

Power Quality Enhancement in Electrical Power System by Using DCM-ICM IRPT UCBPWM Based Genetic Algorithm Optimized Shunt Active Power Filter

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Abstract - Increase in the use of the nonlinear and power electronic loads in modern distribution systems has intensified the power quality problems such as harmonic distortion, reactive power demand, voltage distortion and low power factor. These problems reduces the system efficiency, increases losses and affect the reliable operation of sensitive equipment. This paper proposes a Genetic Algorithm (GA) optimized Shunt Active Power Filter (SAPF) for effective harmonic mitigation and reactive power compensation using Direct Control and Indirect Control strategies combined with the Unit Current Based Pulse Width Modulation (UCBPWM). The GA is utilized to optimize the SAPF controller parameters resulting in improved dynamic response, enhanced stability and accurate compensation under varying nonlinear load conditions. The Direct Control strategy ensures faster compensating current regulation while the Indirect Control method enhances the reference current estimation and synchronization with the source currents. UCBPWM improves the inverter switching pulse generation, current tracking accuracy and reduces the switching stress in the Voltage Source Inverter. The proposed system is modeled in MATLAB/Simulink and evaluated under different nonlinear load conditions. Simulation results demonstrate significant reduction in the Total Harmonic Distortion (THD), improved power factor, stable DC-link voltage regulation and better compensation performance in compliance with the IEEE-519 standards.

Key Words: Shunt active power filter (SAPF), genetic algorithm (GA), direct control method (DCM), indirect control method (ICM), total harmonic distortion (THD), harmonic compensation ratio (HCR).

1. INTRODUCTION

The increasing use of the nonlinear loads in modern electrical distribution systems has created serious power quality problems in industrial, commercial and residential applications. Power electronic devices such as adjustable speed drives, rectifiers, switched mode power supplies, electric vehicle chargers and inverter-based renewable energy systems inject harmonic currents into the utility network resulting in the current distortion, voltage fluctuation, increased power losses, poor power factor and overheating of electrical equipment [8], [6]. Harmonics problem also affects the reliable operation of sensitive electronic devices and reduces the overall efficiency of the power system. Therefore harmonic mitigation and power quality improvement have become major research areas in modern power engineering [8], [5]. According to IEEE-519 standards harmonic distortion in electrical systems must be maintained within permissible limits to ensure the stable and efficient system operation [8], [7]. Conventional passive filters were initially used for harmonic compensation because of their simple structure and low implementation cost. Despite these advantages passive filters suffer from several drawbacks such as resonance problems, fixed compensation characteristics, large size and poor dynamic response under changing load conditions [8], [5]. To overcome these limitations Active Power Filters (APFs) have emerged as one of the effective solution for harmonic suppression and reactive power compensation in distribution systems [6], [1]. Among the various APF configurations the Shunt Active Power Filter (SAPF) is widely used because of its ability to compensate the current harmonics, improve source current waveform, regulate reactive power and enhance power factor simultaneously [8], [2]. SAPF operates by injecting

compensating currents equal in magnitude and opposite in phase to the harmonic components generated by nonlinear loads. As a result the source current becomes nearly sinusoidal and harmonic distortion is significantly reduced [6]. Recent studies have shown that the SAPF systems provide superior harmonic compensation performance compared with passive filtering techniques particularly under dynamic and nonlinear operating conditions [4], [3]. The performance of SAPF mainly depends on the efficiency of the control algorithm employed for reference current generation and inverter switching control. Different control techniques such as instantaneous reactive power theory, synchronous reference frame theory, hysteresis current control and pulse width modulation techniques have been proposed in recent literatures [5], [9], [10]. Direct Control methods provide rapid harmonic compensation by directly controlling compensating currents while Indirect Control methods improve synchronization and maintain accurate reference current estimation under varying load conditions [8], [4], [10]. Furthermore the Unit Current Based Pulse Width Modulation (UCBPWM) improves inverter switching performance by providing accurate current tracking, reduced switching losses and improved DC-link voltage regulation [8]. In the recent years intelligent optimization techniques have gained considerable attention for improving SAPF controller performance. Among these techniques Genetic Algorithm (GA) has emerged as an efficient optimization method for solving nonlinear and multi-objective engineering problems [1]. GA is based on evolutionary principles such as selection, crossover and mutation, which help in obtaining the optimal controller parameters for improved dynamic response and harmonic compensation performance. Several recent studies reported that GA optimized controllers achieve better Total Harmonic Distortion (THD) reduction, faster convergence, lower steady-state error, and improved system stability compared with the conventional tuning methods [1], [3]. Meta-heuristic optimization methods are also increasingly used in SAPF applications because of their robustness and adaptability under varying operating conditions [3]. This paper proposes a Genetic Algorithm optimized Shunt Active Power Filter for power quality improvement in distribution systems using the Direct Control and Indirect Control techniques integrated with the Unit Current Based Pulse Width Modulation (UCBPWM). The proposed system is modeled and simulated in MATLAB/Simulink under nonlinear load conditions. The effectiveness of the proposed approach is evaluated in terms of Total

Harmonic Distortion (THD), source current quality, reactive power compensation, power factor improvement and DC-link voltage regulation. Simulation results demonstrates the significant harmonic reduction and compliance with IEEE-519 standards confirming the effectiveness of the proposed SAPF configuration for the modern distribution system applications.

