

POWER FACTOR CORRECTION OF UNBALANCED UTILITY ELECTRICAL NETWORK FEED MATRIX CONVERTER-BASED NONLINEAR LOAD THROUGH SERIES ACTIVE FILTERING

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ABSTRACT

To rectify power factor in utility systems, this article proposes a three-phase matrix converter with active filtering. The active filter, instead of being used as a variable impedance that improves the voltage profile and power factor, would be more effective in this situation as a voltage-source compensator. A nonlinear, imbalanced model of the utility system is proposed to improve upon the current linear model. Improving the power factor in utility systems and expanding the dynamical modelling of matrix converters are the primary goals of this effort. By adjusting the PI controller, we can sort the voltage profiles unevenly, reduce harmonics in the source current, and maintain the load voltage at optimal power factor. This article discusses the active filter and its reference-controlled method as a voltage compensator, harmonic suppressor, and power factor corrector. Theoretically, compensatory signals are generated using the synchronous reference frame (SRF) principle. The switches of the voltage source inverter will be turned on and off by the SPWM built. The MATLAB/SIMULINK Toolset is used to implement the dynamical simulations.



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I. INTRODUCTION

It is clear that electronic equipment is becoming increasingly important in many aspects of daily life. Power utility lines experience sags and bulges due to the unbalanced impedances caused by this electronic equipment that drives big machinery. This might cause problems such as poor power factor, flicker, voltage distortion, electromagnetic interference, and so on. Researchers and engineers working in power electronics are tasked with finding solutions to these disturbances to compensate for them [1], [2]. Industries could also experience issues, such as system malfunctions or plant shutdowns, due to this PQ disruption. L. Gyugyi [3] first developed the idea of an active power filter in the 1970s. The layout, size, management, and fitting of active power filters are still areas where research is heading in diverse directions.

According to H. Akagi [4], there are three active forms of the APF rule approach that address different real-time engineering problems: The identification of voltage, the discovery of supply current, and the revelation of load current. In [5], the topic of power factor in the utility system is covered, along with international norms, regulations, and suggestions. Most modern medium-power operated grids use voltage levels between 2.3 and 6.9 kilovolts, making traditional topology-based VSIs built with power semiconductor technology unsuitable. Here is a concept that uses a matrix converter-based nonlinear load and an active filter to augment the aforementioned problem and tackle this engineering issue. To generate the pulses required by the active filtering device, SRF theory is used, while the SPWM approach is used to create the reference signal [6]. The block diagram shown in Figure 1 represents the suggested analysis.

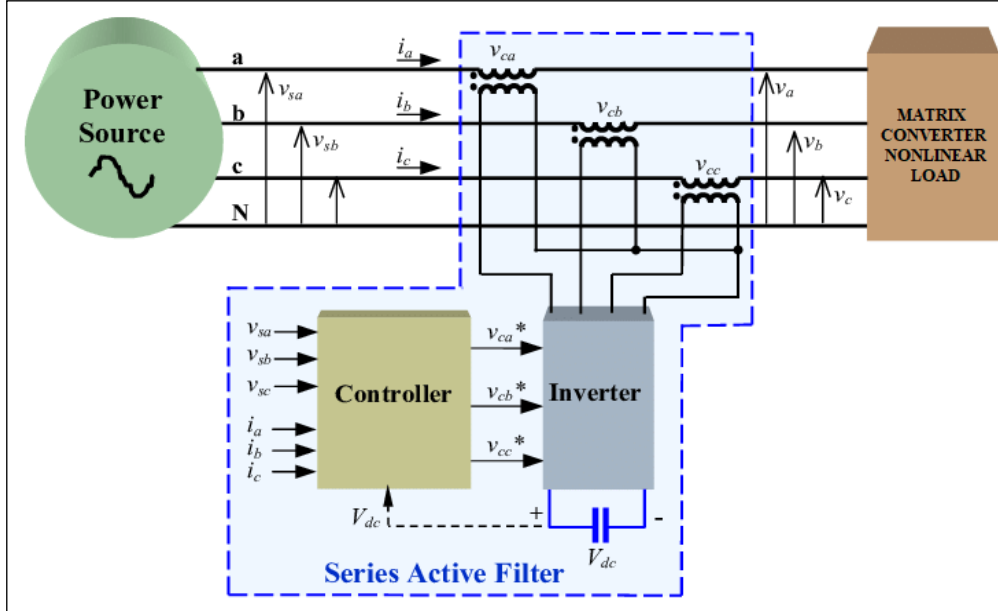


Figure 1: Active Power Filter Compensation Features for Nonlinear Matrix Converter Loads.
Source: Authors, (2026).

Prior to improving the aforementioned voltage fluctuations using the developed SRF theory, the proposed study focuses on applying a matrix converter-based nonlinear load with an active filter for power-factor correction [7]. By using an optimization approach such as PSO, the K_I and K_P gains of the PI controller may be acquired. At a carrier frequency of 1 kHz, Sinusoidal Pulse Width Modulation (PWM) is recommended for the VSI switching [8]. To power the active filter, a passive energy storage device is also used. By running dynamical simulations in the MATLAB/SIMULINK toolbox, we can compare the outcomes with other situations or different AI methodologies.

II. SYSTEM SPECIFICATIONS

The simulation of a three-phase (3- Φ) 415V, 50Hz power supply is performed in MATLAB. Additionally, the simulation includes a transmission utility with a nonlinear load and a DVR system. DVR Design Parameters: The DVR design involves determining key specifications, including voltage and current ratings, CSI power capacity, DC bus voltage, transformer specifications, and filter configuration, as outlined below [9]. Voltage management using a Dynamic Voltage Restorer (DVR): Under non-ideal conditions, the DVR determines the required voltage injection:

$$V_c = \sqrt{V_s^2 - V_L^2} \quad (1)$$

The transformer's KVA rating: As a result of the fact that the injection transformer has to be rated in accordance with the DVR, the following formula is used to calculate its KVA rating:

$$S = (3V_s * I_s)/1000 \quad (2)$$

Voltage across the DC capacitor: The voltage across the DC capacitor can be calculated using the relationship shown below.

$$V_{dc} > \sqrt[3]{2} * V_{DVR} \quad (3)$$

DC bus capacitance of the CSC: The DC link capacitance in a Current Source Converter (CSC) is evaluated during energy transitions using the following approach:

$$E = \frac{1}{2} * C_{DC} (V_{dc}^2 - V_{dc1}^2) \quad (4)$$

Where V_{DC} represents the bus voltage at the DC side, and the fluctuation in bus voltage at the DC side that occurs during a disturbance is denoted by the symbol V_{DC1} .

$$P * \Delta t = \frac{1}{2} * C_{DC} (V_{dc}^2 - V_{dc1}^2) \quad (5)$$

Where $P = 3 * V_C * I_s$

Filter Parameters: A thoughtfully designed filter can efficiently eliminate disturbances originating from the DC side of the CSI from the injected voltage. The ripple filter is composed of a resistor (R_r) and a capacitor (C_r) connected in series.

$$f_r = \frac{1}{2 * \pi * R_r * C_r} \quad (6)$$

The resonant frequency (f_r) is typically half the switching frequency, which typically ranges from 5 kHz to 20 kHz.

