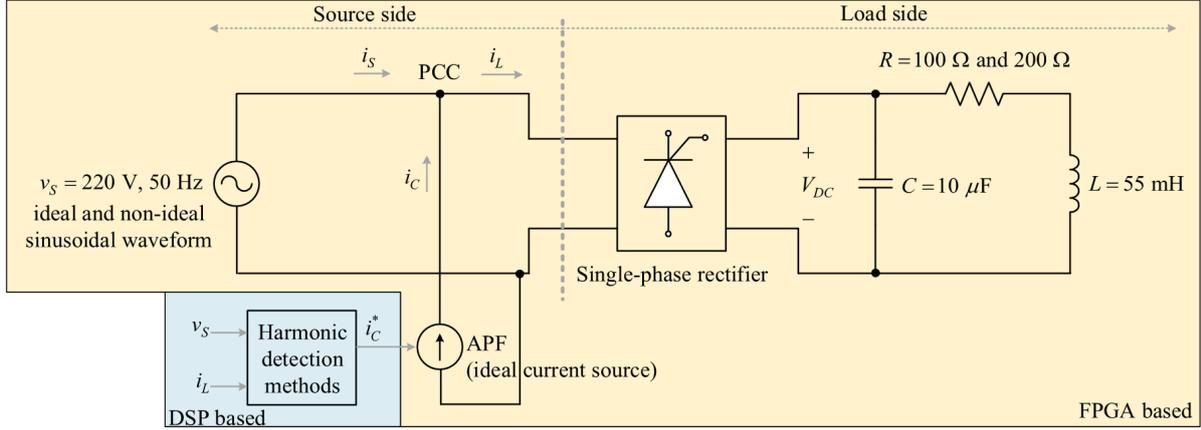


Fig. 1: Considered system.

APF to inject incorrect compensating currents into the distribution system, potentially leading to its failure. Consequently, extensive research has been focused on designing and developing harmonic detection methods for APFs to suit the goals of power quality improvement in the considered systems. This study aims to reduce the resources of high-performance microcontrollers in the harmonic detection process by proposing an approach to decrease the computational time of the PQ method. Furthermore, the PQ method is enhanced to operate effectively under fluctuating voltage source conditions without the need to integrate the PSVD method. Therefore, this section presents the traditional PQ method, the combined PQ method, and the improved PQ method, respectively, with the details provided as follows.

3.1 Traditional PQ Method

To calculate the reference current (i_C^*) of APF using the traditional PQ method involves a total of 5 computational steps, summarized in the diagram in Fig. 2. The first step is to transform the single-phase source voltage (v_S) and load current (i_L) into the $\alpha\beta$ -axis with the phase-shifting technique, represented mathematically by (1) and (2). This transformation simplifies the analysis of the system by converting time-domain signals into components that can be used to determine instantaneous power.

$$v_{S\alpha} = v_S(\theta_{v_S}) \text{ and } v_{S\beta} = v_S(\theta_{v_S} - (\pi/2)) \quad (1)$$

$$i_{L\alpha} = i_L(\theta_{i_L}) \text{ and } i_{L\beta} = i_L(\theta_{i_L} - (\pi/2)) \quad (2)$$

In the second step, the active power (p) and reactive power (q) are calculated using (3) and (4). These power quantities are then decomposed into two parts: the fundamental components (\bar{p} , \bar{q}), which are not affected by harmonics, and the harmonic components (\tilde{p} , \tilde{q}), which are responsible for power quality issues.

$$p = v_{S\alpha}i_{L\alpha} + v_{S\beta}i_{L\beta} = \bar{p} + \tilde{p} \quad (3)$$

$$q = -v_{S\beta}i_{L\alpha} + v_{S\alpha}i_{L\beta} = \bar{q} + \tilde{q} \quad (4)$$

