

Article

Design of Parallel Hybrid Active Power Filter with Adaptive DC-Link Voltage Control Based on Artificial Neural Network

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Abstract

In this study, an Artificial Neural Network (ANN)-based adaptive DC-link voltage (V_{dc}) controller is developed for a Parallel Hybrid Active Power Filter (PHAPF). The proposed controller aims to simultaneously determine the DC-link reference voltage (V_{dc_ref}) and the PI controller gains (K_i , K_p) as a function of the operating conditions. Training data for the ANN are obtained from simulations performed in the MATLAB/Simulink environment. Simulations performed using this training set show that adapting the DC-link reference voltage reduces total harmonic distortion (THD) compared to a PHAPF with a fixed V_{dc_ref} and reduces the DC-link voltage at low-power loads, which has the potential to lower switching losses, while adaptive PI gains improve transient behavior after large load changes. Therefore, the two adaptive quantities affect complementary aspects of performance. The trained ANN model is coded in the C programming language and implemented on a microcontroller-based control card. A 5 kVA PHAPF system is designed and fabricated for experimental verification. Experimental results demonstrate that the proposed ANN-based adaptive DC-link voltage control algorithm achieves lower total harmonic distortion (THD) than PHAPFs employing a constant V_{dc_ref} . In addition, reducing the DC-link voltage under low-power operating conditions has the potential to decrease voltage stress across the power switches and reduce switching losses. Furthermore, the proposed ANN-based adaptive DC-link voltage control algorithm exhibits better harmonic suppression performance despite the processing load and filtering delays.

Keywords: Parallel Hybrid Active Power Filter (PHAPF); Artificial Neural Networks (ANN); adaptive DC-link control; power quality



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1. Introduction

Nowadays, the widespread deployment of power electronic-supported systems, such as converters, adjustable speed drives, arc furnaces, rectifiers, power supplies, computers, fluorescent lamps, elevators, escalators, large air conditioning systems, compressors, and similar motor loads in distribution power systems has caused power quality problems, especially low power factor and harmonic pollution, which is a very serious issue [1,2]. Harmonics originating from nonlinear loads cause various problems in power systems. High harmonic distortion in drawn load currents causes many obstacles such as overheating of equipment in distribution systems and consumer products, blowing of capacitor fuses, faulty operation of protection devices, and overheating of transformers [2,3].

Various solutions have been developed throughout history to solve these harmonic and reactive power problems. First, shunt capacitor banks were used in the 1900s for power factor correction and feeder voltage control. However, capacitor banks were easily damaged when the current harmonic level in the system was high. In the mid-1940s, passive power filters (PPFs) began to be widely used in distribution power systems to suppress harmonic currents and compensate reactive power due to their low cost, simple structure, and high efficiency [4,5]. PPFs can only compensate constant reactive power and constant harmonics. In addition, they have filtering characteristics that are easily affected by small changes in system parameters and can also cause harmonic resonance problems in the system.

In 1976, the first versions of active power filters (APFs) based on power transistor PWM inverters were introduced. Although APFs can overcome the disadvantages of PPFs, their initial and operating costs are quite high because of the DC-link operating voltage requirements, which must be higher than the system voltage [6]. Therefore, different hybrid active power filter (HAPF) topologies consisting of series and/or parallel active and passive parts have been proposed.

The LC-coupled hybrid active power filter (LC-HAPF) has provided lower initial cost and operating losses due to its transformerless structure, use of fewer passive components, and a much lower DC-link voltage requirement than APFs [7,8]. Applications of the LC-HAPF include dynamic reactive power compensation, harmonic current elimination, resonance damping, and renewable energy systems integration.

The performance of LC-HAPF is determined by the reference current control algorithm and the DC-link voltage controller. In practice, there is always a minimum DC-link operating voltage value for power quality circuits that compensate the reactive power and harmonic currents of the load. Switching loss is directly proportional to V_{dc} , and higher V_{dc} results in higher switching loss in the system [9,10]. Therefore, in recent years, studies on the use of adaptive control systems have intensified in order to lower V_{dc} values.

Among adaptive control approaches, model predictive control, fuzzy logic-based, and ANN-based control algorithms stand out [11–13]. In these studies, significant progress has been made in online tuning of system parameters, selective harmonic compensation, and reactive power control [14–16]. Especially with modular cascade multilevel inverter-based PHAPF systems, results that meet the IEEE-519 [2], standard have been obtained in both harmonic and reactive power compensation under distorted/unbalanced supply voltage conditions [17]. Particularly, the utilization of intelligent architectures has proven highly effective; for instance, implementing a shunt hybrid active power filter governed by an artificial neural network optimizer has demonstrated superior capabilities in accurately extracting reference currents and minimizing THD under complex, nonlinear load conditions in distribution systems [18].

New approaches such as the ADALINE-LMM algorithm have been developed for more accurate detection of harmonic components. This approach can identify and eliminate the effect of transient fluctuations in the presence of impulse noise, and demonstrates more accurate and faster tracking capability than traditional methods [19].

A thyristor-controlled LC-coupling hybrid active power filter (TCLC-HAPF), which was developed to solve the problem of the narrow reactive power compensation range of LC-HAPF, provides a much wider reactive power compensation range while maintaining the low DC-link voltage feature [20,21]. This structure offers significant advantages in terms of energy efficiency by not requiring high DC-link voltage when operating outside the compensation range.

Some studies in the literature have employed cascaded multilevel inverter-based hybrid active power filters [22]. It has been reported that these topologies reduce switching

losses by distributing the V_{dc} among several converter cells, thereby simplifying PI controller parameter tuning. However, these systems require multiple power cells, additional gate-driver circuits, capacitor voltage balancing, and increased hardware complexity. In contrast, the proposed LC-PHAPF preserves the conventional single-inverter structure and achieves switching loss reduction through ANN-based adaptive DC-link voltage optimization and real-time PI parameter tuning without requiring additional power hardware.

In this study, an ANN-based adaptive DC-link voltage controller is proposed for a PHAPF designed to eliminate harmonics in a three-phase system. It has three novel aspects. First, unlike conventional adaptive DC-link voltage controller schemes that derive the reference voltage from an explicit analytical model of the filter and the load [4,9,10], the developed algorithm learns the mapping between the operating condition and the approximately optimal V_{dc_ref} directly from data, and therefore requires no circuit-parameter knowledge or online recalculation when the load changes. Second, whereas previous ANN applications in active power filters employ the network for reference current generation, harmonic identification, or fixed V_{dc_ref} regulation [13,18,19], the network here determines the approximately optimal V_{dc_ref} itself as a function of the load condition. Third, the proposed algorithm is implemented on a low-cost microcontroller and validated using a real 5 kVA hardware prototype.

To develop and verify the proposed controller, the PHAPF was first modeled in the MATLAB/Simulink environment under specified system parameters. This model was then executed with a script covering 10,080 different combinations of V_{dc_ref} proportional gain (K_p) and integral gain (K_i) across a range of load values, from which the performance data of the PHAPF was obtained. From these results, the V_{dc_ref} and PI parameters yielding approximately optimal performance for each load condition were selected to train the ANN. Finally, the trained network was tested both in the simulation environment and experimentally, and the PHAPF operated with constant and adaptive DC-link voltage control was compared under identical conditions.

For the experimental study, a three-phase 5 kVA PHAPF was built in the laboratory. An STM32F407 microcontroller was used on the control card prepared for the PHAPF; the control software was developed in the C programming language using STM32CubeIDE and loaded onto the control card for experimental verification.

The remainder of this paper is organized as follows. Section 2 presents the design of the PHAPF and the criteria for determining the system parameters. Section 3 explains the selection of the ANN training data from the simulation studies conducted in the computer environment and the training procedure using these data. Section 4 compares, in simulation, the filter performance obtained under different loads for the PHAPF using constant and adaptive DC-link voltage control algorithms. Section 5 presents and discusses the experimental results obtained in the laboratory for the proposed PHAPF, including the adaptive DC-link voltage control algorithm. Finally, Section 6 concludes the paper.