Table 1: Characteristics of a Series Compensation Mechanism.

Parameters	Values
Input Voltage Supply	415V, 50Hz
Transmission Line impedance	$L=5\text{mH}$, $R=0.1\Omega$
Filter Component Values	$C=1\mu\text{F}$, $R=5\Omega$
DC Link voltage of DVR	280V
Modulation Switching Rate	1KHz
Series Transformer Capacity	1KVA, 200V/300V

Source: Authors, (2026).

III. CONTROL STRATEGY

III.1 SYNCHRONOUS REFERENCE FRAME (SRF) THEORY

The flowchart in Figure 2 illustrates the operational sequence of a Dynamic Voltage Restorer (DVR) for mitigating voltage sag in a power distribution system. The process starts by reading the source voltage (V_s) and load voltage (V_l). A fault or sudden load is applied to simulate disturbances in the system [10]. The voltage at the load end (V_k) is then monitored to determine whether voltage compensation is necessary. If V_k equals V_l , no voltage sag is detected, and the DVR remains inactive ($V_{dvr} = 0$). If V_k is not equal to V_l , the system checks if a voltage sag has occurred. Upon detecting a sag, the DVR injects the missing voltage ($V_{dvr} = V_{sag}$) to restore the load voltage to its nominal value ($V_l = V_k + V_{sag}$). If no sag is present, the system performs no corrective action. This control strategy enhances power quality by dynamically compensating for voltage sags, thereby improving the reliability of sensitive loads in distribution networks. The process is implemented and simulated using MATLAB/Simulink for validation.

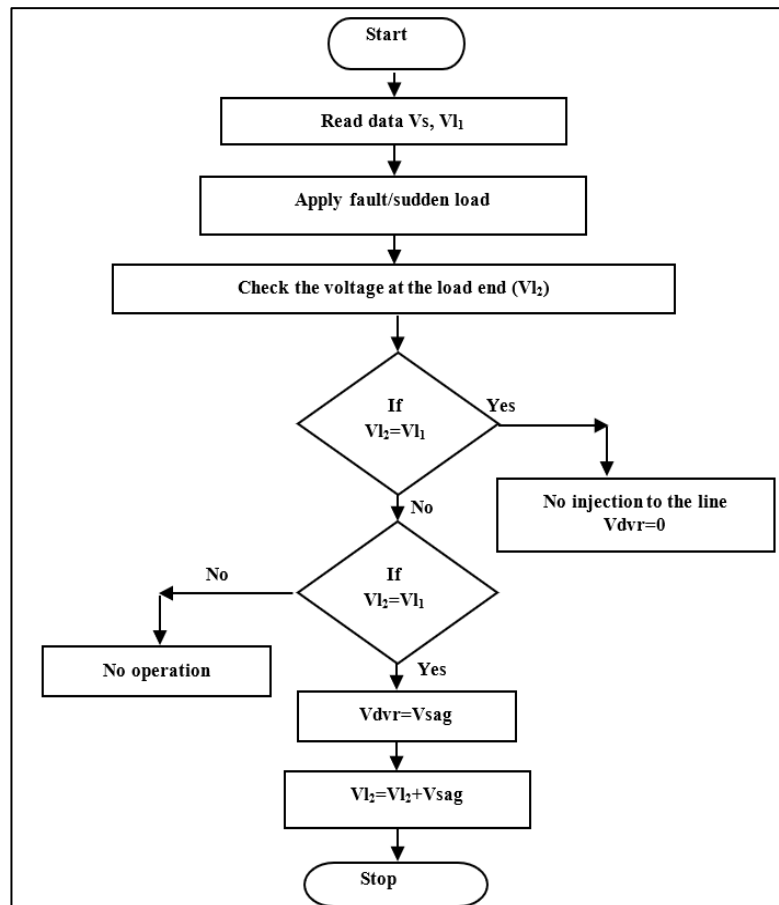


Figure 2: Diagram depicting the DVR control system.

Source: Authors, (2026).

The block diagram in Figure 3 illustrates the control strategy of a Dynamic Voltage Restorer (DVR) using a d-q reference-frame transformation [11]. This scheme is designed to mitigate voltage sag and enhance power quality in a distribution system. The three-phase source voltages (v_{sa} , v_{sb} , v_{sc}) are transformed into the d-q reference frame using the Park transformation. This transformation separates the direct-axis (v_{sd}) and quadrature-axis (v_{sq}) voltage components, facilitating independent control of active and reactive power. The transformed d-q components are processed through low-pass filters (LPFs) to extract the fundamental components while eliminating high-frequency harmonics. The DC voltage regulation loop monitors and regulates the DC link voltage (v_{dc}), ensuring proper DVR operation. A three-phase PLL extracts the system phase angle ($\cos\theta$, $\sin\theta$), ensuring synchronization between the injected compensating voltage and the supply voltage [12]. The PLL also tracks the system frequency to maintain stability.

A PI controller compares the reference voltage (v_L^*) with the measured load voltage (v_L) to generate an error signal. The computed compensating voltage (v_{dvr}) is transformed back to the abc reference frame. The reference voltages (v_{La}^* , v_{Lb}^* , v_{Lc}^*) are processed by a PWM-based voltage-controlled inverter to generate gate pulses for the DVR's Voltage Source Converter (VSC). The VSC injects the required compensating voltage into the system, restoring the load voltage to its nominal value. Figure 3 shows the SRFT block diagram. Using either the dq0 or Park's transformations [13] ensures that the power invariance remains intact. Equations (7) to (8) provide a mathematical illustration of this.

$$\begin{bmatrix} f_{qs} \\ f_{ds} \\ f_{0s} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \end{bmatrix}$$

$$(f_{qd0s}) = KF_{abs} \quad (7)$$

$$(F_{abs}) = K^{-1}(f_{qd0s})^T \quad (8)$$

$$K^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix}$$

Where ' f ' can represent a voltage.

