RESEARCH ARTICLE OPEN ACCESS

A Transit Search Optimization Algorithm (TSOA) Based Shunt Active Power Filter with Hysteresis Control for Power Quality Enhancement

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Abstract:

The routine of non-linear electrical strategies has deformed the sine wave output waveforms of the source current and voltage. If it overheats, linked equipment may sustain harm. Building robust power filters that reduce current and voltage harmonics is essential for modern power systems if they are to meet the utility grid's standards for power quality. In our thesis, the design approach for a transit search optimisation algorithm (TSOA)-enhanced shunt active power filter (SAPF) is addressed in detail. A fractional order PID (FOPID) controller with TSOA is utilised to regulate the DC-link voltage. Utilising the concept of instantaneous reactive power, the reference current is retrieved. By using hysteresis current control, the gate pulses which regulate the voltage source inverter (VSI) switches are produced. The comprehensive SAPF is established and modelled using MATLAB/Simulink for both balanced and unbalanced nonlinear loads. The simulation's findings demonstrate that the suggested filter can lessen harmonic distortion.

Keywords —: **Shunt Active Power Filter (SAPF), Fractional Order PID (FOPID) Controller, Transit Search Optimization Algorithm (TSOA).**

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I. INTRODUCTION

Power quality (PQ) issues are causing power system (PS) engineers more and more concern today. Harmonic distortion is a phenomena that happens when PQ decreases. The use of nonlinear loads more frequently is causing the electric distribution system's harmonic distortion to rise. In an electrical distribution system, large numbers of these loads have the potential to increase harmonic voltage and currents to unacceptable heights, which can have a negative impact on the system currents. Restrictions for harmonic voltages and harmonic have been established by IEEE standards. Current harmonics in distribution feeders result in serious harmonic issues for vulnerable users who have been cut off from the distribution system. There have been some alleged technological solutions to PQ. Every utility in the world uses nonlinear electrical equipment, which depend on electricity to power electronic switches, for both household and commercial applications. Arc furnaces, computers, and variable frequency drives (VFDs) are examples of nonlinear loads that can lead to harmonic distortion, voltage swings, and noise in the power supply. Power losses, electric device heating, insulation failures, communication system interference, and, in the bad situations, electric power organization failure are all caused by harmonic distortion in low-voltage distribution systems. Therefore, it is essential that problems with power quality are fixed for the good of the utility and the client.

PQ problems were first commonly treated with passive power filters (PPF), which are capacitor and inductor combinations. These techniques were widely employed in high voltage direct current (DC) transmission (HVDC) for eliminating the harmonics on the DC and AC sides. Nevertheless, since PPF can only fix certain load circumstances or electrical system states, this strategy is unsuccessful at the network distribution level. These filters cannot adapt to the fluctuating system circumstances. Harmonics and reactive power were taken into consideration when the active power filter (APF) was developed. Shunt, series, and hybrid APF—which combines AP and PPF—are the three different forms of APF. When a nonlinear load is attached to the network, the APF power line conditioner modifies the utility line current waveform such that it approaches a sine wave and is in phase with the line voltage. Traditional shunt power line conditioners (shunt PPF) use power capacitors to raise the utility's or mains' power factor (PF) while reducing harmonics with tuned LC filters and/or high pass filters. However, these conventional techniques have restrictions in terms of set compensation, size, and probable resonance conditions. Therefore, APF is provided as a practical alternate to balance harmonics and increase PF.

- Harmonic distortion is a phenomena which happens when PQ decreases. Harmonic distortion in the electrical distribution system is getting worse and worse as a result of the growing use of nonlinear loads.
- The two major problems that which to be handled are lowering the level of harmonics in the line current and increasing the level of power quality.
- Nonlinear loads generate harmonic current, which affects the PS voltage and current waveforms.
- These loads cause a distortion in the current's sine wave. The harmonic content of the PS can be calculated using the THD measurement. As a result, harmonics compensation is implemented in the PS using APF.