2. SYSTEM CONFIGURATION

The proposed system consists of a three - phase Shunt Active Power Filter (SAPF) connected in parallel with a nonlinear load in a distribution system for power quality improvement. Fig.1 shows the equivalent circuit of shunt active power filter.

Fig.2 shows the closed loop block diagram of shunt active power filter. The complete configuration is designed to compensate harmonic currents, reduce reactive power demand, improve source current waveform quality and maintain near unity power factor under varying load conditions. The system mainly includes a three - phase AC source, nonlinear load, Voltage Source Inverter (VSI), DC-link capacitor, interfacing filter inductor, control unit, Genetic Algorithm optimized controller and Unipolar Carrier Based Pulse Width Modulation (UCBPWM) switching scheme.

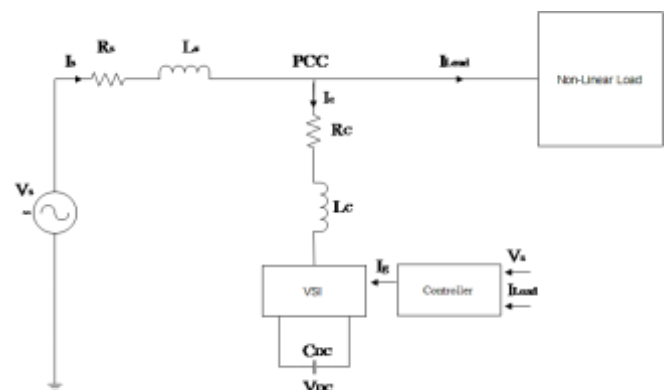


Fig.1 : Equivalent Circuit of Shunt Active Power Filter

The nonlinear load connected to the distribution network generates the harmonic currents and reactive power which distorts the source current waveform and degrades the overall system performance. The SAPF is connected in shunt with the nonlinear load to inject compensating currents equal in magnitude and opposite in phase to the harmonic components produced by the load. As a result

the harmonic currents are cancelled at the Point of Common Coupling (PCC) and the source current becomes nearly sinusoidal.

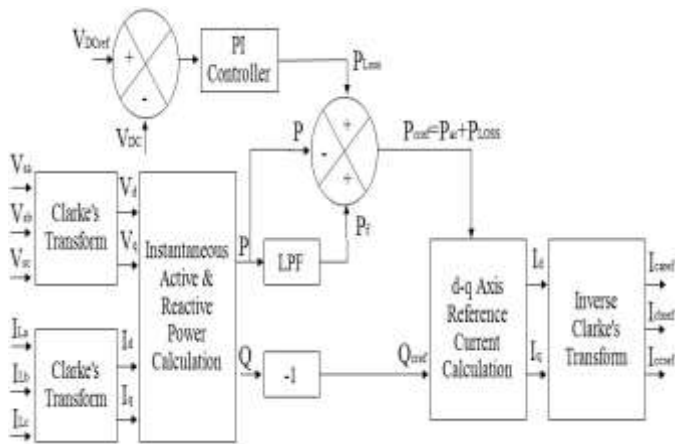


Fig. 2 : Closed Loop Block Diagram of Shunt Active Power Filter

The core component of the proposed SAPF is the Voltage Source Inverter (VSI) which is built using insulated gate bipolar transistor (IGBT) switches. The VSI generates compensating currents based on the reference current obtained from the control algorithm. A DC-link capacitor is connected across the inverter to maintain a constant DC voltage and provide the required energy storage for compensation operation. The interfacing inductor is connected between the VSI and the distribution system to smooth the injected compensating current and reduce the switching ripple. The proposed control structure uses the Direct Control and Indirect Control strategies for harmonic compensation. In the Direct Control strategy the compensating current is directly controlled to get the fast dynamic response and effective harmonic suppression. And the Indirect Control strategy is used for the accurate reference current estimation and synchronization with the supply current. The combination of these two strategies improves the current tracking performance and system stability during load variations.

3. UNIPOLAR CARRIER BASED PULSE WIDTH MODULATION

The UCBPWM technique produces accurate gating signals for the inverter switches by comparing the reference compensating current with the actual current. This method improves current tracking accuracy,

reduces switching losses and enhances inverter efficiency. The UCBPWM scheme also contributes to stabilize the DC-link voltage regulation and improve the compensation performance under nonlinear load conditions. The entire system is modeled and simulated in MATLAB/Simulink to evaluate the effectiveness of the proposed approach. The performance analysis is then carried out under different operating conditions using parameters such as Total Harmonic Distortion (THD), source current waveform, reactive power compensation, DC-link voltage stability and Harmonic Compensation Ratio (HCR). The proposed Genetic Algorithm optimized SAPF demonstrates efficient harmonic reduction and satisfies IEEE-519 harmonic standards for the modern distribution systems.

4. INSTANTANEOUS REACTIVE POWER THEORY

Instantaneous Reactive Power Theory, also known as p-q theory is one of the most widely used control techniques for reference current generation in the Shunt Active Power Filter (SAPF) applications. Fig.3 shows the block diagram of instantaneous reactive power theory. The theory was introduced for real time harmonic and reactive power compensation in three – phase power systems. The main objective of this method is to identify the harmonic and reactive current components generated by nonlinear loads and produce the compensating currents to eliminate these disturbances from the source side. In the proposed system the instantaneous reactive power theory is used to generate the reference compensating currents required for harmonic mitigation and reactive power compensation.