The general, arbitrary rotating reference frame is advantageous over a specific, particular reference frame. Hence, the voltage equation (V_{sa} , V_{sb} , V_{sc}) of the abc reference is transformed into the stationary dq reference frame (V_d , V_q) (where d represents active and q represents unutilized power component). The direct- and quadrature-axis voltage components are given in (9) and (10).

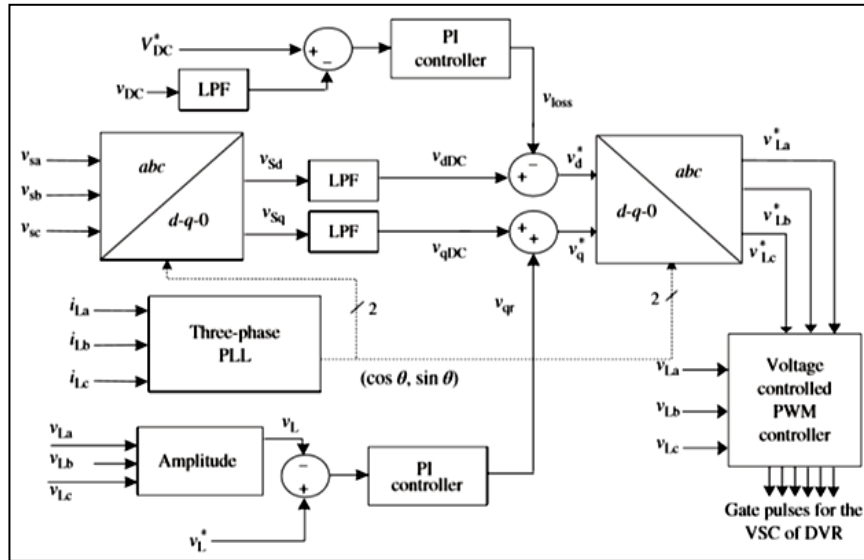


Figure 3: SRFT Control block of DVR.

Source: Authors, (2026).

Additionally, it will be evaluated in relation to the DC-link fault. To determine the actual voltage to inject into the utility system, the error derived from the DC link voltage is used. This voltage is in phase with the line current. The PI controller is used to reduce steady-state error and improve transient performance, ultimately improving the delay-time responsiveness of the utility system. To obtain utility, similar components (V_{sabc}^*) are used. To determine the change in abnormality that must be compensated for, the difference between the reference signals and the actual signals (V_{labc}) is used [14]. The change in signal collected in this manner is then used to activate the VSI switches.

III.2 MATRIX CONVERTER

There is a steady rise in the number of high-power applications being used in today's world. It has been decided to take into account research on high nonlinear phenomena-based matrix converter-based nonlinear loads in the distribution-side utility system to investigate the impacts of power factor [15]. Because of this, the issue can be investigated using a matrix converter in place of a traditional nonlinear load. An illustration of a typical matrix converter topology is shown in Figure 4. The matrix converter is a single-stage converter that is made up of bidirectional switches and is constructed as an array of $m \times n$ bidirectional power switches. Two fast diodes that are linked in anti-parallel to IGBTs are used in the construction of the bidirectional switches that are utilized in matrix converters [16].

In a hypothetical scenario, the number of information stages, denoted by m , should be somewhere in the vicinity of three, whereas the number of yield stages, denoted by n , may be anywhere from one to an infinite number. Figure 4 illustrates the critical network-converter geography connecting a three-stage voltage source to a three-stage load. This connection is crucial to the network's operation. In accordance with a helpful viewpoint, this is the primary framework for geography. Additionally, a network converter is a limitless-recurrence transformer, meaning it can generate a frequency that is either higher or lower than the converter's input frequency. To construct the yield voltage waveforms, selected sections of the information voltage waveforms are sorted individually.

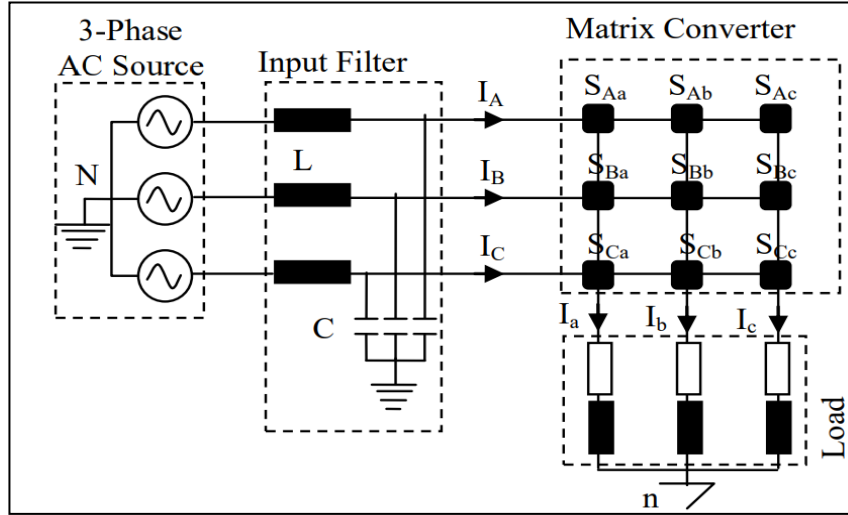


Figure 4: Single line diagram of three phase Matrix Converter nonlinear load with supply and filtering system.
Source: Authors, (2026).