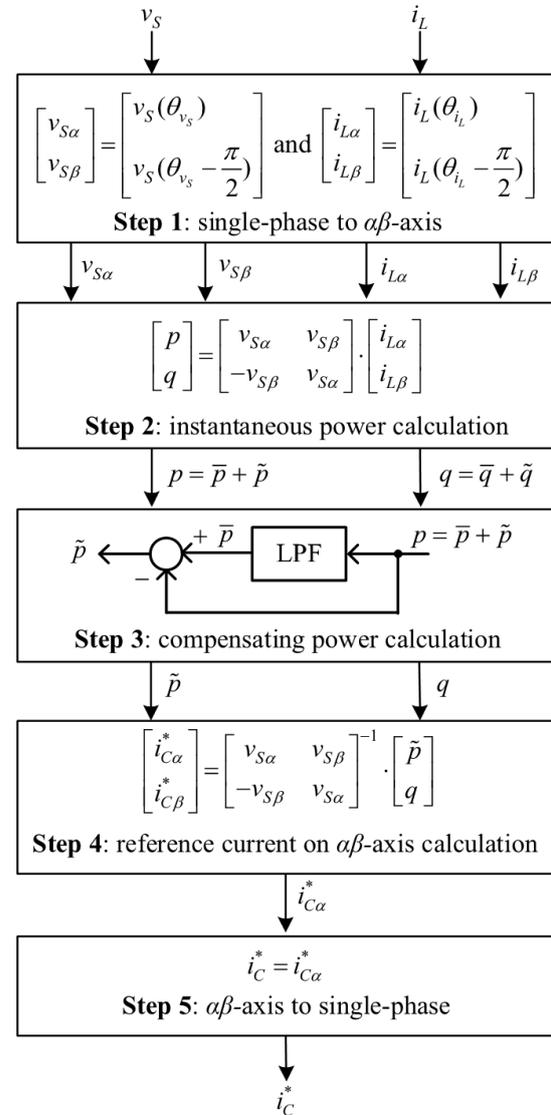


Fig. 2: Diagram of traditional PQ method.

The third step involves filtering the harmonic component of active power (\tilde{p}) using a low-pass filter (LPF)

to isolate the fundamental component, which are then subtracted from the total power to obtain the harmonic content, as shown in (5). The filtering focuses only on active power to eliminate harmonics while simultaneously improving the power factor. In addition, the LPF is designed with a cutoff frequency of 50 Hz, corresponding to the frequency of the system under consideration.

$$\tilde{p} = p - \bar{p} \quad (5)$$

The fourth step involves the calculation of the reference current on the $\alpha\beta$ -axis ($i_{C\alpha}^*$, $i_{C\beta}^*$) using the \tilde{p} and q in step 3. The result of the phase-shifting technique shows that the $i_{C\alpha}^*$ is equivalent to the single-phase reference current (i_C^*). Therefore, only the $i_{C\alpha}^*$ is calculated in Step 4, as expressed in (6).

$$i_{C\alpha}^* = \frac{v_{S\alpha}\tilde{p} - v_{S\beta}q}{v_{S\alpha}^2 + v_{S\beta}^2} \quad (6)$$

Finally, in the fifth step, determining the i_C^* equal to $i_{C\alpha}^*$. The i_C^* is treated as the compensating current (i_C) for the APF to inject to the PCC to cancel out the harmonic components in the system. As a result, the current source is of high quality and free from distortions.

3.2 Combined PQ Method

The integration of various techniques with the PQ-based harmonic detection method aims to achieve accurate reference current calculation while supporting harmonic detection under non-ideal voltage source conditions. The PSVD technique is applied to detect the fundamental voltage at the voltage source. In addition, the SWFA technique is employed to extract the fundamental component of active power instead of using an LPF. This integrated approach is referred to as the combined PQ method, which differs from the traditional PQ method in the following details:

The PSVD technique is designed to detect the fundamental voltage (v'_S) in systems where the voltage source contains harmonic components. The extracted fundamental voltage has a sinusoidal waveform with an initial phase angle ($\theta'_{v'_S}$) equal to the phase angle of the distribution system. This is because the v_S is used to calculate the p and q values in step 2 of the PQ method. Employing a distorted voltage source in this calculation would result in distorted p and q values as well. Therefore, harmonic detection based on the v'_S enables accurate reference current calculation under distorted voltage source conditions. However, the PSVD technique [17] involves calculation steps similar to those of the PQ method, with the additional process of phase angle detection. As a result, this technique significantly increases the computation time of the harmonic detection.

The process of separating \bar{p} from p to calculate the compensating power in step 3 of the PQ method using an LPF has been continuously developed. Since the LPF