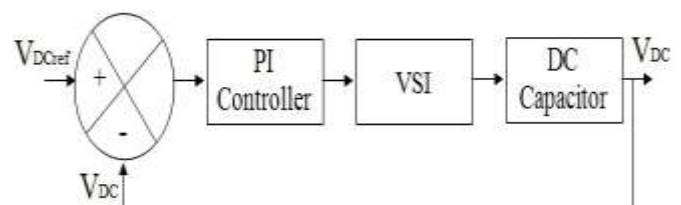


Fig. 3 : Instantaneous Reactive Power Theory

The control algorithm operates in the stationary reference frame obtained through Clarke Transformation. The three-phase source voltages and load currents are transformed into two phase orthogonal

components for simplified mathematical analysis and real time computation. The transformation of three - phase voltages from abc coordinates to p-q coordinates. Similarly, the load currents are transformed into p-q coordinates. Using the transformed voltage and current components, the instantaneous active power p and instantaneous reactive power q are calculated. The instantaneous active power contains the average and oscillating components. The oscillating component represents harmonic power while the reactive power component represents reactive energy exchange between source and load. The SAPF compensates these unwanted components by generating equal and opposite compensating currents through the Voltage Source Inverter (VSI). The reference compensating currents in p-q coordinates are determined from the calculated power components using inverse transformation equations. After obtaining the reference currents in the frame, the inverse Clarke Transformation converts them back into three phase abc reference currents for practical implementation.

5. GENETIC ALGORITHM OPTIMIZED IRPT

The genetic algorithm optimized IRPT block diagram is shown in Fig. 4.

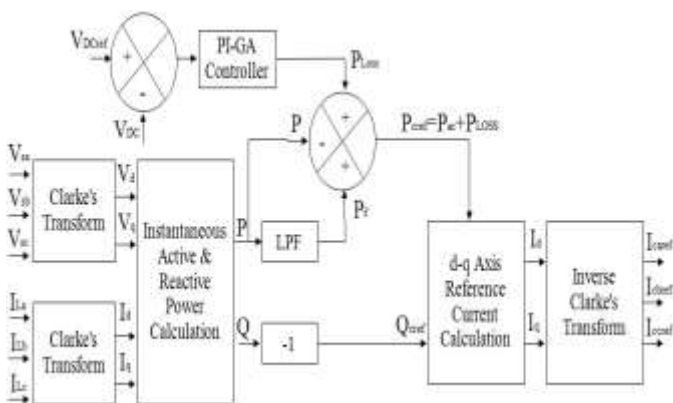


Fig. 4 : Genetic Algorithm Optimized IRPT

The Genetic Algorithm (GA) based optimization technique is used to tune the controller parameters of the SAPF. The GA performs optimization using selection, crossover and mutation operations as shown in Fig. 5 is used to obtain the optimal controller gains for the improved compensation performance. The objective function of the GA is used to minimize Total Harmonic Distortion (THD), maintain stable DC-link voltage and reduce steady-state error.

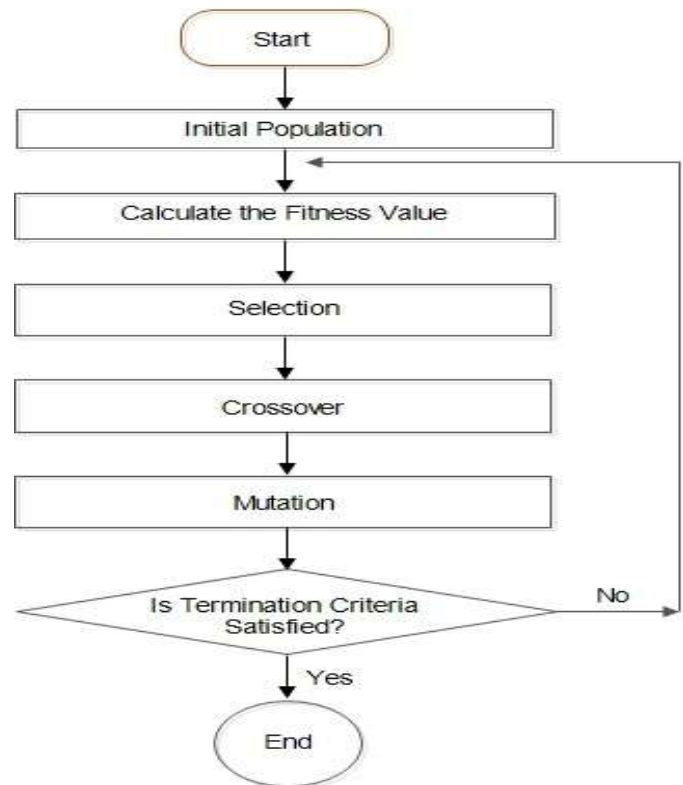


Fig. 5 : Genetic Algorithm

The optimized controller provides fast transient response, improved harmonic mitigation capability and better adaptability under the dynamic operating conditions. The switching pulses for the VSI are generated using UCBPWM technique.

5. UNIPOLAR CARRIER BASED PWM

The generated compensating currents are tracked using the Unipolar Carrier Based Pulse Width Modulation (UCBPWM) switching technique as shown in Fig. 6. The UCBPWM controller produces accurate switching pulses for the inverter switches ensuring proper harmonic compensation and improved current tracking performance. The instantaneous reactive power theory provides several advantages such as fast dynamic response, simple implementation, effective harmonic detection and accurate reactive power compensation. Due to these features the p-q theory is highly suitable for real time control of Shunt Active Power Filters operating under nonlinear and dynamic load conditions.