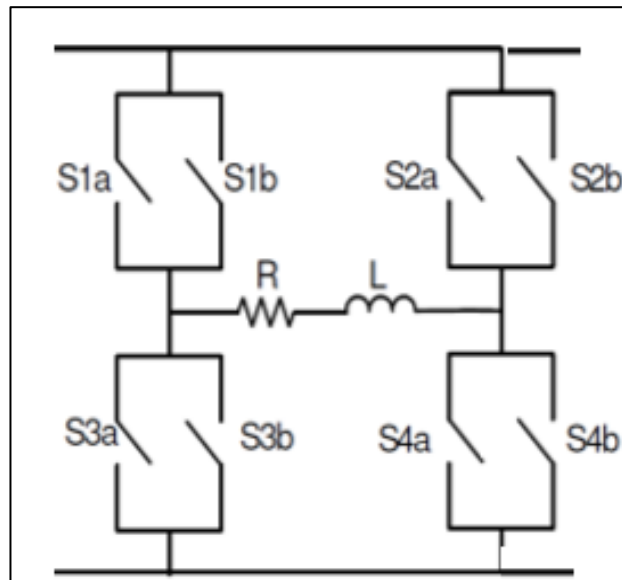


Figure 5: Single line diagram of basic Matrix Converter switch S_{Aa} illustration.
Source: Authors, (2026).

III.3 PI CONTROLLER AND PROPOSED PSO ALGORITHM

The single goal minimization of current harmonic distortion (THD), voltage sag, and error voltage in source current is the concept that is proposed in this study. Therefore, the single-objective fitness function may be expressed in the following manner:

$$F = f(I_{THD}) + f(Vsag) + f(Vdc) \quad (9)$$

For the considered goal function, the K_p and K_i gains of the PI controller are selected as the ideal tuning parameters. The following equation best describes the excitation and response relation of the PI controller:

$$G_c(s) = k_p + \frac{k_i}{s} \quad (10)$$

The block diagram illustrates a Particle Swarm Optimization (PSO)-tuned Proportional-Integral (PI) Controller for optimizing the performance of a dynamic system represented by (s) . The control strategy begins with error computation, where the reference input is compared with the system output to generate an error signal, which is then processed by the PI controller. The PI controller comprises a proportional gain (K_p) and an integral gain (K_i), both optimised using PSO to achieve optimal system performance by minimising an objective function, such as error reduction, overshoot, or settling time. The controller output is applied to the system (s) , and the resulting output is fed back for comparison with the reference input, forming a closed-loop control mechanism. Traditional PI controllers require manual tuning, which can be time-consuming and suboptimal, whereas PSO automates tuning, yielding faster response, reduced overshoot, and improved system stability [17]. This approach finds applications in power system stability enhancement, voltage and frequency control, industrial process control, and renewable energy system optimization. The proposed control strategy is implemented and simulated using MATLAB/Simulink, demonstrating its effectiveness in improving system performance.

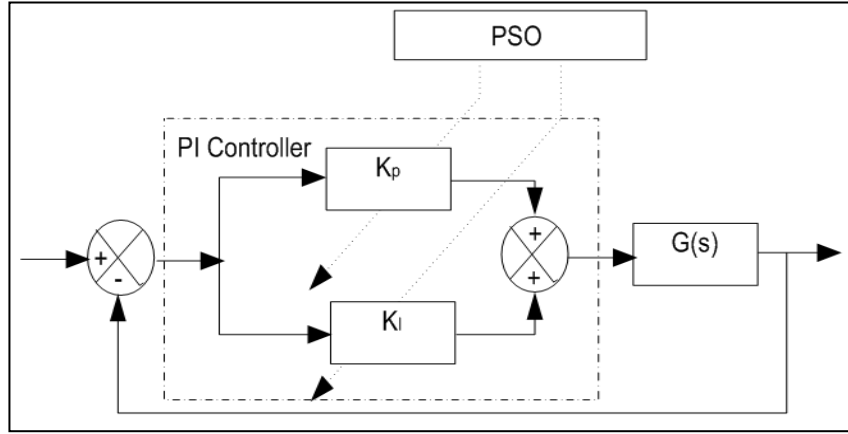


Figure 6: PI controller mechanism illustration.
Source: Authors, (2026).

The response of the PI controller $u(t)$ is specified by:

$$u(t) = k_p e(t) + k_i \int_0^t e(t) dt \quad (11)$$

The flowchart in Figure 7 represents the step-by-step process of the Particle Swarm Optimisation (PSO) algorithm, a nature-inspired metaheuristic technique for solving optimisation problems [18], [19]. PSO is based on the social behavior of particles (agents) moving within a defined search space to find an optimal solution by iteratively updating their positions and velocities based on their own experience and that of their neighbours.

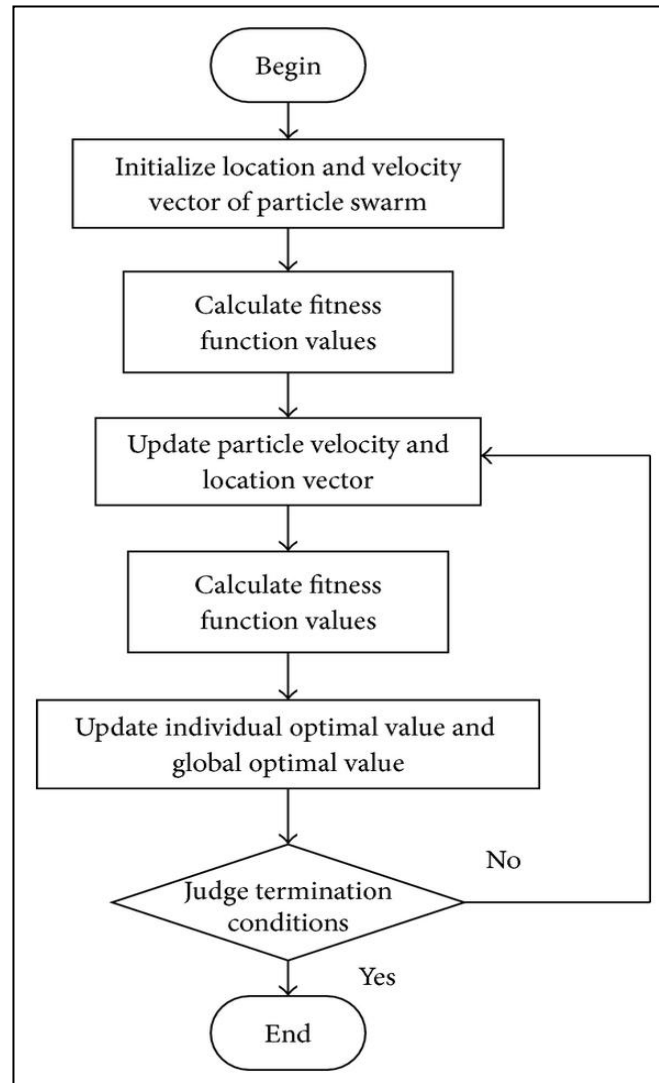


Figure 7: Flowchart of the PSO algorithm.
Source: Authors, (2026).