2. Parallel Hybrid Active Power Filter Design

The basic structure of the three-phase PHAPF system, as shown in Figure 1, consists of an APF circuit containing an LC passive filter for each phase and a three-phase-voltage-source PWM inverter connected in series with them. This system has the feature of being directly connected in parallel to the grid without using a transformer. While the LC filter dampens harmonic currents, the APF enhances its filtering characteristics. A key advantage of this system is that the DC-link voltage value of the APF used in the system is significantly lower than that of traditional active filters. In addition, the LC filter functions as a switching noise filter in addition to providing harmonic filtering [7].

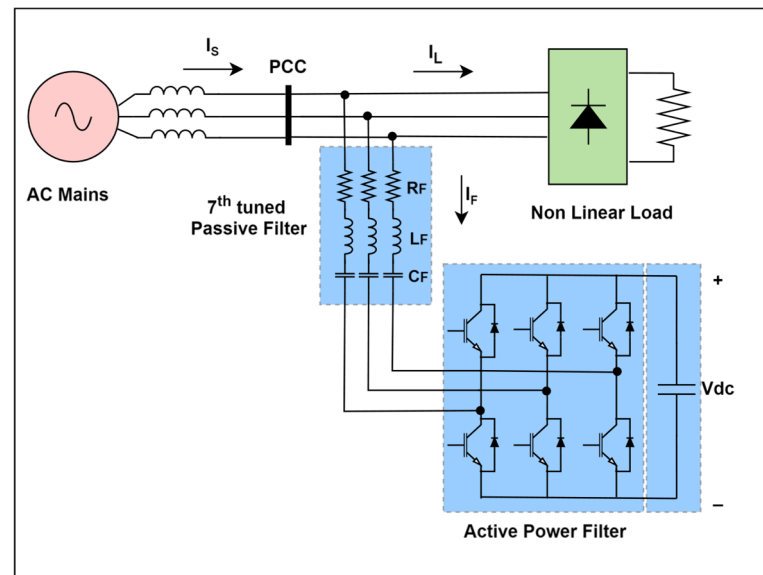


Figure 1. The structure of a parallel hybrid active power filter.

In the passive filter design, the LC filter is set to the seventh harmonic (350 Hz). This selection provides lower impedance at the 11th and 13th harmonics compared to the filter set to the fifth harmonic and increases system efficiency. In the design, the filter inductance (L_f) value is determined as 3 mH, and the filter capacitance (C_f) value is determined as 65 μ F. The value of the filter inductance should be selected approximately ten times the supply inductance (L_s). This selection is an important design criterion in terms of system stability [7].

In the control of the PHAPF system, control algorithms shown in Figure 2 are widely used. Firstly, the supply voltage is applied to a PLL circuit, and the phase information of the supply voltage is obtained. The overall control scheme comprises two distinct paths: feedforward and feedback. In the feedback control path, three-phase supply currents are transformed to d (direct) and q (quadrature) coordinate axes rotating at fundamental frequency (ω_1) using Clarke Equation (1) and Park Equation (2) transforms. Consequently, the fundamental component of the supply current appears as a DC signal on the dq coordinate axes, and harmonic components appear as AC signals. Harmonic current components are separated from the fundamental component using a first-order HPF with a cut-off frequency between 15 and 20 Hz and obtained at the filter output. The transfer function is given in Equation (3). These harmonic currents are transformed to the abc coordinate axis using inverse Park and Clarke transforms. They are multiplied by a K constant and added to the inverter voltage reference value.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}, \quad (1)$$

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

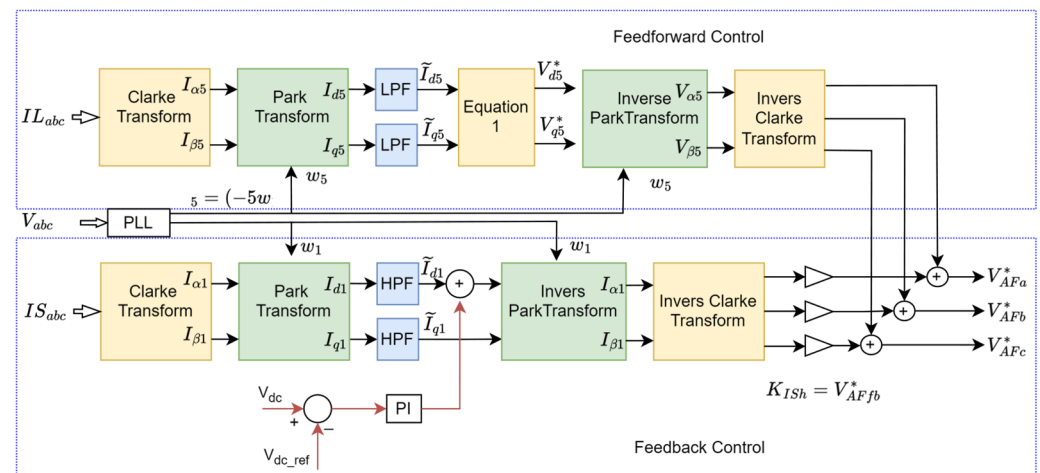


Figure 2. PHAPF control block diagram.

The feedforward control path (Figure 2) is specifically designed to eliminate the fifth harmonic current. In this block, the three-phase load currents are first transformed into the $\alpha\beta$ coordinate axes ($I_{L\alpha}, I_{L\beta}$) by the Clarke transform, and then to the dq coordinate axes (I_{Ld5}, I_{Lq5}) by the Park transform. The Park transform is performed on a reference frame rotating at the same frequency as the fifth harmonic. Therefore, the fifth harmonic current components are observed as DC components in the dq axes. These DC components are separated from the other components by passing them through first-order low-pass filters (LPF) with a cut-off frequency between 15 and 20 Hz. The transfer function is given in Equation (4). Thus, only the fifth harmonic currents $\tilde{I}_{d5}$ and $\tilde{I}_{q5}$ are obtained. The filtered current references are transformed to the voltage references V_{d5}^* and V_{q5}^* using Equation (5). While the w_5 value in Equation (5) represents the 5th harmonic angular frequency ($w_5 = -5w_1$, where w is the fundamental frequency), the R_F parameter represents the passive filter resistance.

$$G_{HPF}(s) = \frac{s}{s + \omega_c}, \quad (3)$$

$$G_{LPF}(s) = \frac{\omega_c}{s + \omega_c}, \quad (4)$$

The fifth harmonic components of the voltage references in the resulting dq axes are transformed to the abc coordinate axis using the inverse Park and Clarke transforms and added to the inverter voltage references. As a result of this process, feedforward voltage references that effectively suppress the fifth harmonic components in steady states are obtained [7].

$$\begin{bmatrix} v_{d5}^* \\ v_{q5}^* \end{bmatrix} = \begin{bmatrix} R_F & -\omega_5 L_F + \frac{1}{\omega_5 C_F} \\ \omega_5 L_F - \frac{1}{\omega_5 C_F} & R_F \end{bmatrix} \begin{bmatrix} \tilde{i}_{Ld5} \\ \tilde{i}_{Lq5} \end{bmatrix}, \quad (5)$$

3. Generation and Use of Training Data for ANN-Based Adaptive DC-Link Voltage Control Algorithm

MATLAB (R2022a)/Simulink was used to generate the dataset for training the ANN-based adaptive DC-link voltage controller. The simulation model created using the PHAPF block diagram shown in Figure 3 and the parameters specified in Table 1 was automated with the help of prepared code and run for 10,080 different situations under different parameters (V_{dc} , K_p , K_i) and different load conditions.