We can tackle harmonics in the distribution system using a variety of harmonic mitigation approaches to address these issues. Depending on the circumstance, they are appropriate solutions with advantages and cons. Filters are one way to address them. In order to alleviate PQ difficulties, filters are routinely used, and as nonlinear loads in the PS rise, more and more filters become essential.

The following five sections make up the paper: In Section 1, the significance, objectives, and explanation of the problem of enhancing power quality are presented. In Section 2, a review of the literature is presented. Section 3 illustrates the suggested approach employing a TSOA-based FOPID Controlled shunt active power filter. Section 4 of this thesis presents the conclusions and a discussion. Section 5 offers a conclusion.

II. RELATED WORK

This section will contain the study's literature review. Journals, research articles, and theses were used as sources to gather data. The shunt active power filter (SAPF) and static compensator (STATCOM) use the same topology. The SAPF is employed in electrical transmission systems to control voltage, make up for reactive power, and rectify power factor [3]. Through the coupling inductor, SAPF is coupled to the line in shunt. By infusing the opposite compensatory harmonic current, which is identical in amplitude to the source current harmonics, the SAPF modifies the load current harmonics [4]. Abhishek Srivastava et al. (2018) proposed a PI controller for the Shunt Active Power Filter (SAPF) based on the Whale Optimisation Algorithm (WOA). Calculating the harmonic current that non-linear loads input into the source involves self-tuning filters. The DC-link voltage is controlled to a constant value by a PI controller. To improve tracking performance, the gains of the controller (KP and KI) were modified using WOA. While the generation of gate signals has been accomplished using a straightforward Pulse Width Modulation (PWM) technique. The gathered results were compared to the conventional technique utilised to choose the constraint standards for this regulator.

When linking photovoltaic (PV) systems to the grid with shunt power quality conditioner (SAPF) systems, Narendra Babu P et al. (2019) proposed an adaptive second order generalised integrator dependent quadrature signal generator-frequency locked loop (SOGI-QSG-FLL) and fuzzy tuned proportional integral (FPI). The SOGI-QSG-FLL adaptive controller has been utilised for a number of applications including harmonic extraction, frequency estimation, and grid synchronisation. It has an easy-to-understand structure and is more versatile. The DC bus voltage was kept at a reference level using the FPI voltage regulator. In dynamic load, stable state, grid voltage unbalance, deformed voltage, voltage fall, rises voltage, and load removal scenarios, the effectiveness of the two controllers working together is increased. The hysteresis current regulator produces PWM signals for the SAPF inverter while the frequency locked loop (FLL) is utilised to estimate frequency. For a shunt active power filter (SAPF), Sabir Ouchen et al. (2020) suggested direct power control (DPC) shared with space vector modulation (SVM). Since the SVM may reduce significant active and reactive power ripples while continuing a constant switching frequency, it has been proposed as a remedy to alleviate the shortcomings of the standard DPC. Supertwisting second-order sliding mode controllers (ST-SMCs) are utilised in place of PI controllers in the active and reactive power control loops in the suggested method to improve performance. High robustness and dynamics against external shocks are provided by this method. Through simulation and actual execution using MATLAB/Simulink and a real-time interface based on a dSPACE 1104 board, the suggested control, DPC-SVM based on ST-SMC, is explored.

The shunt active power filter (SAF) was suggested by S. Kumaresan et al. (2020) for improving the PQ of high and medium power BLDC motor drives. The instantaneous "p-q" theory and a sinusoidal current control technique can be used to manage SAF. A hysteresis controller is used to bring the current control into action. The motor drive loads are constantly susceptible to changes in load and speed, unlike typical electrical loads. The SAF capacitor's DC-link voltage will fluctuate as a result. As a result, a sliding mode controller is utilised to modify the voltage of the DC link. Simulations and an experimental prototype are used to validate the proposed methodology. For various motor loading situations under both distorted and non-distorted distribution network voltage circumstances, the improvement of several PQ parameters is examined. In a straightforward single-phase system, Hao Zhai et al. (2020) look at the limitations of a local compensation technique and offer an optimisation problem. When the theory is applied to a difficult multi-node three-phase system, a matrix prototypical is produced for harmonic and imbalance investigation. After tackling the optimisation problem using a matrix-based least squares approach, a generalised SAPF optimal compensation technique for system-wide voltage quality enhancement is created. A multi-node network with several scattered NLLs and UBLs may be scientifically enhanced with quick response, good performance, and affordable by using a small number of SAPFs, according to the suggested method. Results from simulations and experiments are provided to show that the suggested strategy works.