The process begins by initialising the location and velocity vectors for a swarm of particles. Each particle evaluates a fitness function, which quantifies how well its current position satisfies the optimization objective. The velocity and position of each particle are then updated based on both the individual best position found by the particle and the global best position discovered by the swarm. The fitness function is recalculated after each update, and the particles continue to search for better solutions. The algorithm iterates through these steps until a predefined termination condition is met, such as reaching a maximum number of iterations or achieving a desired level of accuracy, at which point the process ends.

IV. SIMULATION RESULTS

The MATLAB environment was used to run the simulations. Power factor correction and current harmonics are components of power quality disturbances highlighted in this article. The presence of nonlinear loads based on matrix converters results in poor power factor and current disturbances, such as harmonics. The imbalance in the source voltage is produced by a programmable voltage source [20], and harmonics are artificially generated and injected into the utility system via a matrix converter. Figure 8 illustrates a voltage source inverter (VSI) with an energy-storage-based active filter applied to the power transmission line.

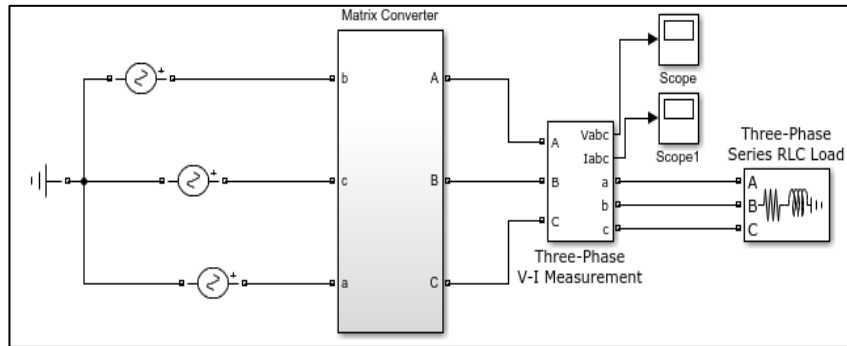


Figure 8: MATLAB/Simulink depiction of the Matrix Converter to examine the non-linear load mechanism.
Source: Authors, (2026).

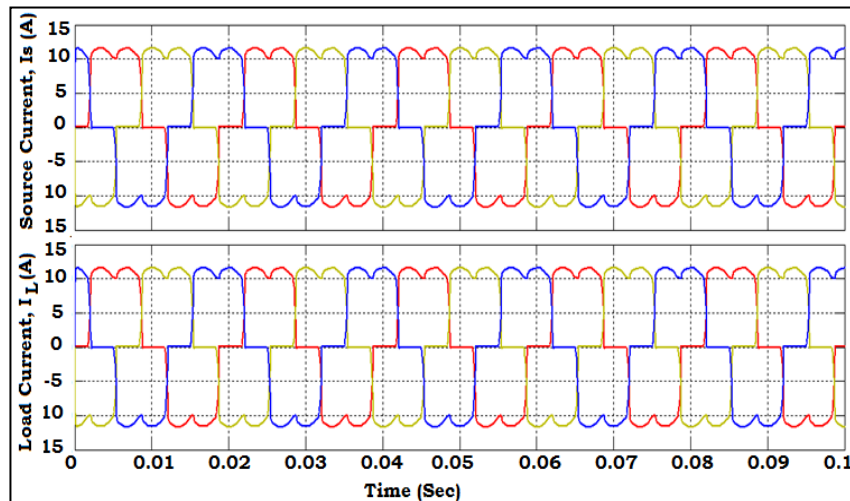


Figure 9: Illustration of the nonlinear load source and load current performance of the transmission line under consideration.
Source: Authors, (2026).

According to the Fourier analysis shown in Figure 10, the source current of the dynamic utility results in a total harmonic distortion (THD) of 222.9% when the filter is not taken into consideration.

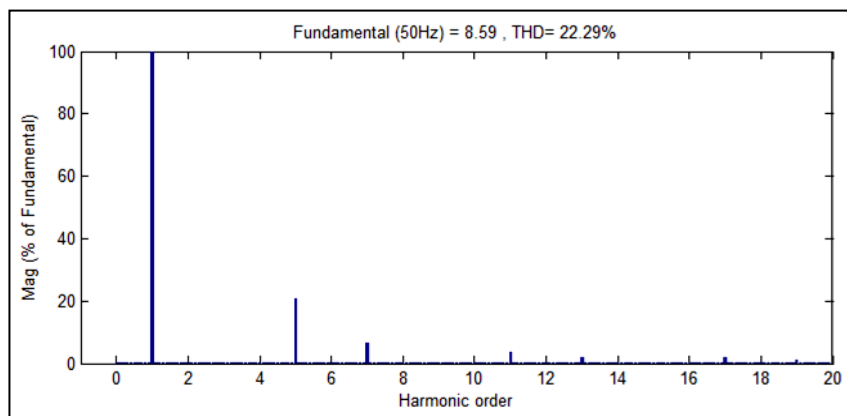


Figure 10: THD representations without series Active filter.
Source: Authors, (2026).

Using AF that is based on a matrix converter, the total harmonic distortion (THD) of the source current for a manually tuned PI controller ($K_P=1$ and $K_I=1$) is decreased to 4.17%, as shown in Figure 11. This is where the reference compensating current conflicts with the instantaneous PQ hypothesis.

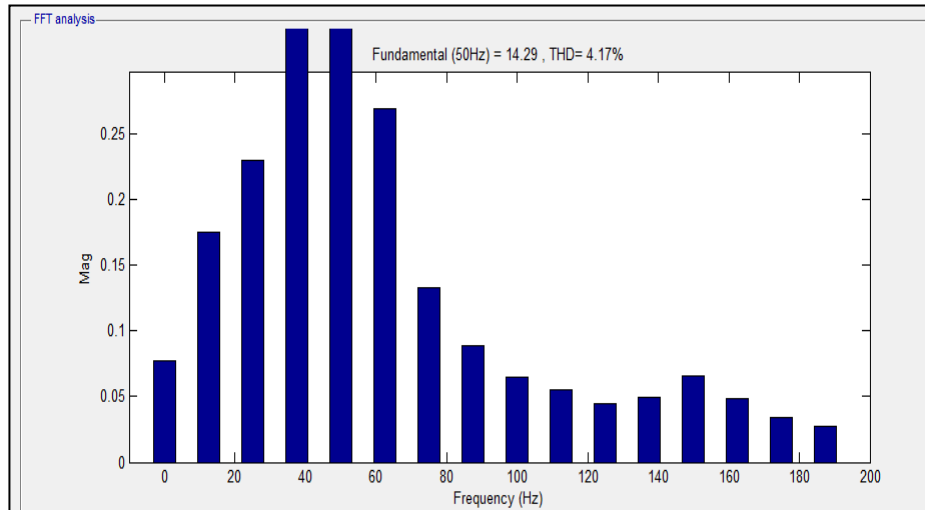


Figure 11: Displays of THD with an Active Filter Managed.
Source: Authors, (2026).