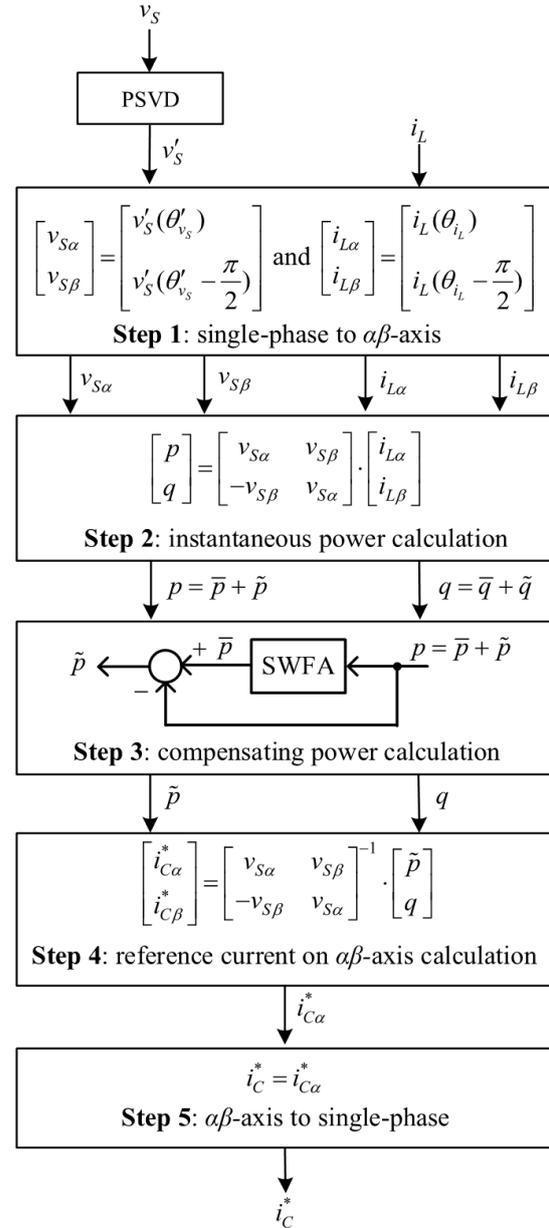


Fig. 3: Diagram of combined PQ method.

uses a cutoff frequency with a bell-shaped response at the 70.7% point, it cannot separate the p with complete purity. To address this limitation, the SWFA technique [21] has been applied as a replacement for the LPF, which can accurately separate electrical quantities at the desired frequency. This substitution enhances the accuracy of harmonic detection. It is well known that the SWFA technique calculates the \bar{p} using the Fourier series equation of p , as expressed in (7). However, the calculation of the Fourier series equation requires more computation time than the LPF. Consequently, the combined PQ method consumes more computational time than the traditional PQ method. The harmonic detection process of the combined PQ method can be summarized in the diagram shown in Fig. 3.

$$\bar{p}(nT_S) = A_1 \cos(\omega nT) + B_1 \sin(\omega nT) \quad (7)$$

where

$$A_1 = \frac{2}{N} \sum_{n=N_0}^{N_0+N-1} p(nT_S) \cos(\omega nT),$$

$$B_1 = \frac{2}{N} \sum_{n=N_0}^{N_0+N-1} p(nT_S) \sin(\omega nT).$$

3.3 Improved PQ Method

To enhance the efficiency of harmonic detection in the PQ method, with a focus on reducing digital computation time and accommodating non-ideal voltage source conditions. This study proposes an improved PQ method, summarized in Fig. 4. The improved PQ method is based on two key factors. The first factor is the assumption that the reactive power component is zero, which simplifies step 2 of the instantaneous power calculation. Previously, both p and q must be computed in this step. This method requires only the calculation of p , thus reducing computation time. In addition, because of this simplification, the compensating power calculation in step 3 requires only the separation of \bar{p} , eliminating the subtraction between p and \bar{p} in (5). The next process in step 4 involves determining the fundamental current (\bar{i}_L), as expressed in (8). Finally, followed by the calculation of the i_C^* , as shown in (9).

$$\bar{i}_L = \frac{\bar{p}}{v_{S\alpha}^2 + v_{S\beta}^2} \times v_{S\alpha} \quad (8)$$

$$i_C^* = i_L - \bar{i}_L \quad (9)$$

The second factor involves improving the detection of the fundamental voltage under distorted voltage source conditions using the modified-PLL technique. The proposed technique improved phase voltage detection of the traditional-PLL technique (Fig. 5(a)) using the SWFA technique instead of an LPF, as shown in Fig. 5(b). The modified-PLL technique operation consists of four main stages: phase detection based on fundamental voltage, loop filtering with a PI controller to generate the control signal, voltage-controlled oscillation to update the estimated phase, and continuous synchronization between the measured fundamental voltage and the internally generated signal. The SWFA extracts the fundamental component of the measured voltage. It can prevent harmonic contamination in the phase error calculation. This structure enables accurate estimation even under distorted or fluctuating voltage conditions. The performance comparison in Fig. 6 shows that the modified-PLL technique enables more accurate detection of the fundamental phase angle ($\theta_{modified-PLL}$) of the distribution system, which is closer to the ideal phase angle (θ_{ideal}) than that achieved by the traditional-PLL technique ($\theta_{traditional-PLL}$). Consequently, harmonic detection under non-ideal voltage source conditions no longer requires the PSVD method. This technique significantly reduces the computation time for fundamental voltage detection compared to PSVD. As a result of these improvements, the improved PQ method achieves