For a grid-connected application that enhances power quality, P. Suresh et al. (2020) proposed a shunt Active Power Filter (APF), backed by a Solar Photovoltaic (SPV) system. Adaptive Proportional Integrative Derivatives (PID), which is based on the Least Mean Eighth (LME) and Unit Vector Template (UVT) technique, are used to produce the reference signal for the shunt APF. The three phase reference source current is determined using the LME method, which also splits the load currents into basic weight portions. The gate signal of the shunt APF is created using these reference currents. The shunt APF with an PID regulator uses the DC-link voltage controller to possess the DC-link voltage constant. A suitable regulator that is developed utilising an intelligent computational method for anticipating the appropriate reference signals eliminates the distortions of the current electric power distribution systems. The maximum power point tracking algorithm serves as the foundation for the MPPT-based SPV system, which is connected to the electrical grid and strives to maximise energy production from the SPV panel. The DC-link of the shunt APF is continuously maintained by the SPV network for long-term harmonic justification. Mathematical analysis of the existing reference signal creation method is done, and the outcomes of digital simulations are shown for various stable and dynamic state scenarios. The entire technique is then validated using the hardware prototype.

A three-phase, three-wire shunt active filter is an effective approach to lower total harmonic distortion, claim T. M. Thamizh Thentral et al. (2021). Three separate control techniques—real and reactive power theory, synchronous reference frame theory and indirect reference current theory—have all been used to research this strategy. The use of recognised control techniques with the fuzzy controller improves the induction motor drive's performance. The hardware configuration of the suggested fuzzy-based control methodology was made in order to outperform other control methods in terms of decreased total harmonic distortion, higher DC link voltage, and enhanced induction motor drive speed capabilities. Improved reactive power compensation and additional power factor correction result from hardware implementation. In order to control harmonics within the confines of the IEEE-519 standard, A. Lakum et al. (2021) determined the optimal placement and size (OPAS) of an active power filter (APF) taking into account photovoltaic distributed generation (PVDG) and nonlinear demand. The introduction of harmonics into the distribution system is thoroughly investigated for the changing nature of PVDG output by including hourly solar irradiance data. Here, the ideal position for an APF is established for three distinct scenarios: 1) just one state with the fewest APFs, 2) numerous states with various total harmonic distortion in voltage (THDv), and 3) numerous states with identical THDv and all the same APFs. The grey wolf optimisation (GWO) and its adaptive version (AGWO) algorithms are used to calculate and compare the size and cost of the APF for each hour. For the best outcomes, GWO and AGWO algorithms are also used to validate the ENLPCI. The IEEE-69 bus test network is utilised to assess the proposed technique. The findings demonstrate the profound impact fluctuations in solar irradiation have on the OPAS of APF. The AGWO outperformed the GWO in determining the optimal price for APF.

III. PROPOSED TSOA BASED FOPID CONTROLLED SHUNT ACTIVE POWER FILTER FOR POWER QUALITY IMPROVEMENT

Every utility in the world uses nonlinear electrical utilizations, which depend on power electronic switches, for both household and commercial applications. Arc furnaces, computers, and variable frequency drives (VFDs) are examples of nonlinear loads that can lead to harmonic distortion, voltage swings, and noise in the power supply. Power losses, electric device heating, insulation failures, communication system interference, and, in the bad situations, electric power system failure are all caused by harmonic distortion in low-voltage distribution systems. Therefore, it is essential that problems with power quality are fixed for the good of the utility and the client. According to this standard, there can be no more than 5% total harmonic distortion (THD). Power filters are therefore utilised to stay inside the 5% limit.