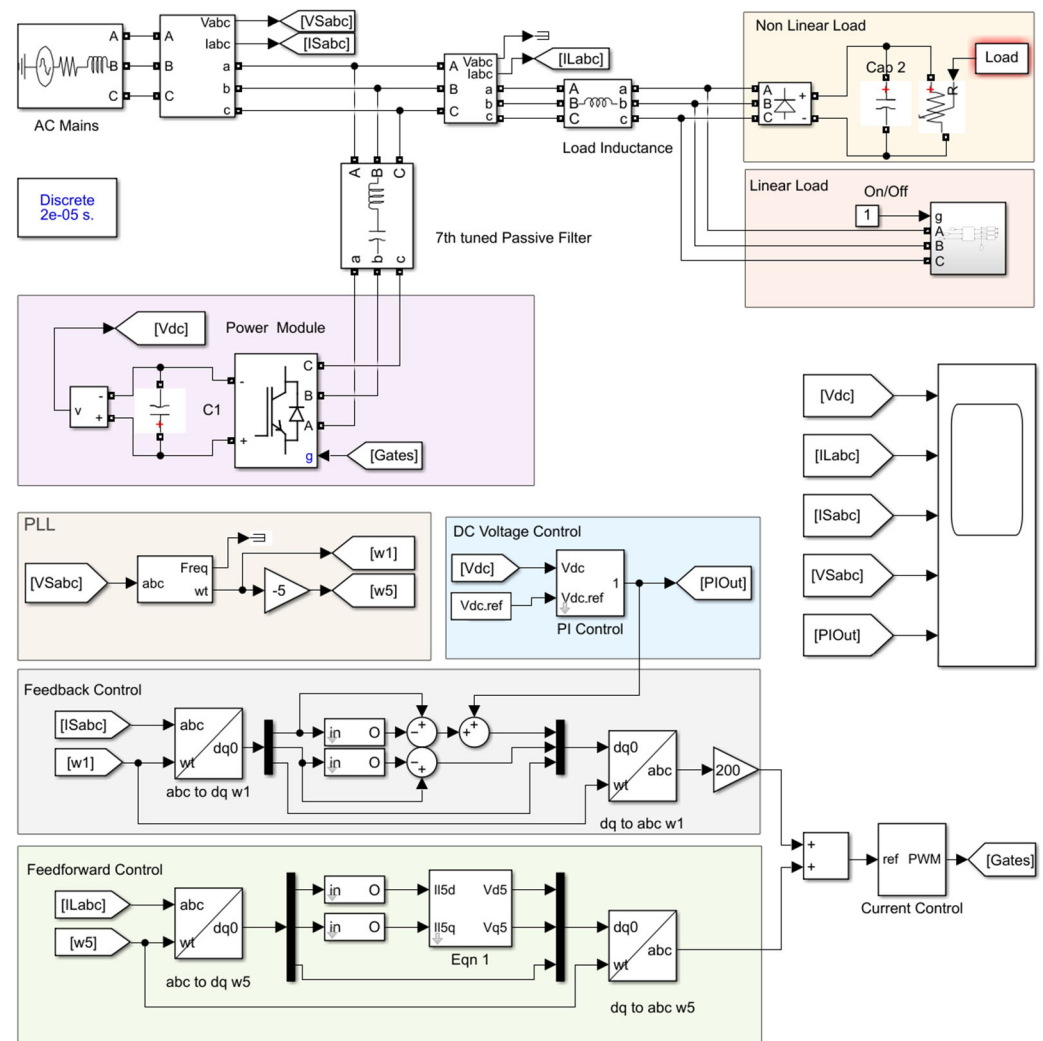


Figure 3. Simulation of PHAPF in MATLAB/Simulink environment.

Table 1. System parameters used in training, simulation, and experimental studies.

Parameters	Symbols	Values
Supply Voltage (phase–phase)	V_s	346 V
Supply Frequency	f	50 Hz
Supply Inductance	L_s	0.21 mH
Simulation Sampling Frequency	f_s	50 kHz
LPF Cutoff Frequency	-	20 Hz
HPF Cutoff Frequency	-	20 Hz
Passive Filter Capacitance	C_f	65 μ F
Passive Filter Inductance	L_f	3 mH
Passive Filter Resistance	R_f	0 Ω
Load Inductance	L_L	5 mH
Nonlinear Load Capacitance	C_L	1500 μ F
Voltage Gain	K	200
DC-link Reference Voltage	V_{dc_ref}	[20:10:80] V
PI Proportional Gain	K_p	[0.05:0.01:0.12]
PI Integral Gain	K_i	[0.0002:0.0001:0.001]
Nonlinear Load Resistance	R_{L_DC}	[30:20:90] Ω
Linear Load Resistance	R_L	[20 30 40 50 ∞] Ω

As seen in Table 1, the V_{dc_ref} value used in the simulations was changed by increasing it in 10 V steps between 20 V and 80 V. Similarly, the nonlinear load (three-phase diode

rectifier + R_{L_DC}) was used by changing it in 20 Ω steps between 30 Ω and 90 Ω , and the linear load was used by changing it in 10 Ω steps between 20 Ω and 50 Ω . In addition, the system was tested to operate only with a nonlinear load. This situation, where there is no linear load, is shown as “ $\infty \Omega$ ” in Table 1.

The data obtained from each simulation were recorded in matrix form. These data include the reference and actual V_{dc} values, linear and nonlinear load parameters, the RMS values of the supply and fifth harmonic currents, the THD values of the load and supply currents, and the PI controller parameters. Since the main purpose of the study was to achieve the lowest supply current THD value using the lowest V_{dc_ref} value, the data that best satisfy these criteria were selected from all simulation results.

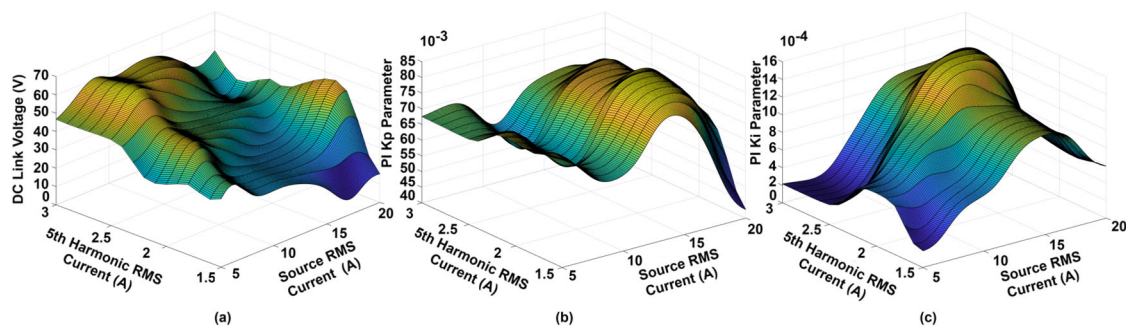
This selection procedure followed a two-stage approach. In the first stage, the data was filtered according to physical constraints, isolating valid operating points at which the relative deviation from the V_{dc_ref} was at most 7%; the grid current THD was limited to 5% in accordance with the IEEE 519 standard. In the second stage, the filtered data were examined for each individual load profile to determine the optimal operating conditions that minimize harmonic distortion. Among results exhibiting equivalent performance, the operating point with the lowest V_{dc_ref} was selected in order to minimize switching losses. The approximately optimal V_{dc_ref} obtained through this optimization process, combined with the controller gain parameters, formed the target values for each load condition. To improve the generalizability of the dataset, simulation results that provided low THD at different V_{dc_ref} levels under the same load profile were also added. As a result, the 197 derived training samples map the input features to the three target parameters.

The ANN structure created via the MATLAB Neural Network Toolbox is designed to take the rms values of the supply and fifth harmonic current as input parameters and produce the approximately optimal V_{dc_ref} , K_i , and K_p values as output parameters. The network consists of 12 hidden-layer neurons using the tansig transfer function and three output neurons using the purelin transfer function. During training, the dataset was randomly divided into 70% for training, 15% for validation, and 15% for testing.