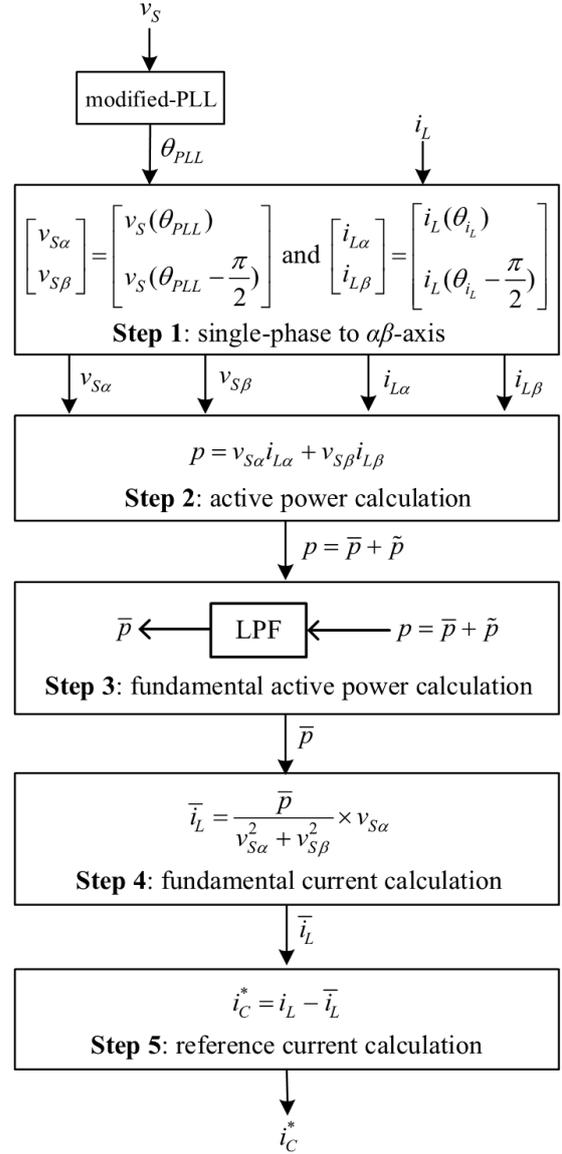


Fig. 4: Diagram of improved PQ method.

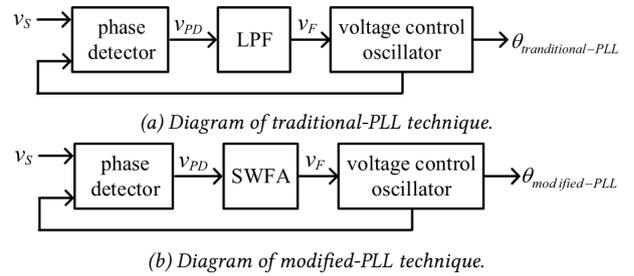


Fig. 5: PLL technique.

reduced computation times relative to the combined PQ method, while maintaining a computation time comparable to the traditional PQ method. At the same time, it achieves superior performance in accurately calculating reference currents under non-ideal voltage source conditions.

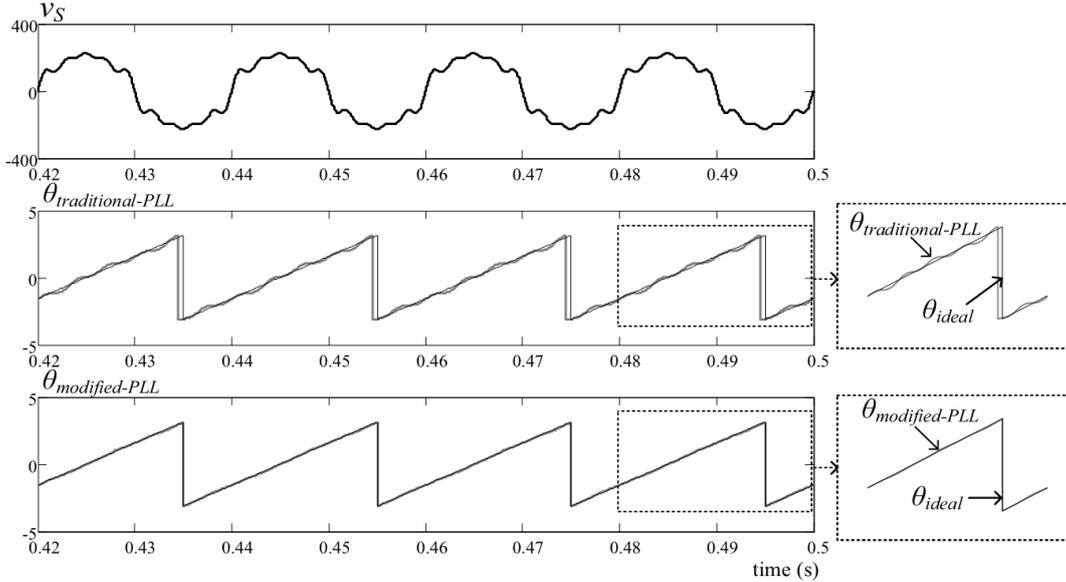


Fig. 6: Result of phase angle detection using modified-PLL.