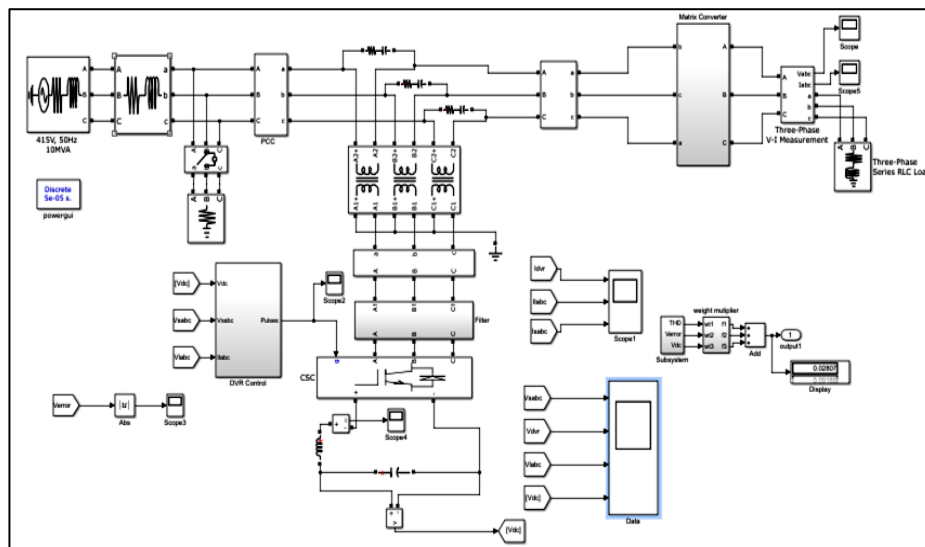


Figure 12: A matrix converter-based AF system for improving power quality is shown in this MATLAB/Simulink Project
Source: Authors, (2026).

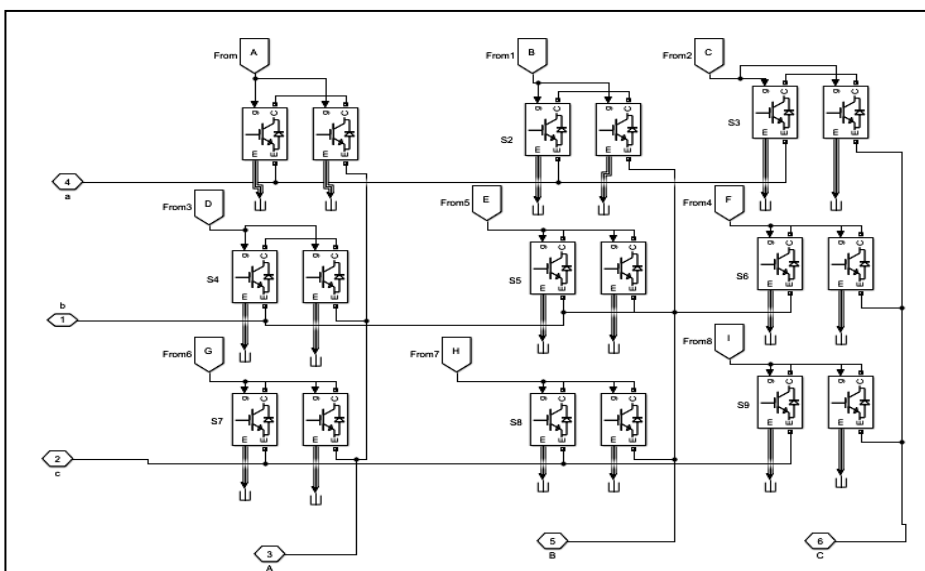


Figure 13: A two-way mechanical switch matrix converter.
Source: Authors, (2026).

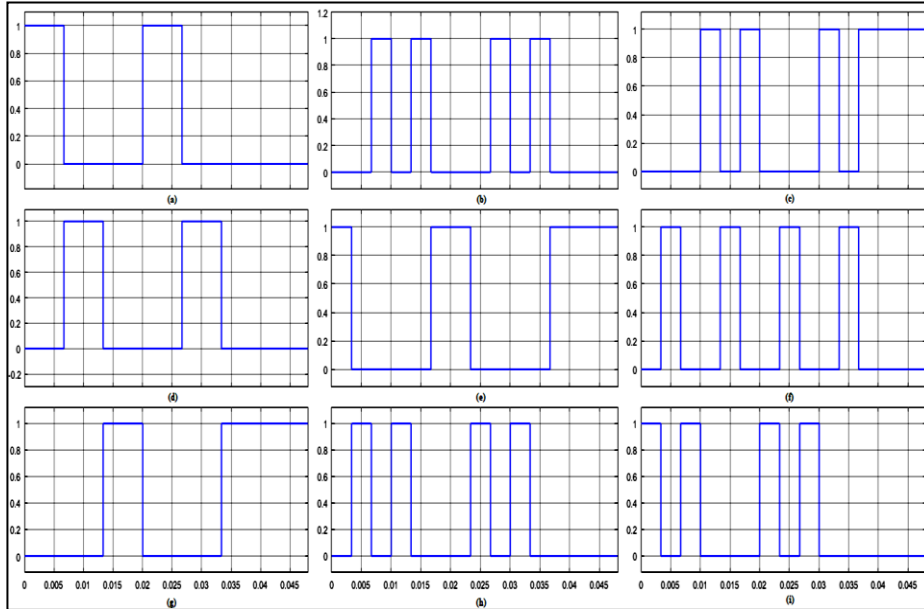


Figure 14: Pulse trains are switched by the matrix converter

Source: Authors, (2026).