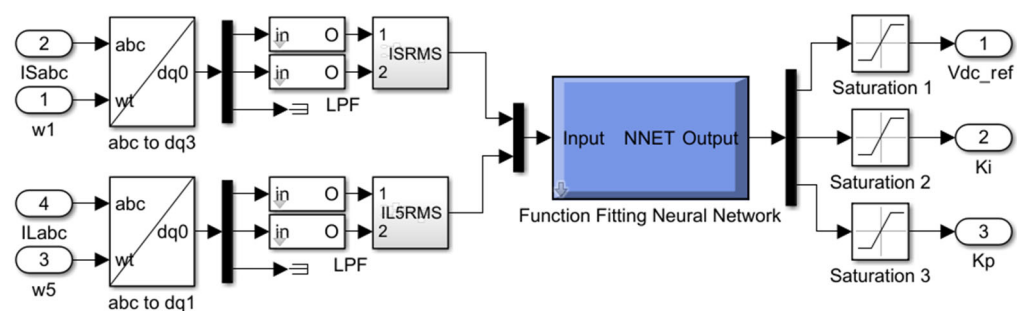
The training algorithm for this structure was selected by comparing seven candidates using repeated holdout validation. The performance metrics obtained for all seven algorithms are summarized in Table 2. Among the simulated algorithms, the Radial Basis Function (RBF) network achieved the highest average coefficient of determination (R^2 mean = 0.83), while Bayesian regularization produced the lowest average error (MSE mean = 0.156). However, the RBF network attains this accuracy only by expanding its architecture to a large number of neurons, and the resulting structure exceeds the limited memory and processing budget of the target microcontroller (MCU). The compact 12-neuron structure described above, by contrast, remains well within the MCU’s resource constraints. For this reason, the Levenberg–Marquardt (LM) algorithm was selected, which also delivered the best single-run performance observed in the study, yielding the lowest minimum error of all algorithms (MSE min = 0.001) and the second-highest maximum coefficient of determination (R^2 max = 0.673). Because the models were trained 100 times and the best-performing network was retained for deployment, these best-case metrics—rather than the ensemble averages—constitute the relevant selection criterion; it should be noted that LM exhibits comparatively high run-to-run variance (MSE std = 1.355), so its strong performance is contingent on this select-the-best procedure. The control surface graphics of the designed ANN outputs are given in Figure 4.

Table 2. ANN algorithm performance comparison.

Algorithm	MSE Mean	MSE Std	MSE Min	R Mean	R ² Mean	R ² Std	R ² Max
Radial Basis Function	1.221	1.222	0.24	0.904	0.83	0.086	0.947
Bayesian Regularization	0.156	0.952	0.001	0.588	0.477	0.063	0.658
Polynomial	3.535	0.679	1.749	0.617	0.472	0.065	0.613
Levenberg–Marquardt	1.254	1.355	0.001	0.362	0.384	0.062	0.673
Scaled Conjugate Gradient	4.676	2.34	1.543	0.307	0.335	0.049	0.537
Support Vector Regression	25.151	6.604	11.483	0.282	0.24	0.022	0.293
Gradient Descent Momentum	540.78	529.81	24.125	0.029	0.124	0.073	0.334

**Figure 4.** Output surface plots for the ANN-based adaptive V_{dc} control algorithm: (a) V_{dc_ref} ; (b) K_p ; (c) K_i .

After the ANN design for PHAPF control was completed, the adaptive DC-link voltage control algorithm given in Figure 5 was added as a block to the simulation model in Figure 2. In this way, the V_{dc_ref} , K_p , and K_i parameters were determined by the ANN in real time. Saturation blocks were then applied to the V_{dc_ref} , K_p , and K_i values at the ANN output, preventing them from reaching levels that could drive the system into instability. The saturation limits applied are $V_{dc_ref} \in [10, 100]$ V, $K_p \in [0.02, 0.1]$, and $K_i \in [10^{-4}, 10^{-3}]$.

**Figure 5.** Control block diagram for ANN-based adaptive DC-link voltage control algorithm.

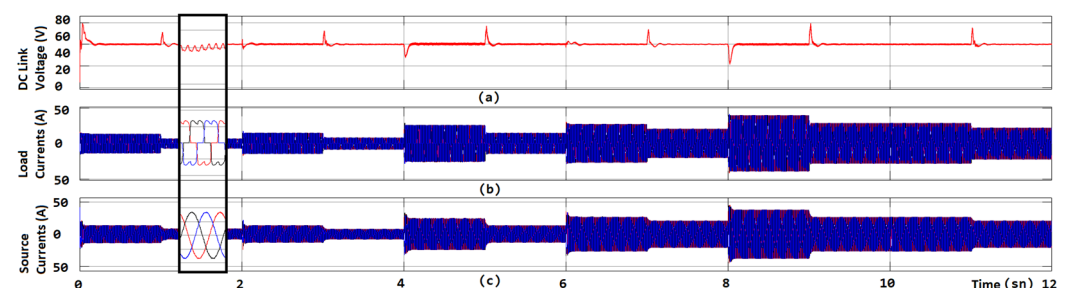
4. Simulation Studies

To evaluate the performance of the proposed ANN-based adaptive DC-link voltage controller, first, simulations were conducted for the PHAPF system using the constant V_{dc_ref} in Figure 3. The constant V_{dc_ref} values specified in Table 1 and the load parameters given in Table 3 were used, and the obtained results were recorded. While creating the 12 different load cases in Table 3, a load containing linear resistance, a nonlinear load containing a three-phase diode rectifier, and a second three-phase diode rectifier circuit combination containing a resistor and a capacitor in the dc section were used. While determining these loads, the values that were different from the training dataset and close to the loads used in the laboratory experiments were selected.

Table 3. Load test cases used in simulations.

Cases	Three-Phase Linear Load	Nonlinear Load 1 (Three-Phase Diode Rectifier + DC Side Load)	Nonlinear Load 2 (Three-Phase Diode Rectifier + DC Side Load)
1	N/A	36 Ω	N/A
2	N/A	72 Ω	N/A
3	N/A	N/A	36 Ω // 1500 μ F
4	N/A	N/A	72 Ω // 1500 μ F
5	N/A	36 Ω	36 Ω // 1500 μ F
6	N/A	72 Ω	72 Ω // 1500 μ F
7	20 Ω	36 Ω	N/A
8	20 Ω	72 Ω	N/A
9	20 Ω	36 Ω	36 Ω // 1500 μ F
10	20 Ω	72 Ω	72 Ω // 1500 μ F
11	20 Ω	N/A	36 Ω // 1500 μ F
12	20 Ω	N/A	72 Ω // 1500 μ F

Subsequently, the proposed ANN-based adaptive DC-link voltage controller was integrated into the PHAPF simulation, and simulations were performed. The simulation results of the models including constant and adaptive V_{dc_ref} are illustrated in Figures 6 and 7, and the THD values of the obtained load and supply currents are presented in Table 4. Although simulations were performed for different constant V_{dc_ref} values, and the results are given in Table 4, a single representative value was selected for comparison. Under all load conditions, the lowest average of the obtained supply current THD values, 60 V, was determined for comparison. The performance comparison was made between the 60 V constant V_{dc_ref} and adaptive V_{dc_ref} conditions.

**Figure 6.** PHAPF system simulation results ($V_{dc_ref} = 60$ V): (a) DC-link voltage; (b) load current; (c) supply current.

In order to see the PHAPF performance, the waveforms of V_{dc} , supply, and load currents obtained from simulations performed for a constant V_{dc_ref} value of 60 V are presented in Figure 6. In the graph, each load case is active for 1 s, and at the end of this period, the load in the other load case is activated. Thus, both the results of the situations and the transients can be observed. In addition, in Figure 6, the region where the highest THD value is observed is shown in detail by enlarging it in a black frame.

Figure 6 shows that the PHAPF, operating with a constant V_{dc_ref} of 60 V, successfully maintains this reference voltage. The controller was able to successfully maintain the V_{dc} reference voltage level under different load conditions. The system was able to stabilize in very short periods of time in transient regime conditions seen in load changes. In addition, the supply currents were transformed into a form close to sinusoidal, and THD values were reduced to very low levels.

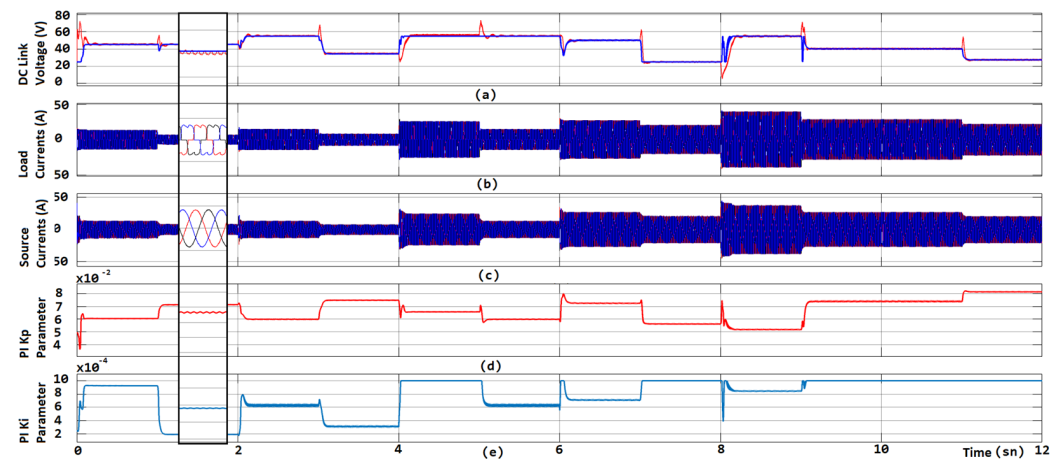


Figure 7. Simulation results for the PHAPF adaptive DC-link voltage reference voltage control algorithm: (a) DC-link voltage and ANN V_{dc_ref} estimation; (b) load current; (c) supply current; (d) ANN K_p estimation; (e) ANN K_i estimation.