4. OPAL-RT HARDWARE SETUP

Real-time simulation with the OPAL-RT hardware is applied to validate the performance of harmonic detection using the traditional, combined, and improved PQ methods. The OPAL-RT hardware setup in Fig. 7 consists of an oscilloscope model Yokogawa DLM5058HD, an OPAL-RT model OP4512 including DSP and FPGA devices, the MATLAB/Simulink program, and RT-LAB software. The advantage of FPGAs is their ability to simulate the behavior of electrical devices using logic gates with a maximum sampling time of 2 nanoseconds. DSPs are utilized for processing control systems that have a maximum sampling time of 1 microsecond. It is evident that the FPGA and DSP in OPAL-RT hardware operate at different sampling times. Moreover, OPAL-RT hardware can generate the electrical waveforms of the system under study and display them in real time on an oscilloscope without digital delay. This capability enables OPAL-RT hardware to produce study results that closely approximate those of an actual platform, facilitating performance evaluation prior to system deployment, reducing costs, and preventing potential damage.

In this study, the OPAL-RT hardware models the power system and the active power filter (APF) using an ideal current source, as shown in Fig. 1, implemented on the FPGA with a sampling rate of 1 nanosecond, while the three harmonic detection methods are implemented in the C programming language on the DSP with a sampling rate of 50 microseconds. The ideal current source-based APF model was used in place of a voltage-source inverter (VSI) because the objective of this work is to compare the performance of harmonic detection methods without interference from other control factors. If a VSI-based APF were used, the results would be influenced by the current-control loop and the DC-bus voltage-control loop, making it impossible to isolate and

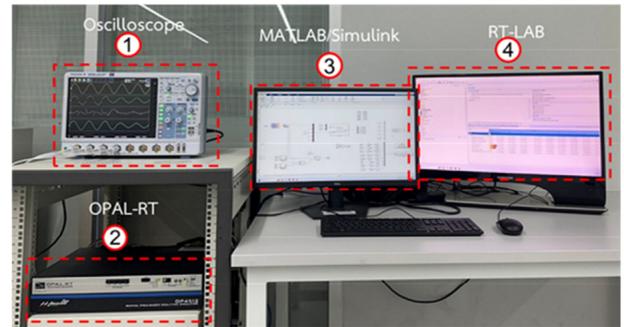


Fig. 7: OPAL-RT hardware setup.

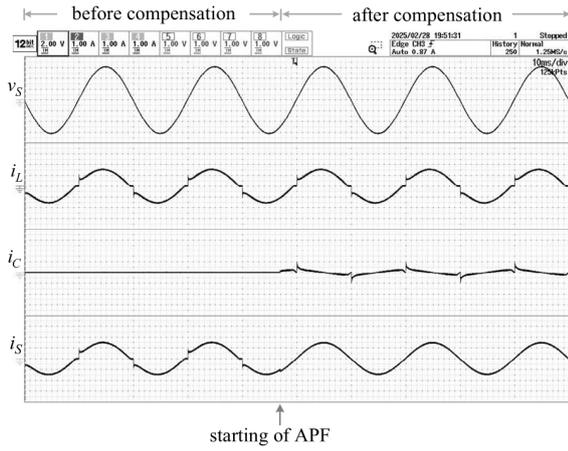
accurately evaluate the true performance of the harmonic detection method.

5. RESULTS AND DISCUSSION

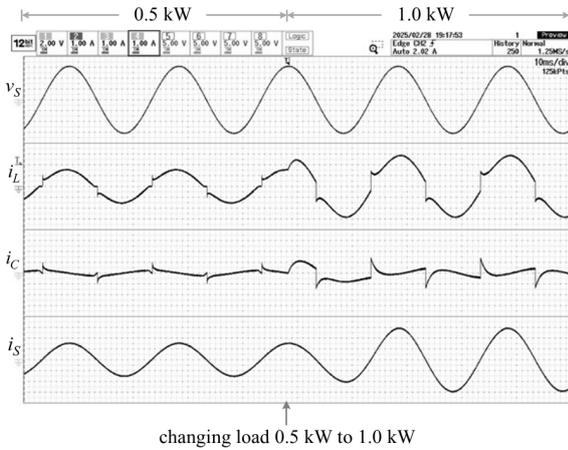
The performance of harmonic detection using the traditional PQ method, the combined PQ method, and the improved PQ method is evaluated in two key aspects: the power quality improvement and the computation time required for reference current calculation in each harmonic detection method. The details are as follows:

5.1 Results of Power Quality Improvement

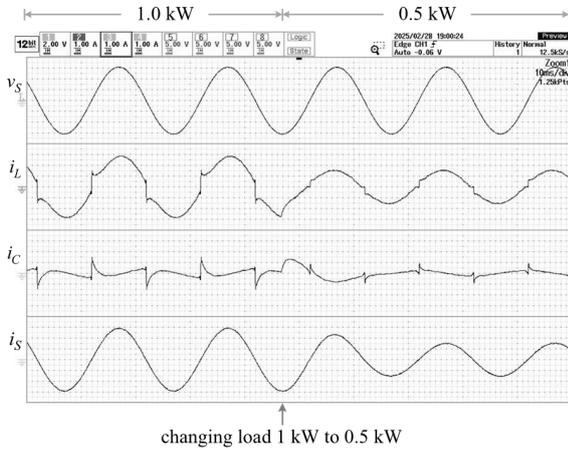
The testing results for power quality improvement consider the source current at the PCC (i_S) using performance indicators such as %THD in accordance with IEEE standard 519-2022 and PF in accordance with IEEE standard 1159-2019 [22]. The tests were conducted under different operating conditions of the electrical system, reflecting typical behaviors of systems with nonlinear loads. These conditions include both ideal and non-ideal voltage sources with varying load levels, either



(a) Situation of initiating compensation current injection.



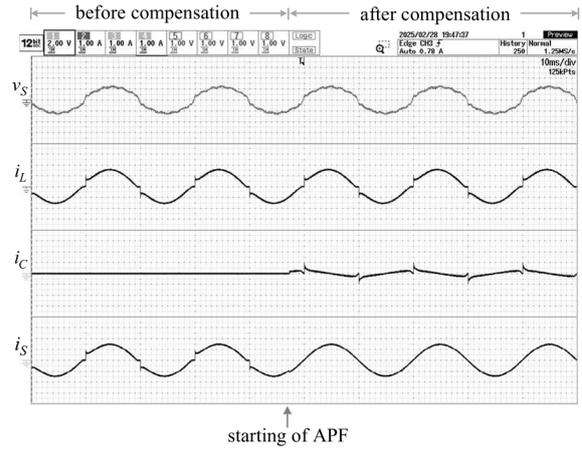
(b) Situation of load power increasing.



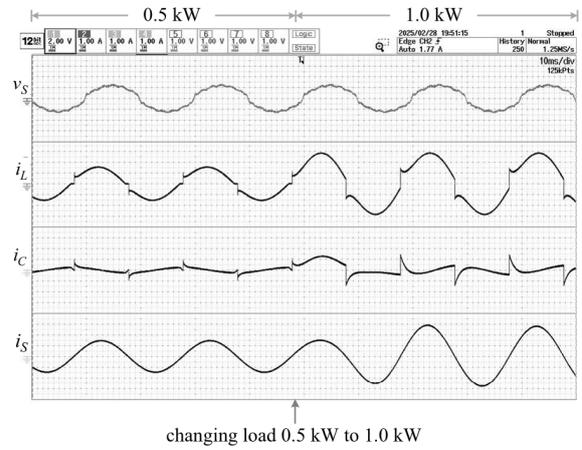
(c) Situation of load power decreasing.

Fig. 8: Results of considering systems with ideal voltage source conditions.

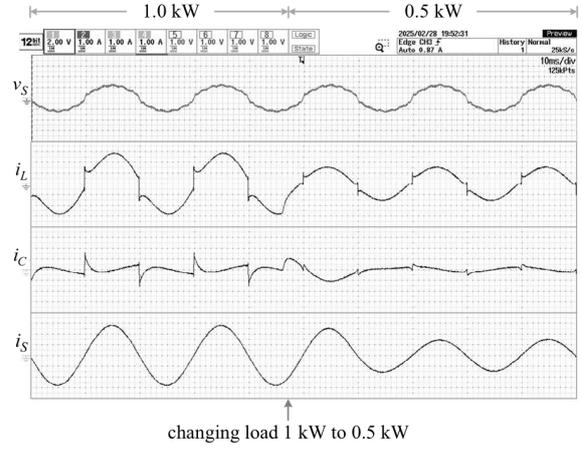
increasing or decreasing. Based on numerous previous studies, it is well established that the traditional PQ method provides good power quality improvement under ideal voltage source conditions, while the combined PQ method achieves good performance under both ideal and non-ideal voltage source conditions. Accordingly, this study presents the results of power quality improvement



(a) Situation of initiating compensation current injection.



(b) Situation of load power increasing.



(c) Situation of load power decreasing.

Fig. 9: Results of considering systems with non-ideal voltage source conditions.

using the improved PQ method. The results of the system with ideal voltage source condition are as shown in Fig. 8 and non-ideal voltage source condition as shown in Fig. 9. The i_s waveforms in Figs. 8 and 9 can be summarized as follows:

- Before compensation (Figs. 8(a) and 9(a)): The i_s waveform is distorted and exhibit the same character-

istics as the i_L waveform. Under these situations, the %THDi and PF values exceed the limits specified by IEEE standards. The %THDi and PF values of the situations without compensation are shown in Table 1 and Table 2, respectively.