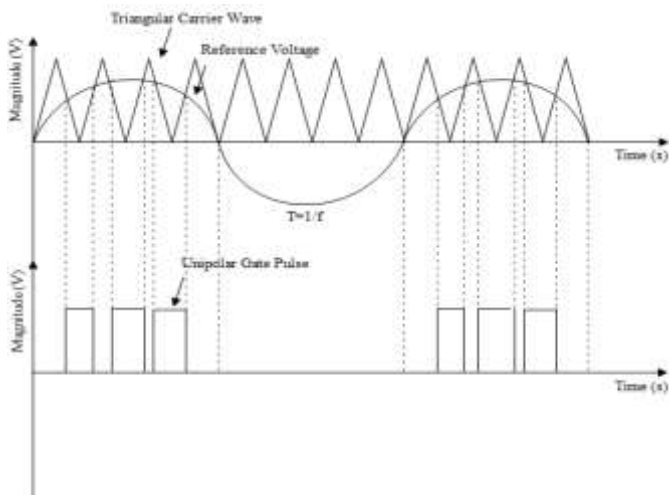


Fig. 6 : Unipolar Carrier Based PWM

5. DIRECT CONTROL METHOD

The Direct Control based Unipolar Carrier Based Pulse Width Modulation (UCBPWM) technique is used in the proposed Shunt Active Power Filter (SAPF) system to achieve the fast harmonic compensation and accurate current tracking performance shown in Fig. 7. In this method the compensating currents generated by the SAPF are directly controlled according to the reference current obtained from the instantaneous reactive power theory. The block diagram of direct control method is shown in Fig. The main objective of the Direct Control strategy is to minimize the error between the reference compensating current and the actual filter current in real time. The Direct Control method continuously monitor the source current and compensating current signals.

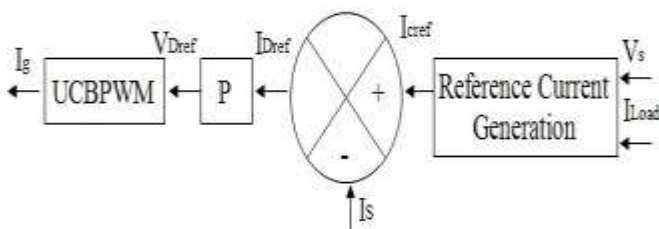


Fig. 7 : Direct Control Method

The harmonic and reactive current components generated by the nonlinear load are extracted using the p-q theory. These extracted components are used to generate the reference compensating currents required for the harmonic mitigation and reactive power compensation. The error signal between the reference current and actual compensating is then processed

through the controller to generate suitable switching signal for the Voltage Source Inverter (VSI). The UCBPWM technique compares the reference unit current signal with a high frequency carrier signal to produce Pulse Width Modulated gating pulses for the inverter switches. The switching pulses generated through UCBPWM ensures the accurate tracking of the compensating current and maintain the proper synchronization with the source current waveform. The Direct Control approach provides rapid dynamic response and the efficient harmonic suppression under varying nonlinear load conditions. The main advantages of Direct Control based UCBPWM is reduced Total Harmonic Distortion (THD), fast transient response, improved reactive power compensation and better stability of the DC-link voltage. The technique also improves the inverter switching efficiency and reduces current from ripple in the distribution system.

5. INDIRECT CONTROL METHOD

The Indirect Control based Unipolar Carrier Based Pulse Width Modulation (UCBPWM) technique is used in the proposed SAPF system to improve the reference current estimation and maintain accurate synchronization between the source voltage and compensating current shown in Fig. 8. Unlike the Direct Control method the Indirect Control strategy does not directly regulate the compensating currents. Instead of it this estimates the desired source reference currents and generates compensating currents indirectly through the Voltage Source Inverter (VSI).

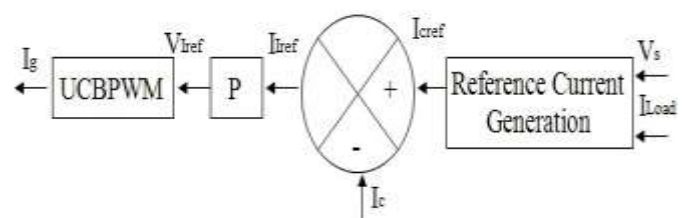


Fig. 8 : Indirect Control Method

In this method the source voltage and load current signal are measured and processed using the instantaneous reactive power theory. The active power component required from the source is separated from the harmonic and reactive power components. The SAPF then injects compensating currents to eliminate the unwanted

harmonic and reactive components generated by the nonlinear loads. The reference source current is then determined. The calculated reference compensating current is applied to the UCBPWM controller for generation of inverter switching pulses. The UCBPWM technique ensures the accurate modulation of inverter output current by comparing the reference current with the measured compensating current signal. The generated PWM pulses controls the IGBT switches of the VSI and force the SAPF to inject appropriate compensating currents into the distribution system. The Indirect Control based UCBPWM technique provides improved synchronization with the source voltage, stable steady-state operation and enhanced current waveform quality. This method also maintains better DC link voltage regulation during load variations and reduces steady state current error. Combined implementation of these Direct Control and Indirect Control based UCBPWM techniques results in the improved SAPF performance providing faster dynamic response, accurate harmonic compensation, enhanced power factor correction and reduced Total Harmonic Distortion (THD) in the distribution system.