Table 4. Simulation results comparison table for constant and adaptive V_{dc} control methods.

Cases	THD of Load Current (%)	THD of Supply Current (%) (Constant V_{dc_ref})							THD of Supply Current (%) (Adaptive V_{dc_ref})
		20 V	30 V	40 V	50 V	60 V	70 V	80 V	
1	24.18	11.1	4.5	1.01	0.91	0.97	1.08	1.23	0.81
2	26.07	2.08	1.07	1.13	1.31	1.55	1.79	2.03	1.16
3	27.99	18.28	11.91	2.19	1.23	1.09	1.15	1.24	1.05
4	36.48	16.31	2.24	1.39	1.37	1.61	1.83	2.1	1.6
5	21.2	18.45	12.79	8.1	2.24	0.89	0.73	0.75	1.03
6	27.99	18.23	11.91	2.17	1.23	1.1	1.14	1.26	1.04
7	10.93	4.35	0.42	0.34	0.39	0.45	0.53	0.6	0.4
8	7.87	0.36	0.34	0.41	0.5	0.59	0.7	0.78	0.25
9	13.13	10.94	7.49	3.84	0.35	0.32	0.36	0.42	0.27
10	13.1	8.2	4.78	0.35	0.38	0.45	0.52	0.6	0.31
11	13.1	8.23	4.78	0.35	0.38	0.45	0.52	0.59	0.32
12	11.56	5.2	0.35	0.4	0.49	0.57	0.68	0.78	0.31

Figure 7 presents the 12 s performance of the PHAPF system equipped with the proposed ANN-based adaptive DC-link voltage controller. In Figure 7a, the blue line represents the V_{dc_ref} and the red line represents the actual value of V_{dc} . When this graph is examined, it is seen that the ANN can determine the reference value appropriately for different load conditions and that the PI controller can successfully follow this value. When all load cases are examined, it is seen that the V_{dc_ref} values determined by the ANN vary between approximately 20 V and 60 V, and most of these values are lower than the PHAPF with a constant V_{dc_ref} value. During load transitions, short-term fluctuations occur in the V_{dc} , and the system responds quickly to reach a stable state. When the load and supply currents shown in Figure 7b,c are examined, it is seen that the supply current maintains its sinusoidal form even under variable load conditions. Among the results of all cases, the 1–2 s time interval, where the highest THD value is observed, is displayed in detail within the black frame. Despite the changes in the load currents, the preservation of the sinusoidal structure of the supply current shows that the harmonic compensation performance of the system is high. In Figure 7d,e, it is seen that the ANN dynamically adjusts the K_p and K_i parameters of the PI controller at each load change.

The harmonic distortion values in the supply current obtained as a result of simulations performed for 12 different load cases using PHAPF's constant and adaptive V_{dc_ref} are presented in Table 4. From these values, a comparative analysis of the simulation results of the 60 V constant V_{dc_ref} and adaptive DC-link voltage control system was performed.

Overall, the simulation results in Table 4 indicate that lower supply current THD values are generally obtained with the use of the adaptive DC-link voltage control algorithm. For example, as seen in Table 4, while the supply current THD value for the 60 V constant V_{dc_ref} in Case 2 is 1.55, this value is measured as 1.16 in the case where the adaptive DC-link voltage control system is used. This result shows that an improvement of approximately 25% is achieved in harmonic compensation.

An important feature of the ANN-based adaptive DC-link voltage control algorithm is its ability to adjust the V_{dc_ref} according to the load characteristics. By employing the adaptive system, lower V_{dc_ref} values can be adjusted, and lower supply current THD values can be achieved. The main reasons for the observation of lower THD values with the use of the adaptive control algorithm are having V_{dc_ref} , K_p , and K_i parameters adapted to the load conditions and better minimization of oscillations at the PI controller output. Since a lower V_{dc} reduces the voltage stress across the switching devices, a reduction in switching losses is also expected. However, converter losses, input/output power, and overall efficiency were not directly measured in this study; therefore, only a potential switching loss reduction is implied, and no experimental efficiency improvement is claimed.

A partial deactivation study was conducted to isolate the individual contributions of two adaptive quantities (DC-link voltage reference and PI gains) generated by the ANN. In this study, using the same load profiles and the same control structure, one of the quantities was fixed at its nominal value while the other was left adaptive. The results of the simulations are given in Table 5. The DC-link overshoot is defined as $OS = (\max(V_{dc}) - V_{dc_ref})/V_{dc_ref} \times 100$ within each load case; the settling time is measured from the load change to the last instant at which $|V_{dc} - V_{dc_ref}|$ exceeds 7% of V_{dc_ref} (a 7% tolerance band). The average DC-link overshoot value was calculated from data obtained with the sequential load transfer profile in Figures 6 and 7.

Table 5. Algorithm comparison table (cases 1 . . 12).

Method	Average THD (%)	Average DC-Link Settling Time (ms)	Average DC-Link Overshoot Percentage (%)
ANN-adaptive V_{dc_ref} and PI gains	0.717	83.76	47.52
ANN-adaptive V_{dc_ref}	0.69	102.33	48.771
ANN-adaptive PI gains	0.805	53.75	20.132
Polynomial Regression method	3.338	331.56	67.15
-adaptive V_{dc_ref} and PI gains	0.694	80.15	45.29
Look-Up Table method			
-adaptive V_{dc_ref} and PI gains			

When the adaptive PI effect was also implemented in addition to the adaptive DC-link voltage (fully adaptive scheme), the average DC-link overshoot decreased from 48.77% to 47.52%. This reduction was observed in ten of the twelve load steps, and the average settling time shortened from 102.33 ms to 83.76 ms. This improvement in the transient regime was accompanied by a small increase in the average source current THD from 0.690% to 0.717%. These results demonstrate that adaptively adjusting the PI parameters primarily contributes to the transient behavior of the DC-link, limiting overshoot and accelerating recovery after load changes, but at the cost of a small degradation in steady-state harmonic performance.

The ANN algorithm was compared with two simpler alternatives implemented on the same inputs and control structure, using the same dataset for ANN training: the linear interpolated Look-Up Table and the Polynomial Regression algorithm. The results of the simulations are given in Table 5. The interpolated Look-Up Table achieved an average source current THD of 0.694% and an average V_{dc} overshoot percentage of 45.29%,

which is lower than the ANN algorithm's THD (0.717%) and V_{dc} overshoot percentage (47.52%). Therefore, within the range covered by the training data, the interpolated Look-Up Table performs equivalent to or slightly better than the ANN, and it cannot be said that the ANN is a necessity due to its within-range estimation accuracy. In contrast, global Polynomial Regression is severely degraded, reaching an average THD of 3.338%. The ANN was chosen as a conscious design choice in this study, and this choice was determined by two characteristics. First, in terms of memory and scalability, according to the data obtained from the hardware-executed library, the complete set of proposed artificial neural network parameters—including network weights, biases, and normalization coefficients—consists of 78 single-precision constants, occupying only 312 bytes and stored as constant data in Flash memory. The Look-Up Table must store all independent operating points (approximately 3.9 kB for the current 197-point dataset), i.e., it utilizes significantly more memory. More importantly, while the Look-Up Table's memory grows exponentially with the number of inputs, the ANN's grows approximately linearly; this makes scaling the Look-Up Table more difficult as the input size increases, but makes the network more efficient. Secondly, regarding behavior outside the region defined by the training data, the ANN's limited and smooth activation functions provide smooth (continuous) extrapolation beyond the sampled region. In contrast, the Lookup Table, by definition, cannot generate new information outside the training grid and only clamps to boundary values through nearest neighbor extrapolation. Although the interpolated Lookup Tables yield better results in simulations, ANN was preferred due to its parametrically compact structure and flexible scalability according to input dimensions.