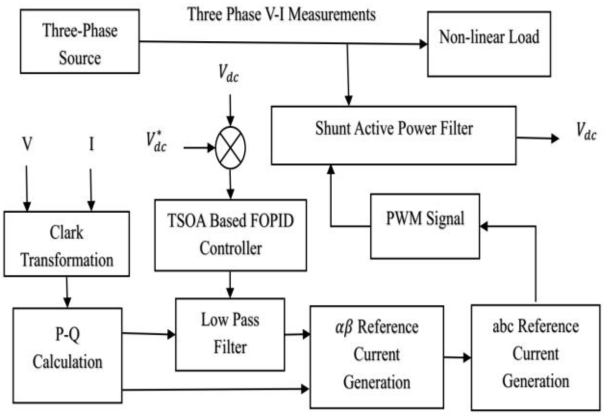

Figure 1. Proposed Block Diagram with FOPID Controller

Figure 1 depicts the suggested block diagram for enhancing power quality using a FOPID Controller. The power the control circuit are the two circuits that make up a shunt active power filter. The task of generating the necessary compensatory current falls on the power circuit. To control and maintain the DC voltage as well as store energy, it is made up of a DC-link capacitor and a PWM-based voltage source inverter (VSI). Before controlling the power circuit to accurately synthesise the needed harmonic current, the control circuit continuously monitors the harmonic current variation to control the instantaneous reference compensation current. The effectiveness of the harmonic extraction and current control procedures has a considerable influence on the harmonic current compensation process.

A. Design of SAPF based on instantaneous PQ theory

A collection of instantaneous values of active and reactive powers established in time domain serves as the basis for the instantaneous active and reactive power theory, also known as the p-q theory. The three-phase generic current as well as voltage waveforms can be utilised in systems that operate on three phases with or without a neutral wire and have no restrictions on the voltage or current waveforms. As a result, both the steady state and the transitory state are applicable. When constructing regulators for power conditioners based on power electronics strategies, this method is very helpful and adaptable. A three-phase system is differentiated by being seen as three single-phase networks in other traditional notions of power. Before defining instantaneous power according to these coordinates, the p-q theory first applies the Clarke transformation to voltages and currents from the a, b, and c coordinates to the 0 coordinates. As a result, this theory always views the three-phase system as a single entity rather than as a superposition of or total of three single-phase circuits. In three-phase systems with or without a neutral conductor, the p-q theory can be established. Equation (1) shows how to determine the three instantaneous powers using instantaneous phase voltages and line currents on the 0 axis. These three powers are the instantaneous zero-sequence power P0, the instantaneous P, and the instantaneous q.

$$\begin{pmatrix} P_0 \\ P \\ Q \end{pmatrix} = \begin{pmatrix} V_0 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & -V_\beta & V_\alpha \end{pmatrix} \begin{pmatrix} I_0 \\ I_\alpha \\ I_\beta \end{pmatrix} \qquad (1)$$

Consider a three-phase system with instantaneous phase voltages of $V_a, V_b,\ and\ V_c$ and instantaneous line currents of $I_a, I_b\ and\ I_c$. Equation (1) becomes true because zero sequence power in a three phase, three-wire system is always zero:

$$\begin{pmatrix} P \\ Q \end{pmatrix} = \begin{pmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{pmatrix} \begin{pmatrix} I_\alpha \\ I_\beta \end{pmatrix} \qquad (2)$$

The currents α and β will be established as functions of voltages and the real power (P) and imaginary power (Q), respectively, in order to clarify the physical relevance of the power described in the p-q theory. Equation (2) is shown as follows:

$$\begin{pmatrix} I_\alpha \\ I_\beta \end{pmatrix} = \begin{pmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{pmatrix}^{-1} \begin{pmatrix} P \\ Q \end{pmatrix} \qquad (3)$$

$$P = V_a I_a + V_b I_b + V_c I_c \qquad (4)$$

Equation (3)'s instantaneous q will be if the current and voltages from the variables and are swapped out for their equivalent a, b, and c variables:

$$Q = V_\alpha I_\beta - V_\beta I_\alpha = \frac{1}{\sqrt{3}}\{(V_a - V_b)I_c + (V_b - V_c)I_a + (V_c - V_a)I_c\} \qquad (5)$$

This equation is used in some equipment for measuring the three-phase Q and is comparable to it.