- After compensation during initiation (Figs. 8(a) and 9(a)): The i_S waveform becomes sinusoidal, in contrast to the distorted i_L waveform.

- After compensation under dynamic conditions: Consider instantaneous load changes from 0.5 kW to 1.0 kW (Figs. 8(b) and 9(b)) and from 1.0 kW to 0.5 kW (Figs. 8(c) and 9(c)), the i_S waveform remained sinusoidal. This confirms the effectiveness of the harmonic detection under dynamic load conditions.

- After compensation under steady-state load conditions of 0.5 kW and 1.0 kW (Figs. 8 and 9), the i_S waveform remains sinusoidal, with %THDi and PF values following the requirements of IEEE standards, as summarized in Table 1 and Table 2, respectively. These results confirm that the improved PQ harmonic detection method delivers strong performance in improving power quality under ideal and non-ideal voltage sources in both dynamic and steady-state conditions.

- In the case of the ideal voltage source, the %THDi and PF values indicating the waveform characteristics in Table 1 show that after compensation using all three methods, the %THDi and PF are equal. Therefore, the waveform characteristics of the three methods are duplicate, as illustrated in Fig. 8. For the case of a non-ideal voltage source, the %THDi and PF values presented in Table 2 indicate that after compensation using the combined PQ method and the proposed method, the %THDi and PF of both methods are equal. Therefore, the waveform characteristics of the combined PQ method and the proposed method are duplicate, as shown in Fig. 9. In contrast, the PQ method exhibits a higher %THDi value after compensation, indicating that this method leads to unreliability in the power systems.

5.2 Results of Computation Time

The computational time results of the traditional PQ, combined PQ, and improved PQ detection methods proposed in Section 3 are shown in Figs. 10-12 and conclusion data are shown in Table 1 and Table 2. The harmonic detection process is executed on the DSP. Therefore, the computation time is evaluated based on the control system sampling time on the DSP. In this study, the sampling time of the control system is set to 50 microseconds. Consequently, a computation time of 50 microseconds corresponds to 100% utilization of the DSP's processing capability. The test results for the computation time of harmonic detection can be summarized as follows:

- The traditional PQ, combined PQ, and improved PQ detection methods have different computation times due to variations in their calculation processes, as illustrated in Figs. 2-4, respectively.

- The traditional PQ method takes less computation

Model: APF_detection Ts=5.0E-5[s] T=4.74495[s] Number of overruns=0

Probes	Usage [%]	Min	Max	Mean
APF_detection Ts=5.0E-5[s]	14.7%			
SM_test Ts=4...873689376E-5[s]	12.12%	dt= 5.88 [us]	dt= 6.39 [us]	dt= 6.06 [us]
New data acquisition	0.06%	dt= 0.02 [us]	dt= 0.06 [us]	dt= 0.03 [us]
Major computation time	2.52%	dt= 1.17 [us]	dt= 1.34 [us]	dt= 1.26 [us]
Minor computation time	8.35%	dt= 4.03 [us]	dt= 4.31 [us]	dt= 4.17 [us]
Execution cycle	12.12%	dt= 5.88 [us]	dt= 6.39 [us]	dt= 6.06 [us]
Total step size	99.92%	dt= 49.66 [us]	dt= 50.27 [us]	dt= 49.96 [us]
Total idle	87.28%	dt= 43.27 [us]	dt= 44.01 [us]	dt= 43.64 [us]
Update Iv panels	0.0%	dt= 0.00 [us]	dt= 0.00 [us]	dt= 0.00 [us]
Op7160ex1_wait_rcv0_opctrl	0.12%	dt= 0.04 [us]	dt= 0.08 [us]	dt= 0.06 [us]

Fig. 10: Computational time of traditional PQ method.

Model: APF_detection Ts=5.0E-5[s] T=55.41520[s] Number of overruns=0

Probes	Usage [%]	Min	Max	Mean
APF_detection Ts=5.0E-5[s]	57.22%			
SM_test Ts=4...873689376E-5[s]	57.22%	dt= 27.17 [us]	dt= 30.15 [us]	dt= 28.61 [us]
New data acquisition	0.12%	dt= 0.06 [us]	dt= 0.06 [us]	dt= 0.06 [us]
Major computation time	9.35%	dt= 4.51 [us]	dt= 4.93 [us]	dt= 4.68 [us]
Minor computation time	46.16%	dt= 21.70 [us]	dt= 24.49 [us]	dt= 23.08 [us]
Execution cycle	57.22%	dt= 27.17 [us]	dt= 30.15 [us]	dt= 28.61 [us]
Total step size	99.92%	dt= 49.63 [us]	dt= 50.29 [us]	dt= 49.96 [us]
Total idle	41.97%	dt= 19.47 [us]	dt= 22.49 [us]	dt= 20.98 [us]
Update Iv panels	0.0%	dt= 0.00 [us]	dt= 0.00 [us]	dt= 0.00 [us]
Op7160ex1_wait_rcv0_opctrl	0.19%	dt= 0.08 [us]	dt= 0.11 [us]	dt= 0.10 [us]

Fig. 11: Computational time of combined PQ method.