5. Experimental Studies

To perform laboratory experiments of the proposed algorithm, the 5 kVA three-phase PHAPF setup, whose photograph is given in Figure 8, was constructed and tested using the load parameters listed in Table 6. The system was supplied in a controlled manner via a three-phase variac. For the 7MBP50RJ120 IPM module with 1200 V, 50 A values were used in the power stage of the PHAPF. Current measurements were performed with LA100-P hall-effect sensors.

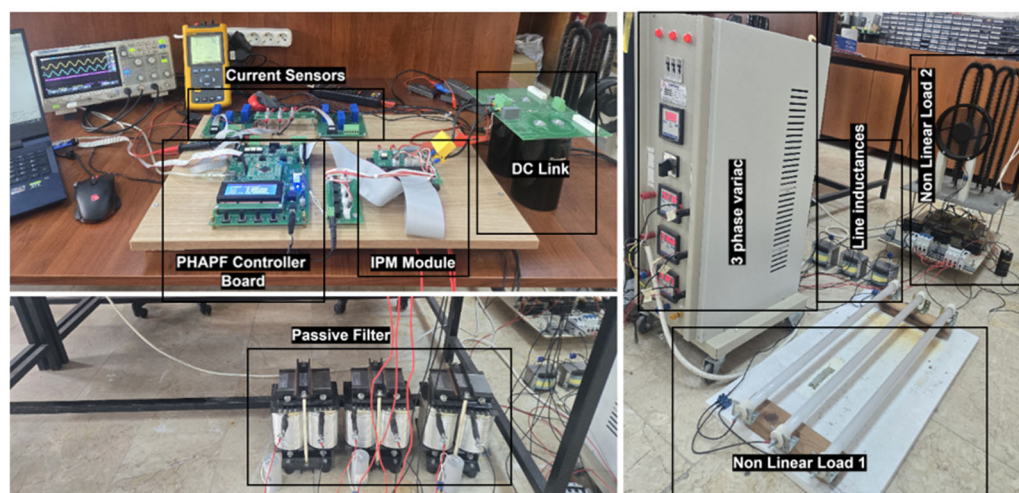


Figure 8. Image of the designed PHAPF experimental study setup.

Table 6. Load test cases used in the experiments.

Cases	Nonlinear Load 1	Nonlinear Load 2
1	N/A	78 Ω // 1500 μ F
2	N/A	36 Ω // 1500 μ F
3	66 Ω	36 Ω // 1500 μ F
4	66 Ω	78 Ω
5	N/A	36 Ω
6	66 Ω	36 Ω
7	66 Ω	78 Ω // 1500 μ F
8	66 Ω	N/A

The PHAPF control board was built around the STM32F407VGT6 ARM microcontroller from STMicroelectronics, operating at a clock frequency of 168 MHz. The board integrated an LCD display, control buttons, USB communication ports, and signal-conditioning circuits for current and voltage measurements. The embedded firmware was developed in C using the STM32CubeIDE 2.2.0 environment.

The proposed ANN-based controller was implemented using single-precision floating-point arithmetic, with the corresponding operations executed on the hardware floating-point unit (FPU). To distribute the computational load across the control cycle, the ANN library was partitioned into segments so that its full evaluation is completed over 24 successive calls. At each call, the index of the sector to be processed is passed to the routine as a parameter, and the network outputs are updated only after the final sector has been executed.

The complete set of proposed ANN parameters, including the network weights, biases, and normalization coefficients, comprises 78 single-precision constants that occupy only 312 bytes, stored as constant data in Flash memory. The ANN state structure requires just 80 bytes of RAM. At the system level, the entire project consumes approximately 65.8 KB of Flash memory and roughly 24.6 KB of RAM in total. Consequently, the ANN's contribution to the overall memory footprint is negligible.

The inverter is switched using a fixed 20 kHz edge-aligned PWM scheme. Two 12-bit ADCs operate in continuous scan mode with circular DMA transfer at a 21 MHz ADC clock. These units continuously sample the V_{dc} , load current, source current, and load voltages, storing them in the corresponding variables. The control algorithm reads these values from their respective registers as required during execution.

The control algorithm is invoked by a timer interrupt running at 50 kHz. In each cycle, the PI control for V_{dc} regulation, the PLL, harmonic extraction, digital filtering, and reference-generation operations are computed. Within the same cycle, only a single sector of the ANN is executed; once the final sector is completed, the V_{dc_ref} , K_p , and K_i parameters are updated. In this way, the ANN computation is completed without exceeding the 50 kHz cycle time. In addition, saturation limiters were applied to the reference values generated by the ANN to ensure that they remain within physically meaningful and stable ranges: $V_{dc_ref} \in [10, 100]$ V, $K_p \in [0.02, 0.1]$, and $K_i \in [10^{-4}, 10^{-3}]$.

All parameters utilized in the experiment correspond to the system values listed in Table 1. The experimental study was carried out in two primary stages. In the first stage, PHAPF was evaluated for the loads in Table 6 using 60 V constant V_{dc_ref} and $K_i = 0.0004$, $K_p = 0.05$ PI control parameters. In the second stage, the same tests were repeated by activating the ANN-based adaptive DC-link voltage control in PHAPF. In both stages, experiments were carried out under different load combinations and load-change cases to verify the simulation findings.

5.1. PHAPF Experiments Using Constant V_{dc_ref}

As a result of the experiments conducted for the PHAPF system using a constant V_{dc_ref} , the oscilloscope graphs of the load current, supply current, and V_{dc} obtained during operation under the load condition in Case 1 are given in Figure 9 for the steady-state condition. The experimental results when the load was changed from Case 1 to Case 2 were recorded for the purpose of examining the transient response and are shown in Figure 10. Additionally, Figure 11 displays screenshots of the power analyzer measuring device showing the supply current THD values obtained as a result of the experiments performed for each load condition.

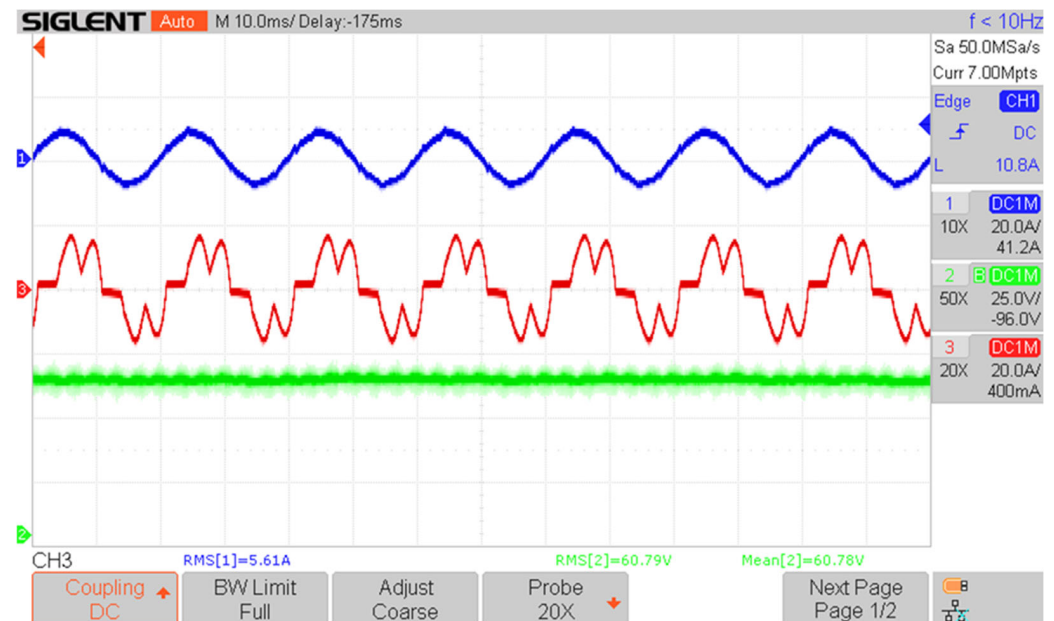


Figure 9. Experimental results of the PHAPF system under constant V_{dc_ref} for Case 1: (blue) supply current; (red) load current; (green) DC-link voltage.