The usage of voltage and current phases distinguishes those instruments. In this case, instantaneous voltage and current values are utilised. Real and reactive powers can be expressed using the p-q theory as:

$$P = \widetilde{P} + \overline{P}, Q = \widetilde{Q} + \overline{Q}, P_0 = V_0 I_0 \quad (6)$$

Where:

P =The entire instantaneous energy flow per second between the source and the load that is represented by the active power for a three-phase system in steady state or during transients, whether it has a neutral conductor or not.

$\widetilde{P}$ = The power source and the load exchange a fluctuating value of instantaneous real power using the a-b-c coordinates. Since the alternating value of the instantaneous real power does not involve the energy transfer by harmonic currents from the source to the load, it must be made up for.

$\overline{P}$ =The amount of real power that is transmitted from the power source to the load on average at any given moment. Due to fundamental active current, it is the sole desired power component to be supplied by the power source.

Q = the hypothetical power and proportionate to the amount of energy that is transferred between the system's phases. It never aids in the passage of energy between the source and the load.

$\widetilde{Q}$ = It is not inferred by the fluctuating value of the instantaneous imaginary power exchanged across system phases that energy is transferred from the power source to the load. It must be accounted for since the instantaneous imaginary power's alternating value is undesirable. In addition, harmonic currents are to blame. In Figure 2, each of these abilities is described.

$\overline{Q}$ =Average value of the imaginary power that is exchanged across system phases; this value excludes any energy transfer between power sources and loads. Reactive power compensation and fundamental reactive current determine how the average value of the instantaneous imaginary power is compensated.

P0= The active power resulting from components in zero sequence.

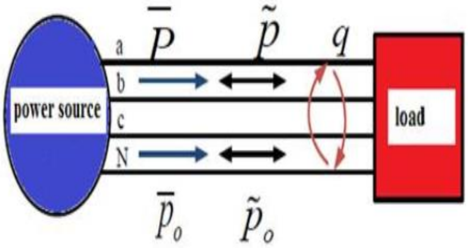

Figure 2. The idea of various power ratios between a power source and a load

Figure 3 illustrates the fundamental concept of the shunt current correction. It displays a power source feeding a nonlinear load that the filter is compensating for. SAPF is a shunt compensator in reality.

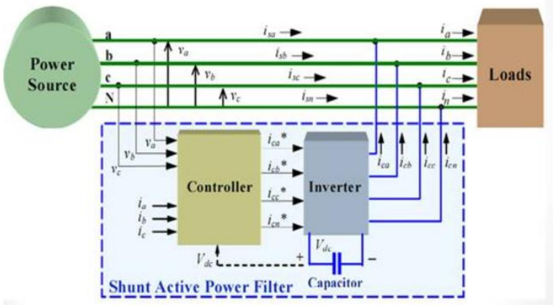

Figure 3. 3-phase SAPF system

B. Design of Fractional Order PID Controller:

Recent research has shown that FO controllers may beat conventional (integer-order) controllers in terms of system performance and robustness. Beginning in the year 1960, FO calculus has been used to model dynamic systems. Since then, research on FO control has been expanded to numerous engineering disciplines. A combination of fractional operators and controller gains make up the fractional order PID controller.