Model: APF_detection Ts=5.0E-5[s] T=11.33530[s] Number of overruns=0

Probes	Usage [%]	Min	Max	Mean
APF_detection Ts=5.0E-5[s]	14.47%			
SM_test Ts=4...873689376E-5[s]	14.47%	dt= 7.05 [us]	dt= 7.64 [us]	dt= 7.23 [us]
New data acquisition	0.04%	dt= 0.01 [us]	dt= 0.02 [us]	dt= 0.02 [us]
Major computation time	2.93%	dt= 1.38 [us]	dt= 1.57 [us]	dt= 1.47 [us]
Minor computation time	10.29%	dt= 5.01 [us]	dt= 5.46 [us]	dt= 5.15 [us]
Execution cycle	14.47%	dt= 7.05 [us]	dt= 7.64 [us]	dt= 7.23 [us]
Total step size	99.92%	dt= 49.66 [us]	dt= 50.26 [us]	dt= 49.96 [us]
Total idle	84.88%	dt= 41.87 [us]	dt= 42.74 [us]	dt= 42.44 [us]
Update Iv panels	0.0%	dt= 0.00 [us]	dt= 0.00 [us]	dt= 0.00 [us]
Op7160ex1_wait_rcv0_opctrl	0.12%	dt= 0.04 [us]	dt= 0.08 [us]	dt= 0.06 [us]

Fig. 12: Computational time of improved PQ method.

time compared to the improved PQ method (1.23 microseconds). This variance is because the traditional PQ method does not include a process for handling non-ideal voltage sources. Considering this little time difference, it can be concluded that both methods have comparable computation times. However, the improved PQ method demonstrated effective power quality improvement by accurately calculating the reference current for both ideal and non-ideal voltage source conditions. This ability is demonstrated by the %THDi and PF results presented in Table 1 and Table 2, respectively.

- A comparison of the computation times for harmonic detection methods that support non-ideal voltage source conditions found that the improved PQ method used 21.38 microseconds less computation time than the combined PQ method, equivalent to 42.76% of DSP's processing capacity. This confirms that the improved PQ method in this study effectively reduces the harmonic detection computation time of the APF. Such a reduction in processing time enhances its suitability for real-time control applications, particularly in systems utilizing microcontrollers with limited computational resources. These findings demonstrate that the improved

Table 1: Performance indicators of harmonic detection methods in ideal voltage source system.

Load (kW)	THDi (%)	PF	Computation time (μ s)	DSP's capacity (%)
Before compensation				
0.5	7.01	0.88	-	-
1	15.61	0.87	-	-
After compensation (traditional PQ method)				
0.5	0.16	1.00	6.06	12.12
1	0.16	1.00		
After compensation (combined PQ method)				
0.5	0.16	1.00	28.61	57.22
1	0.16	1.00		
After compensation (improved PQ method)				
0.5	0.16	1.00	7.23	14.47
1	0.16	1.00		

Table 2: Performance indicators of harmonic detection methods in non-ideal voltage source system.

Load (kW)	THDi (%)	PF	Computation time (μ s)	DSP's capacity (%)
Before compensation				
0.5	10.37	0.78	-	-
1	18.11	0.76	-	-
After compensation (traditional PQ method)				
0.5	41.69	0.18	6.06	12.12
1	43.52	0.21		
After compensation (combined PQ method)				
0.5	0.16	1.00	28.61	57.22
1	0.16	1.00		
After compensation (improved PQ method)				
0.5	0.16	1.00	7.23	14.47
1	0.16	1.00		

PQ method provides an efficient and practical solution for improving power quality in single-phase power systems.

6. CONCLUSION

This study proposes an enhanced harmonic detection method for calculating reference currents in active power filters within single-phase power systems. Based on instantaneous power theory, the improved PQ method aims to eliminate harmonic currents and correct the power factor while reducing computational complexity. Real-time testing on OPAL-RT hardware validates the performance of traditional, combined, and improved PQ methods. Power quality indicators and processing time value confirm that the improved PQ method achieves superior harmonic elimination and faster computation, particularly under non-ideal voltage and dynamic load conditions, in compliance with IEEE standards. The results highlight the method's suitability for real-time, resource-constrained microcontroller-based systems, offering a practical solution for improving electrical efficiency and reliability using an active power filter.

In future work, this method is applied to an active power filter for power quality improvement in an electric railway system to further validate its scalability and robustness.

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