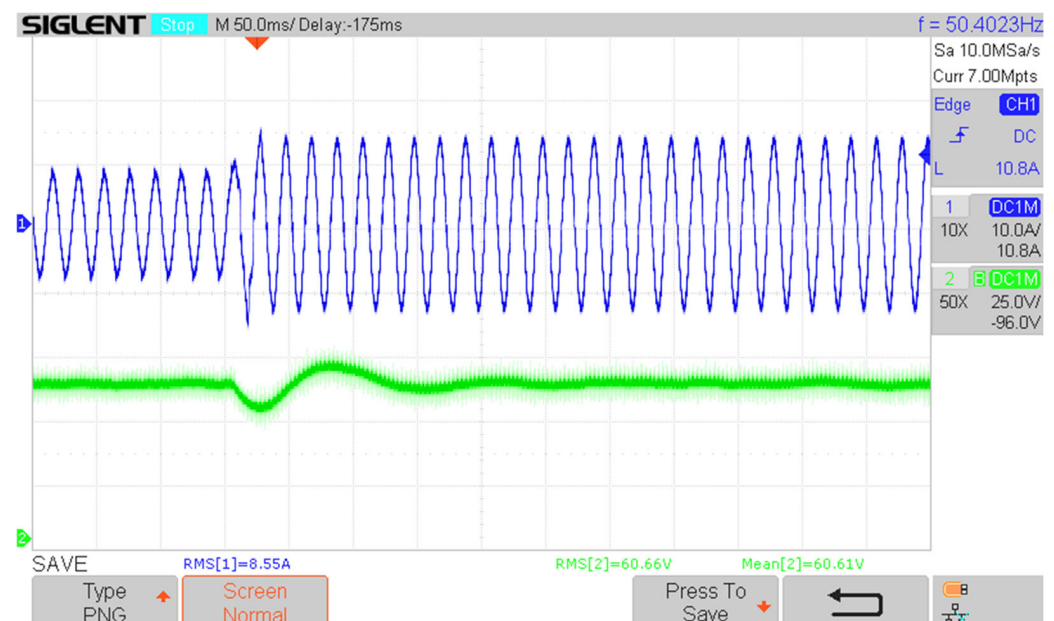


Figure 10. Transient response of the PHAPF system under a constant V_{dc_ref} : (blue) supply current; (green) DC-link voltage.

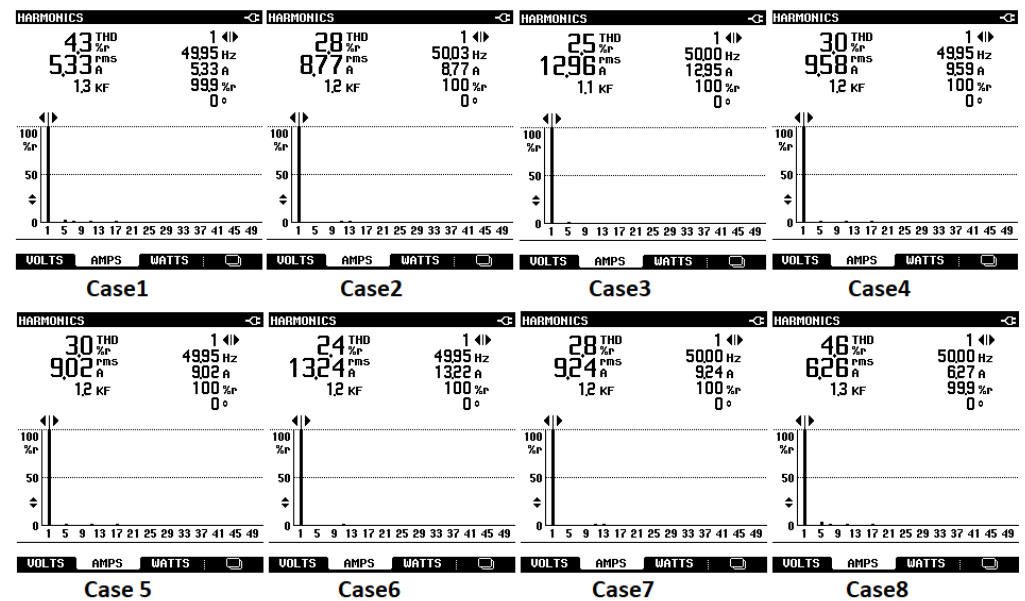


Figure 11. Supply current THD values obtained from experiments of PHAPF using a constant V_{dc} reference voltage for each load case.

The oscilloscope images presented in Figure 9 show the performance of PHAPF using a constant V_{dc_ref} . In the test condition (Case 1) where a three-phase diode rectifier and a $78\ \Omega$ resistor are used as loads and a $1500\ \mu\text{F}$ capacitor connected in parallel, it is observed that the supply current (blue signal) is quite close to the sinusoidal form and the V_{dc} (green signal) remains stable at 60 V. These results demonstrate the DC-link voltage stability and effective harmonic suppression performance of the system.

The oscilloscope images presented in Figure 10 show the transient response of the load when it is changed from Case 1 to Case 2. After this change, the rms value of the supply current in the steady state is measured as 8.55 A and the average value of the V_{dc} as 60.61 V. As shown in the oscilloscope image, there is a slight decrease in the V_{dc} at the time of the load change, and the PI controller responds in approximately 150 ms and returns the voltage to the reference value.

The supply current maintained its sinusoidal form despite the load change, which shows that the PHAPF system using a constant V_{dc_ref} maintains its harmonic suppression performance in the transient regime. Power analyzer measurements for all load cases given in Table 6 are presented in Figure 11.

5.2. PHAPF Experiments Using ANN-Based Adaptive DC-Link Voltage Controller

All experiments performed for PHAPF using constant V_{dc_ref} were repeated by activating the ANN-based adaptive DC-link voltage control algorithm. Oscilloscope graphs taken during steady-state operation for load condition in Case 1 are given in Figure 12, and oscilloscope graphs of transient response during load transition from Case 1 to Case 2 are given in Figure 13. Supply current THD measurements performed with a power analyzer as a result of experiments performed for all load conditions are presented in Figure 14.

When the experimental results of the PHAPF system for the Case 1 load given in Figure 12 are examined, it is observed that the supply current maintains the sinusoidal form and the V_{dc} is generated and monitored as 42.55 V.

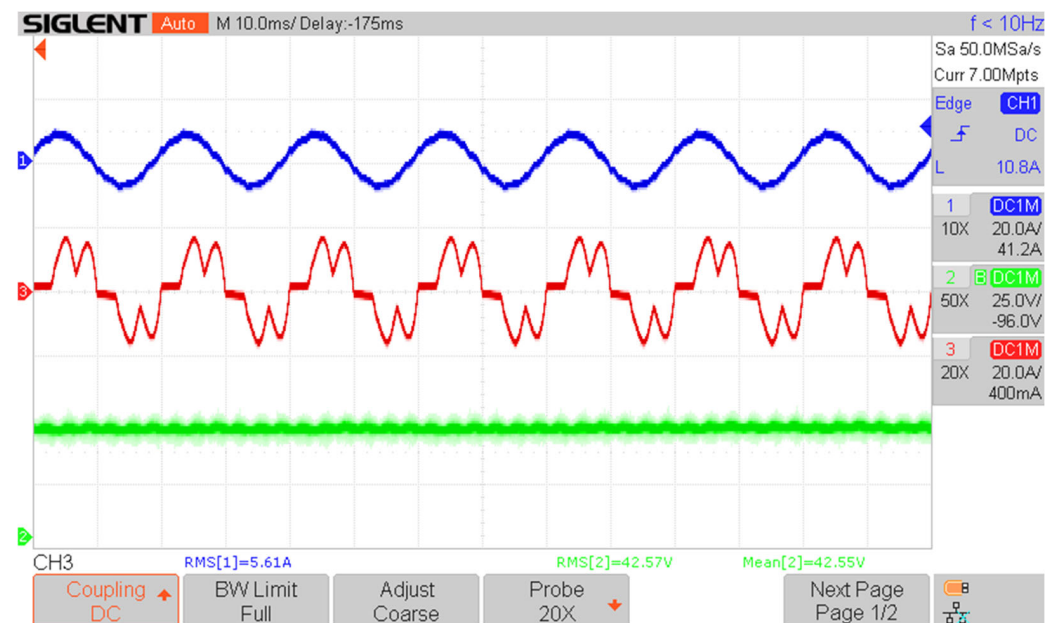


Figure 12. Experimental results of the PHAPF system using ANN-based adaptive V_{dc} for Case 1: (blue) supply current; (red) load current; (green) DC-link voltage.