5. SIMULATION RESULTS

The proposed Genetic Algorithm optimized Shunt Active Power Filter (SAPF) using Direct Control and Indirect Control based Unit Current Based Pulse Width Modulation (UCBPWM) was modeled and simulated in MATLAB/ Simulink to evaluate its effectiveness for power quality improvement in three - phase distribution systems. Fig. 9-16 shows the various simulation results obtained in MATLAB/SIMULINK. The simulation study was carried out under nonlinear load conditions to analyze the harmonic compensation capability, reactive power compensation, source current improvement, DC-link voltage regulation and Total Harmonic Distortion (THD) reduction.

Table 1: The Performance Comparison Under Various Operating Conditions

Condi tion	CM	OS	%THD Before Comp.	%THD After Comp.	%HCR	%HCR Deviati on
Witho ut SAPF	-	SS	1.34	—	—	—
	-	TS	132.84	—	—	—
PI	DC	SS	1.34	1.34	100	96.93
	IC	TS	132.84	4.09	3.07	—
	DC	SS	1.34	1.16	86.56	83.49
	IC	TS	132.84	4.09	3.07	—
PI-GA	DC	SS	1.34	1.25	93.28	90.33
	IC	TS	132.84	3.92	2.95	—
	DC	SS	1.34	0.93	69.40	66.33
	IC	TS	132.84	4.09	3.07	—

The simulation model consists of a three - phase AC supply, nonlinear rectifier load, Voltage Source Inverter (VSI), DC link capacitor, interfacing filter inductor and GA optimized control system. The nonlinear load generates distorted source currents containing harmonic components which degrades the power quality of the distribution network. The SAPF injects compensating currents into the system to eliminate harmonics and improve the source current waveform quality. Initially the system was analyzed without connecting the SAPF. The source current waveform was highly distorted due to the presence of nonlinear loads. The harmonic analysis performed with Fast Fourier Transform (FFT) indicated high Total Harmonic Distortion value that was exceeding the permissible limits specified by IEEE-519 standards. The source current also gave poor sinusoidal characteristics and low power factor conditions. But after connecting the proposed GA optimized SAPF significant improvement in the source current waveform quality was seen. The compensating currents generated by the SAPF effectively cancelled the harmonic components produced by the nonlinear loads. The source current became nearly sinusoidal and synchronized with the supply voltage waveform. The proposed control system maintained stable operation during the steady-state and dynamic load conditions. The Direct Control based UCBPWM technique demonstrated faster dynamic response and accurate harmonic compensation capability. The controller tracked the reference compensating current and reduced harmonic distortion within a short response time rapidly. The injected compensating current closely followed the

reference current waveform which improved the current tracking accuracy and reduced steady-state error.

Fig. 9 : Simulation Results (Source Voltage, Source Current, Load Voltage, Load Current, Voltage Across DC Capacitor) Steady State Condition with Direct Control Method PI-IRPT-UCBPWM

The Indirect Control based UCBPWM method provided improved synchronization between source voltage and source current. This technique helped to maintain the stable DC-link voltage and achieved smooth compensation performance during the sudden load variations. The indirect control approach also results in improved the power factor correction and reduced reactive power demand from the source side.

This optimized controller achieved faster convergence, reduced overshoot, improved transient response and enhanced harmonic mitigation compared with the conventional tuning methods. The stable DC link capacitor voltage throughout simulation shows the effectiveness of the proposed optimization approach. FFT analysis of the compensated source current confirmed substantial reduction in Total Harmonic Distortion after implementation of the proposed SAPF. The THD value reduced within the acceptable range recommended by IEEE-519 standards.

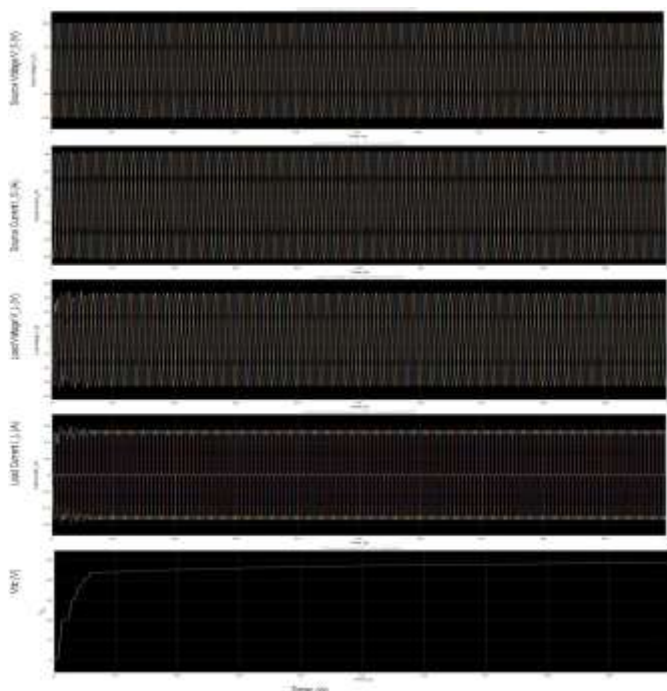
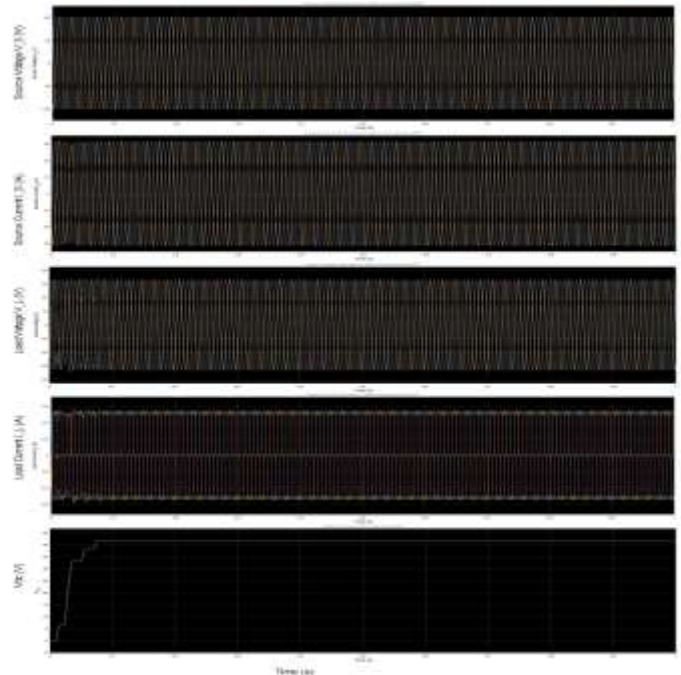