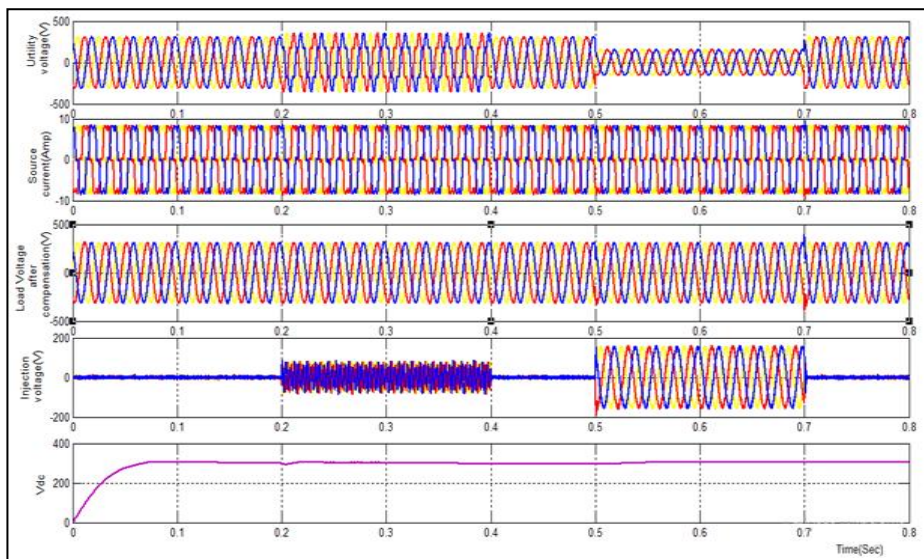


Figure 15: Active filtering system emerges from PI controller tuning using PSO algorithm.

Source: Authors, (2026).

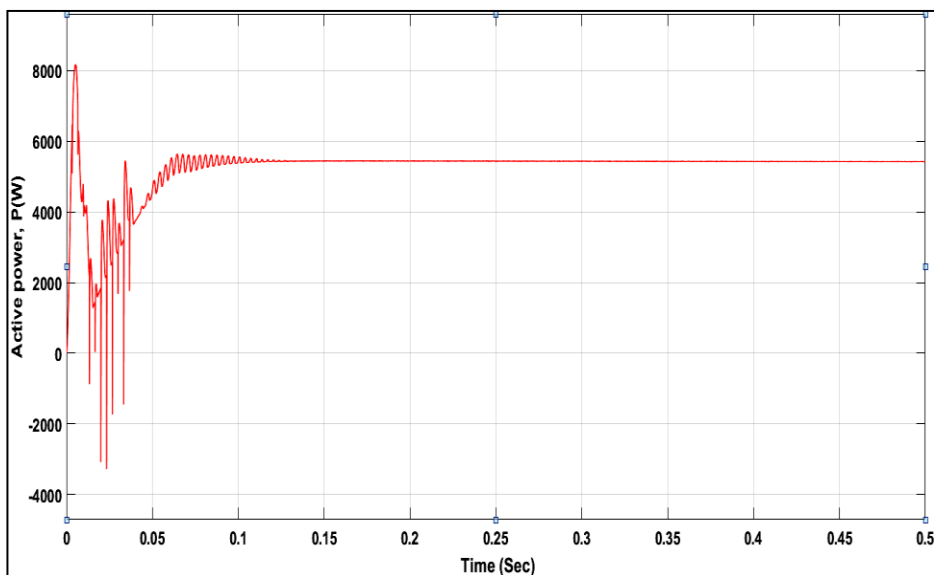


Figure 16: The active power handled by the utility network.

Source: Authors, (2026).

Figure 12 shows a Simulink model of the Matrix converter-based AF. Figure 15 depicts the dynamic performance of an AF module that is based on a matrix converter. This performance is measured by the applied utility current, the compensatory current, and the final mitigated utility current at the dispersed end. A further optimization is performed using the PSO technique on this dynamical Simulink model. When the matrix converter-based AF is used as a mitigating device, and additional optimization is performed using PI-PSO with control variables serving as PI controller gains (K_p and K_i), the fit value is lowered to 2.65%, as shown in Figure 17. An expert-calculated approach determined that the K_p and K_i ranges should be between 0 and 180, without compromising system stability. In accordance with the relation $C_1 + C_2 = 4$, the social parameters of the PSO algorithm are selected to be $C_1 = 2$ and $C_2 = 2$ (expert knowledge). As a consequence of the dynamical assessment and optimization, the PSO method yields a solution with 15.572 as K_p and 180 as K_i . It has been decided that the search population will be 10, and the acceleration division for displacement will be 20. Both the fitness convergence illustration and the associated DC link voltage are shown in Figures 17 and 19, respectively. The optimization of the suggested PSO method is carried out for seventy iterations to ensure that it remains mostly unchanged after that (by means of several test runs).

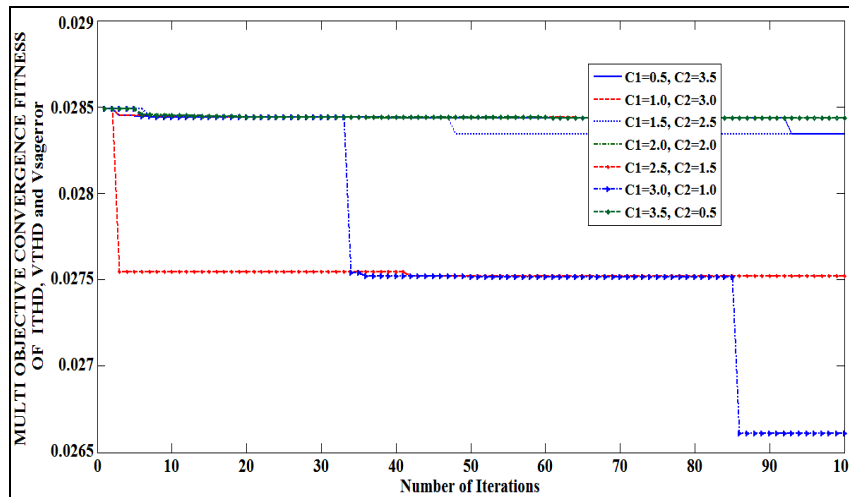


Figure 17: Convergence of Total Harmonic Distortion Using the PI-PSO Algorithm.