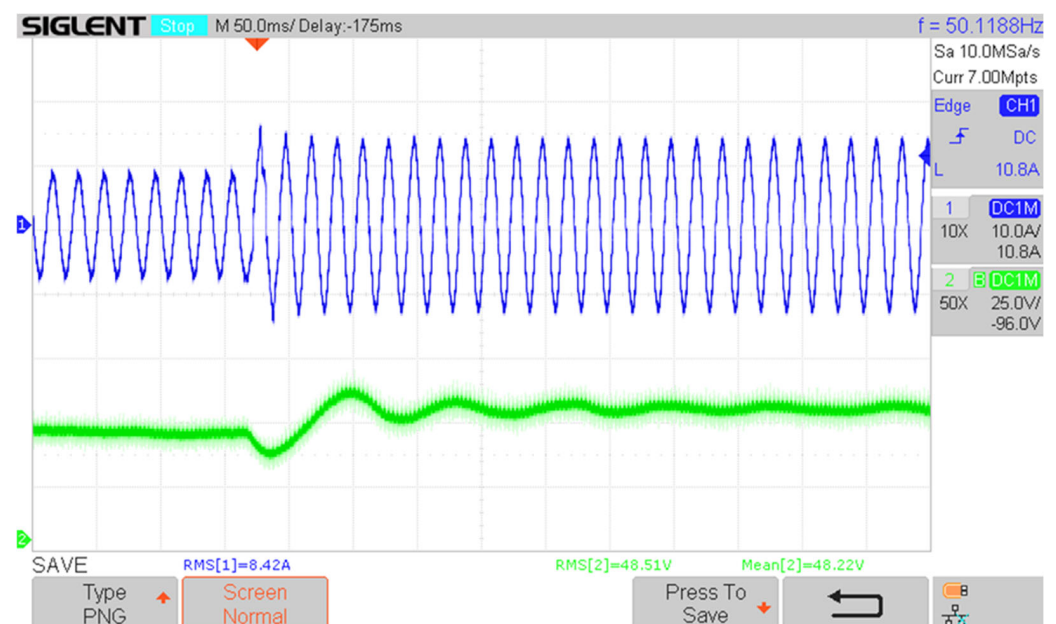


Figure 13. Transient response of the PHAPF system when the ANN-based adaptive V_{dc} algorithm is used: (blue) supply current; (green) DC-link voltage.

As seen in the oscilloscope images presented in Figure 13, the V_{dc} is constant at an average of 43 V before the load change. When the load was changed from Case 1 to Case 2, the adaptive system increased the V_{dc_ref} value from 45 V to 50 V. The PI controller achieved this new reference value in approximately 180 ms. Since the ANN-based adaptive V_{dc} algorithm can produce a different reference value at different load transitions, it may exhibit a slower response time compared to systems using constant V_{dc_ref} .

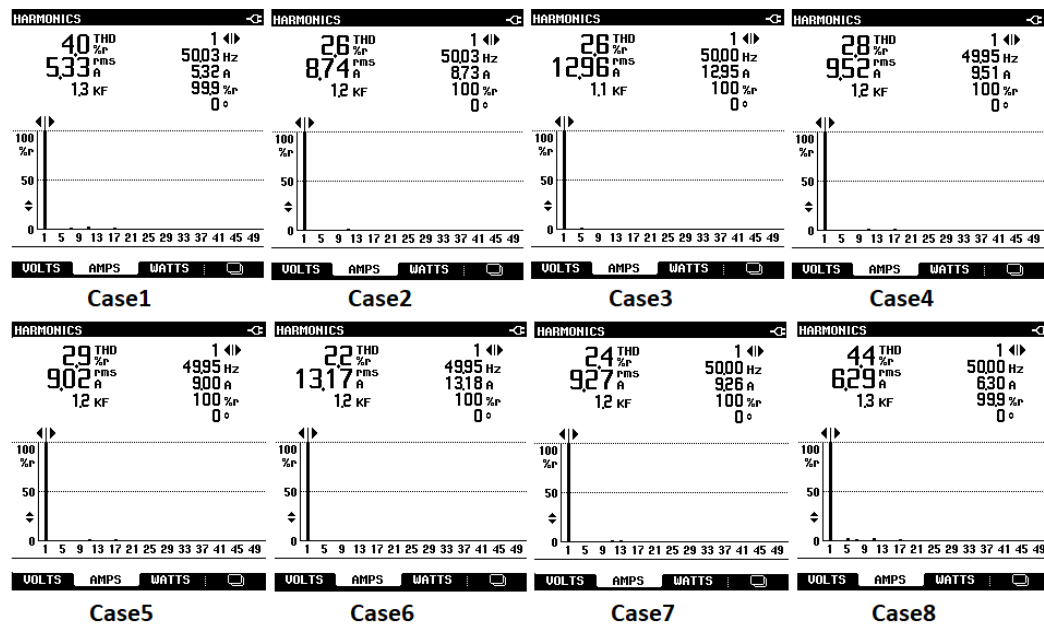


Figure 14. THD values of PHAPF using ANN-based adaptive DC-link voltage controller.

5.3. Comparison of PHAPF Experimental Results Using Constant and Adaptive DC-Link Voltage Control

Table 7 summarizes the supply current THD results obtained across eight distinct experimental load scenarios. It is seen that using the PHAPF system with ANN-based adaptive V_{dc} control provides similar or better supply current THD values than the results of the PHAPF system with constant V_{dc_ref} . It was observed that the PHAPF using ANN-based adaptive V_{dc} is more successful than the PHAPF system using constant V_{dc} (60 V), especially when it produces low reference voltage levels (40–55 V).

Table 7. Comparison table of PHAPF experimental results using constant and adaptive DC-link voltage control.

Cases	THD of Load Current (%)	THD of Source Current (%) (Constant V_{dc_ref})	THD of Source Current (%) (Adaptive V_{dc_ref})	Output Reference Voltage of Adaptive V_{dc_ref} Algorithm (V)
1	35.6	4.3	4	40
2	28	2.8	2.6	50
3	23.8	2.5	2.6	60
4	23.34	3	2.8	50
5	23.7	3	2.9	55
6	21.16	2.4	2.2	65
7	27.2	2.8	2.4	55
8	25.3	4.6	4.4	40

Considering all experimental cases, it is seen that the adaptive system can determine the approximately optimal V_{dc_ref} value for each load condition and improve the system performance by avoiding unnecessarily high voltage levels. In addition, the adaptive system can use lower V_{dc_ref} values compared to the PHAPF using constant V_{dc_ref} operating under the same conditions while achieving low supply current THD values. The reduced DC-link voltage is expected to alleviate voltage stress across the power switches and reduce switching losses.

6. Conclusions

In this study, an ANN-based adaptive DC-link voltage control algorithm for PHAPF was developed and experimentally validated. The proposed ANN determines both the DC-link reference voltage and the PI controller gains from the load current components. Simulation and experimental tests confirmed that the adaptive DC-link voltage control algorithm yields lower supply current THD levels in most operating scenarios compared to the PHAPF structure using constant V_{dc_ref} . A 5 kVA PHAPF was designed and used for experimental verification. Experimental results demonstrated that while the current THD load reached up to 35.6%, the proposed adaptive control algorithm successfully suppressed the source current THD below the 5% international standard limit across all tested cases, achieving values as low as 2.2%. Furthermore, the adaptive algorithm dynamically adjusted the DC-link voltage reference between 40 V and 65 V according to the load conditions, allowing operation at lower DC-link voltage levels under low-power operating conditions, which is expected to alleviate voltage stress across the power switches and reduce switching losses. Future studies will focus on optimizing the ANN structure for dynamic transient states and testing the algorithm under highly unbalanced load conditions.

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