Fig. 10 : Simulation Results (Source Voltage, Source Current, Load Voltage, Load Current, Voltage

Across DC Capacitor) Steady State Condition with Indirect Control Method PI-IRPT-UCBPWM



The simulation results helped to confirm that the proposed Genetic Algorithm optimized SAPF using Direct Control and Indirect Control based UCBPWM provides effective harmonic compensation, improved source current quality, reduced reactive power burden, stable DC-link voltage regulation and enhanced power factor. These obtained results demonstrated that the proposed system is suitable for practical power quality improvement applications in modern distribution networks.

The Genetic Algorithm optimization technique resulted in significant improvement in controller performance by selecting optimal control parameters for the SAPF system.

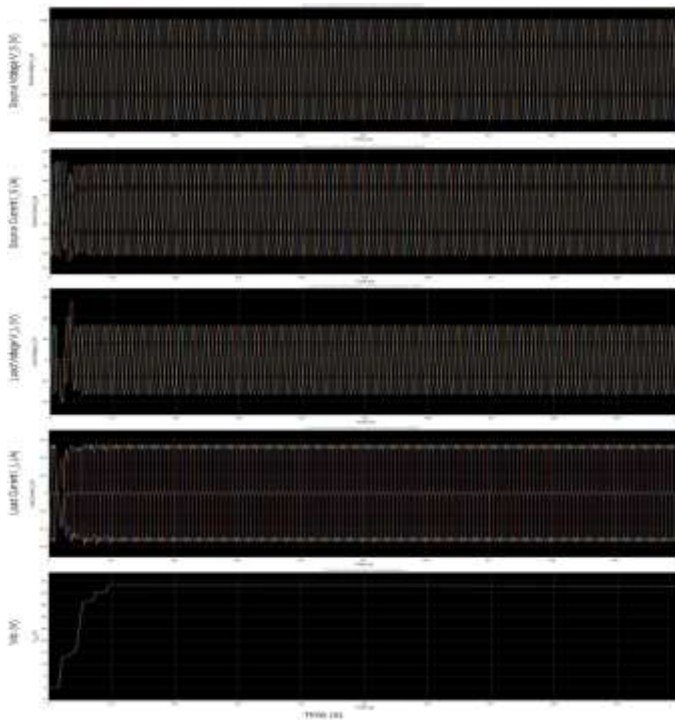


Fig. 11 : Simulation Results (Source Voltage, Source Current, Load Voltage, Load Current, Voltage Across DC Capacitor) Transient State Condition with Direct Control Method PI-IRPT-UCBPWM

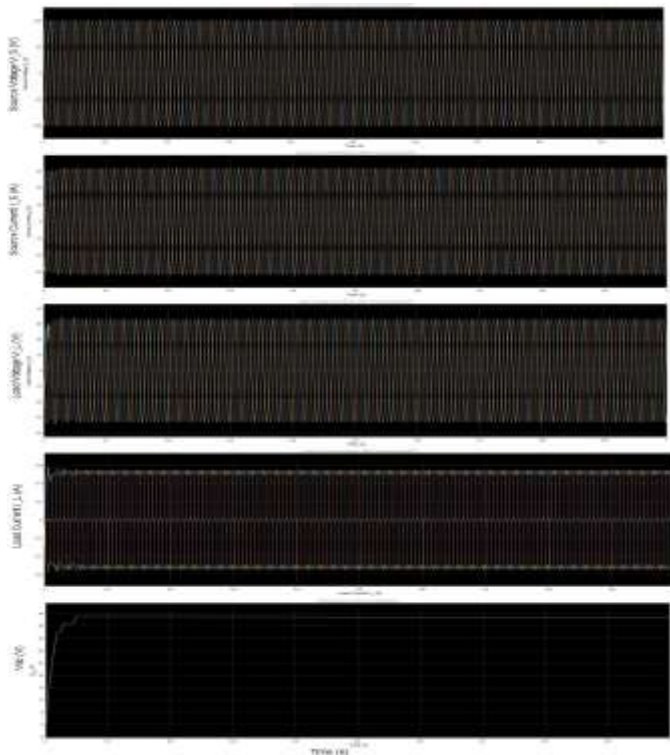


Fig. 12 : Simulation Results (Source Voltage, Source Current, Load Voltage, Load Current, Voltage Across DC Capacitor) Transient State Condition with Indirect Control Method PI-IRPT-UCBPWM