Source: Authors, (2026).

Figure 17 illustrates the convergence behaviour of the multi-objective optimisation fitness over a series of iterations, as assessed across different parameter settings of C_1 and C_2 . The results indicate that fitness values gradually improve over iterations, with distinct jumps in certain parameter settings, suggesting significant updates in search space exploration. Some parameter configurations exhibit a smoother convergence, while others show abrupt changes, likely due to diverse exploration and exploitation balances in the optimization process. The trend suggests that selecting appropriate values for C_1 and C_2 is crucial for achieving optimal convergence, affecting the speed and stability of the solution. This analysis is particularly relevant in Particle Swarm Optimization (PSO) and other heuristic algorithms, where tuning these coefficients significantly affects performance.

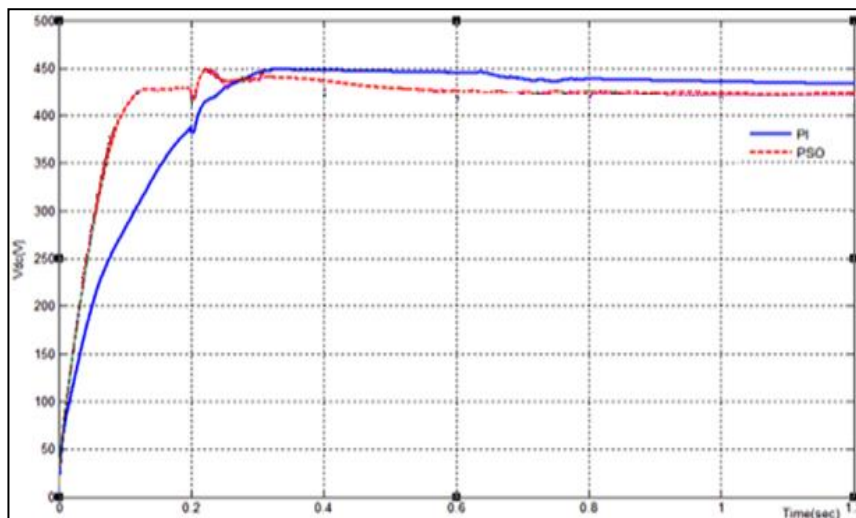


Figure 18: Visualization of DC link voltage using PI and PSO algorithms.

Source: Authors, (2026).

Figure 18 highlights the dynamic response characteristics of both controllers. Initially, the PI-controlled system exhibits a slower rise time, taking longer to reach the desired voltage, whereas the PSO-tuned controller demonstrates a faster transient response with a quicker rise time. The PSO-based approach also shows a reduced overshoot compared to the PI controller, which momentarily exceeds the steady-state value. Additionally, steady-state performance is more stable with the PSO-tuned controller, as it minimizes oscillations and settles to the desired voltage more efficiently. This analysis confirms the superior performance of the PSO-based PI controller, making it a better choice for improved system stability, faster response, and reduced overshoot.

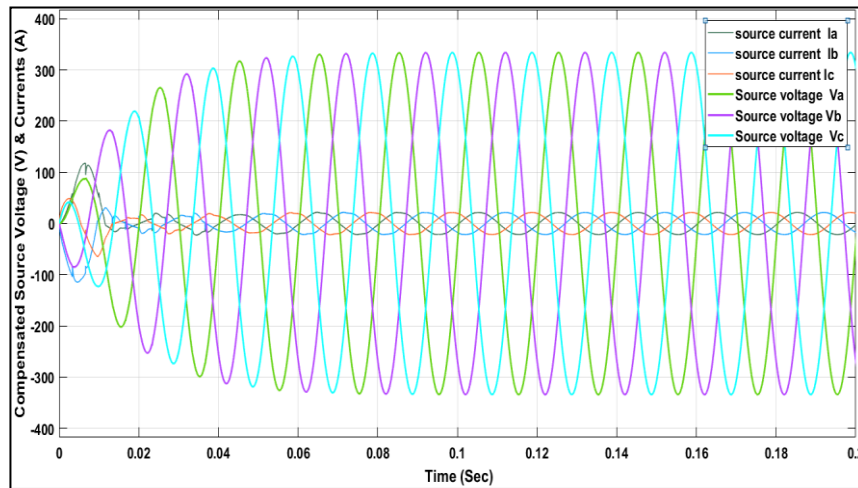


Figure 19: Illustration of voltages and currents for power factor evaluation.

Source: Authors, (2026).

Figure 19 illustrates the compensated three-phase source voltage and current waveforms in a power system. At the beginning of the waveform (0 to 0.02 sec), there is a transient response, indicating the system's initial instability due to a fault, a sudden load change, or a disturbance. As the compensation mechanism activates, the waveforms stabilize and become well-synchronized sinusoidal signals, ensuring balanced three-phase operation. The compensation helps eliminate distortions and restore power quality, making the source currents and voltages nearly pure sinusoidal with minimal harmonics.

V. CONCLUSIONS

The study emphasizes the development of a Matrix Converter-based Active Filter (AF) system aimed at improving power quality, addressing power factor correction, imbalance sorting, and mitigating non-ideal current signals in the utility network. Subsequently, the conventional AF control mechanism is evaluated against the proposed PSO algorithm in terms of performance efficiency. A comparative analysis between the PI controller and the PSO algorithm demonstrates the superiority of PSO in power factor correction and harmonic reduction (as illustrated in Fig. 19). Despite transient conditions and system abnormalities, the DC bus voltage remains stable, aligning with the reference input, thereby achieving an almost unity power factor (as depicted in Fig. 19). The effectiveness of the proposed PSO-based AF system utilizing a Matrix Converter is validated through dynamic simulations conducted in the MATLAB environment.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Patil Mounica, Gouthami Challa, Devineni Gireesh Kumar and Natarajan Karuppiiah.

Methodology: Patil Mounica and Gouthami Challa.

Investigation: Patil Mounica and Gouthami Challa.

Discussion of results: Patil Mounica, Gouthami Challa and Natarajan Karuppiiah.

Writing – Original Draft: Patil Mounica.

Writing – Review and Editing: Patil Mounica and Gouthami Challa.

Resources: Gouthami Challa.

Supervision: Devineni Gireesh Kumar and Natarajan Karuppiiah.

Approval of the final text: Patil Mounica, Gouthami Challa, Devineni Gireesh Kumar and Natarajan Karuppiiah.

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