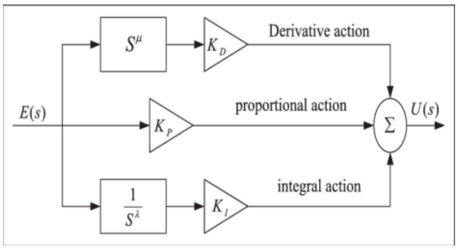

Figure 4. FOPID Controller Block Diagram

Figure 4 depicts the block diagram of the FOPID Controller. The Fractional order PID Controller, which differs from the Conventional PID Controller yet is developed from it, is a non-integer order operator. Two additional control parameters, λ and μ denoted as the order of the integral and derivative, respectively, are present in such a controller. The representation of the transfer function for the FOPID controller is expressed as

$$G_c(s) = \frac{u(s)}{e(s)} = K_P + K_I s^{-\lambda} + K_D s^{\mu} \qquad (7)$$

where $e(s)$ stands for error, $u(s)$ for output, and $G_c(s)$ for controller transfer function. The gains for proportional, integral, and derivative terms are denoted by K_P, K_I and K_D . The fractional components of integral and derivative parts are denoted by the terms λ and μ respectively. The time domain model of the FOPID controller is provided in (8)

$$u(t) = K_P e(t) + K_I D^{-\lambda} e(t) + K_D D^{\mu} e(t) \qquad (8)$$

The FOPID Controller's parameter vector is made up of the five parameters listed as (8), as per the definition in (7). Verifying a discernible improvement in the specifications of the controller's flexibility and durability is one of the investigations' most crucial goals regarding FOPID Controller tuning.

TABLE 1

FRACTIONAL ORDER PID CONTROLLER PARAMETERS

S.No	Parameters	Value
1	KP	6.23
2	ki	0.09
3	kd	0.91
4	λ	0.33
5	μ	1.33

It is obvious that, in addition to the standard three parameters KP, KI, and KD, the parameters of integral order λ and derivative-order μ should be taken into account. Therefore, the FOPID controller design process entails solving five nonlinear equations with five system-related unknowns: KP, KI, KD, λ, and μ. On the other hand, the fractional order plays a major role in the five nonlinear equations' substantial complexity. To develop the controller, it may be preferable to use MATLAB with the appropriate tool after taking the challenges into account. Additionally, the MATLAB optimisation toolbox provides the greatest results with the least amount of error.

C. Proposed Transit Search Optimization Algorithm

The details of the suggested algorithm are presented in this section. The algorithm structure defines two variables: the signal-to-noise ratio (SN) and the number of host stars (ns). The SN parameter is selected using the transit model. Additionally, the noise is evaluated using the standard deviation of observations made outside of the transit. In actuality, there is a chance that photons from star images could contain noise.

Algorithm 1. FOPID Controller-based Transit Search Optimisation Algorithm for Improving Power Quality

```
Inputs:
Number of host stars $n_s$; The parameter $L_s$ for each star
Outputs;
Luminosity $L_i$; The new Luminosity $L_{i,new}$; Transit Probability $P_T$
Initialization:
The random location for the telescope, $L_s$
Use the definition of $m_2$ and determine the brightness for each star $f_s$
Use the definition of $m_2$ for ranking the stars
For $i = 1:n_s$
    Determine the distance between the star and telescope
    Determine the luminosity of the star ($L_i$)
End
Use definition of $m_2$ and update the light signals of the stars as $L_{S,New}$
Use the definition of $m_2$ and determine the brightness for each star $f_s$
Use the definition of $m_2$ for ranking the stars
for $i = 1:n_s$
    Determine the new luminosity of the star ($L_{i,New}$)
    If $L_{i,New} < L_i$
        Do plant phase
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Otherwise $(P_T = 0)$
Do neighbour phase
End
End
Return $L_{i,New}, L_i, P_T, L_{S,New}$ (for each star)
```

IV. RESULTS AND DISCUSSION

To ascertain how successfully the suggested shunt active power filter control technique reduces current harmonics brought on by nonlinear loads, a system simulation using the MATLAB/Simulink power tool is employed. Table 2 presents the system parameters for the simulation.