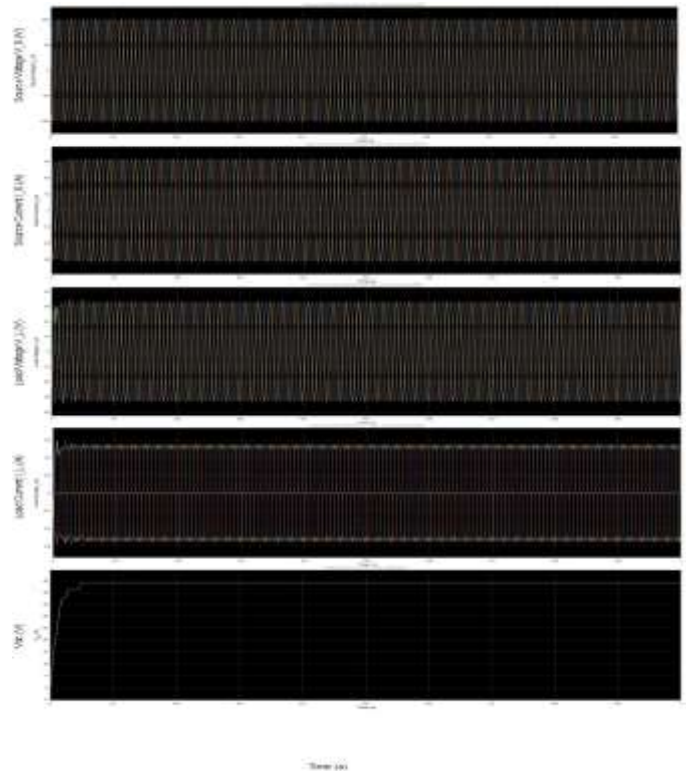


Fig. 13 : Simulation Results (Source Voltage, Source Current, Load Voltage, Load Current, Voltage Across DC Capacitor) Steady State Condition with Direct Control Method PI-GA-IRPT-UCBPWM

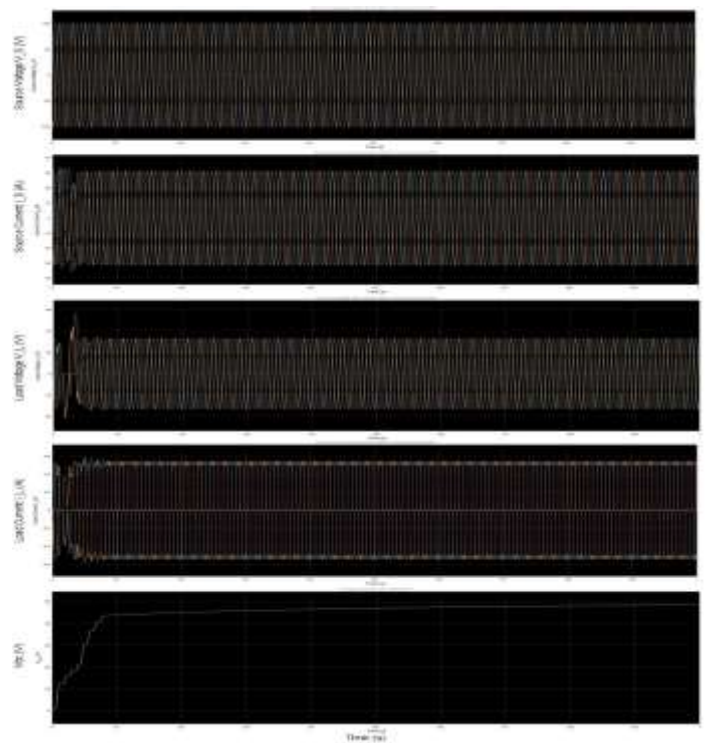


Fig. 14 : Simulation Results (Source Voltage, Source Current, Load Voltage, Load Current, Voltage Across DC Capacitor) Steady State Condition with Indirect Control Method PI-GA-IRPT-UCBPWM

Across DC Capacitor) Steady State Condition with Indirect Control Method PI-GA-IRPT-UCBPWM

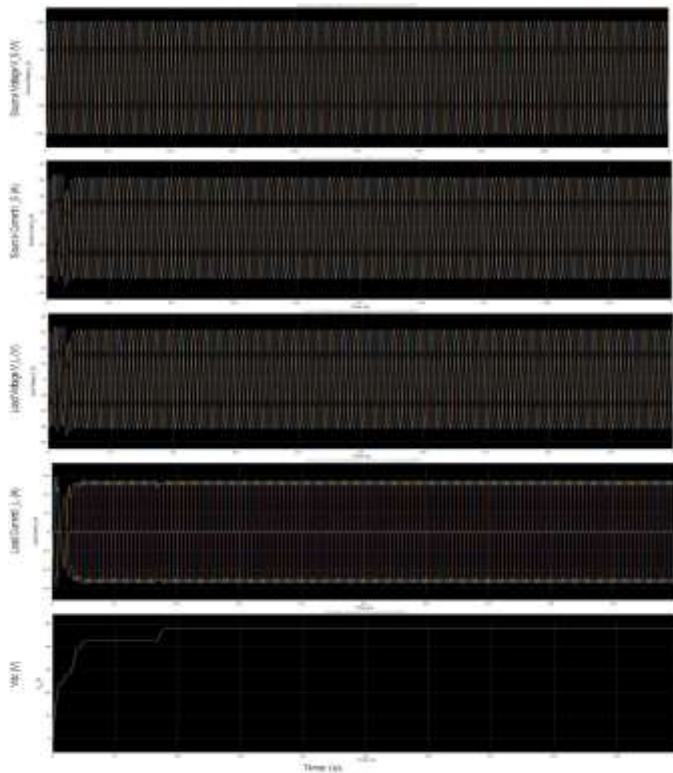


Fig. 15 : Simulation Results (Source Voltage, Source Current, Load Voltage, Load Current, Voltage Across DC Capacitor) Transient State Condition with Direct Control Method PI-GA-IRPT-UCBPWM

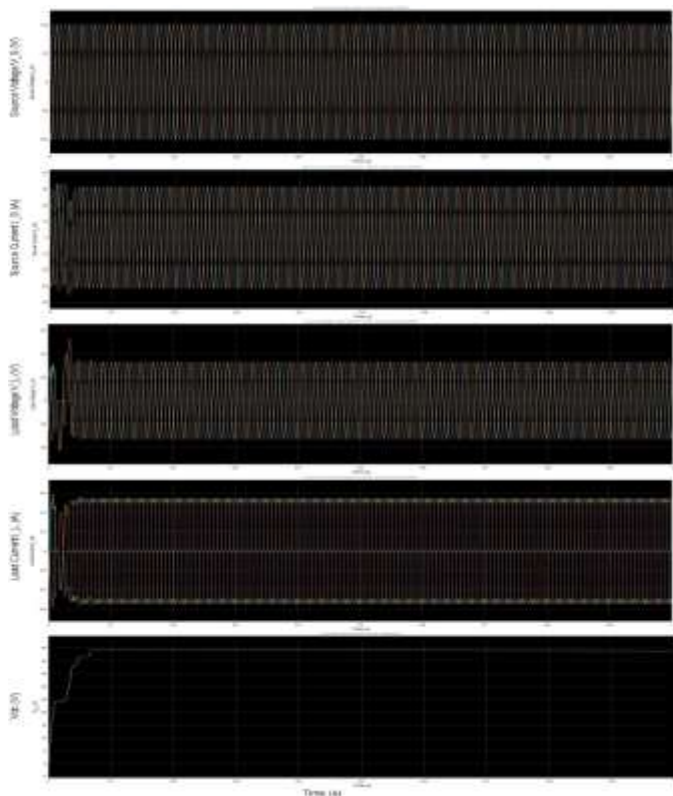


Fig. 16 : Simulation Results (Source Voltage, Source Current, Load Voltage, Load Current, Voltage Across DC Capacitor) Steady State Condition with Indirect Control Method PI-GA-IRPT-UCBPWM

Across DC Capacitor) Transient State Condition with Indirect Control Method PI-GA-IRPT-UCBPWM

3. CONCLUSIONS

This paper presented a Genetic Algorithm optimized Shunt Active Power Filter (SAPF) for power quality improvement in three - phase distribution systems using Direct Control and Indirect Control based Unit Current Based Pulse Width Modulation (UCBPWM). The proposed system is developed to reduce the harmonic distortion, compensate reactive power, improve source current waveform quality and maintain stable operation under nonlinear load conditions. The SAPF system was modeled and simulated in MATLAB/ Simulink using a Voltage Source Inverter based compensation structure. Instantaneous reactive power theory was employed for reference current generation while the Genetic Algorithm is used to optimize controller parameters for improved dynamic performance and harmonic compensation capability. The Direct Control technique provided the fast current tracking and rapid transient response whereas the Indirect Control method improved the synchronization accuracy and DC link voltage stability. The UCBPWM switching technique generated the accurate inverter gating pulses and improved the compensating current injection performance. Simulation results demonstrated significant improvement in overall power quality after implementation of the proposed SAPF. The distorted source current waveform became nearly sinusoidal after compensation and reactive power demand from the source was effectively reduced. The proposed controller also maintained a stable DC-link voltage under varying load conditions. FFT analysis confirmed substantial reduction in the Total Harmonic Distortion (THD) and the obtained THD value satisfied the harmonic limits specified by IEEE-519 standards. The Genetic Algorithm optimized controller achieved better harmonic mitigation performance, improved steady-state accuracy, reduced transient oscillations and faster convergence compared with the conventional controller tuning methods. The combined implementation of Direct Control and Indirect Control based UCBPWM enhanced the overall compensation capability and operational stability of the SAPF system. The obtained results confirm that the proposed Genetic Algorithm optimized SAPF provides an efficient and reliable solution for the harmonic mitigation and power quality enhancement in modern distribution systems. The proposed method is suitable for industrial and utility applications where the nonlinear loads create severe

harmonic disturbances and reactive power problems. Future work may include real time hardware implementation and investigation of advanced hybrid optimization techniques for further improvement in the SAPF performance.

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