Table 2. System Parameter

Parameter	**Value**
AC Source Voltage	$380V_{ph}$
Frequency	50Hz
Source Impedance	$R_s = 0.1\Omega, L_s = 10mH$
Filter Impedance	$R_s = 0.1\Omega, L_s = 1.0\ mH$
DC Link Capacitor	$1000\mu F, 400V$
K_p	1.2
K_i	20
K_d	10

The efficiency of the SAPF in removing harmonic current is assessed under both balanced and unbalanced nonlinear load scenarios using FOPID Controller and TSOA based FOPID Controller. Figure 5 displays the FOPID Controller's Transit Search Optimisation Algorithm's optimisation outcomes.

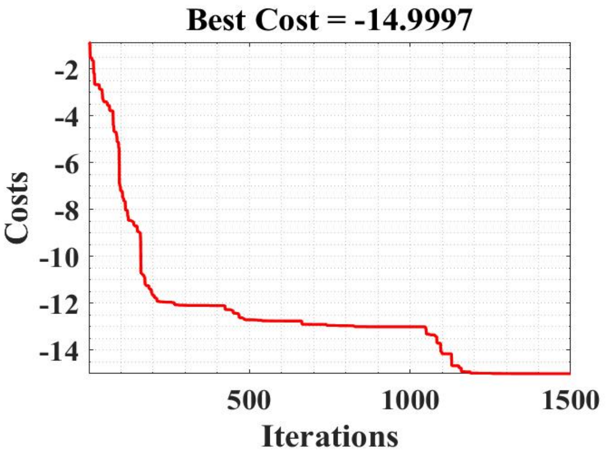
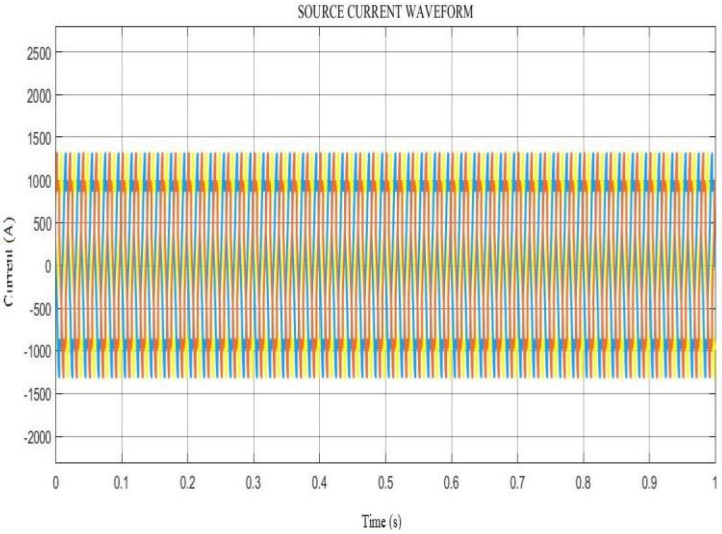
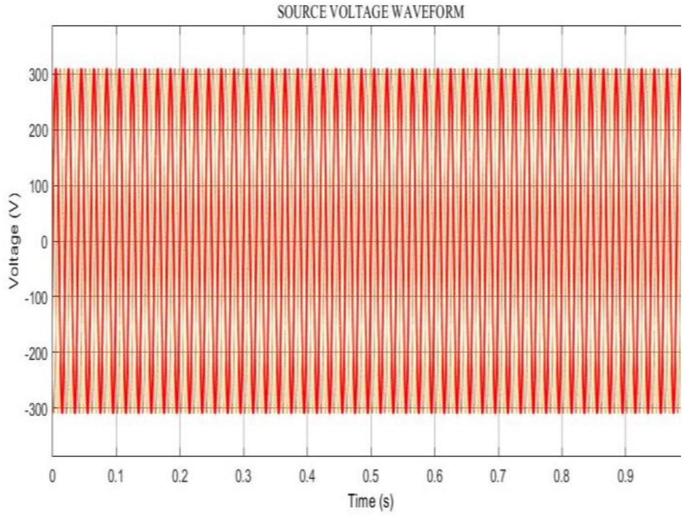


Figure 5. Transit Search Optimization Algorithm based FOPID Controller Waveform

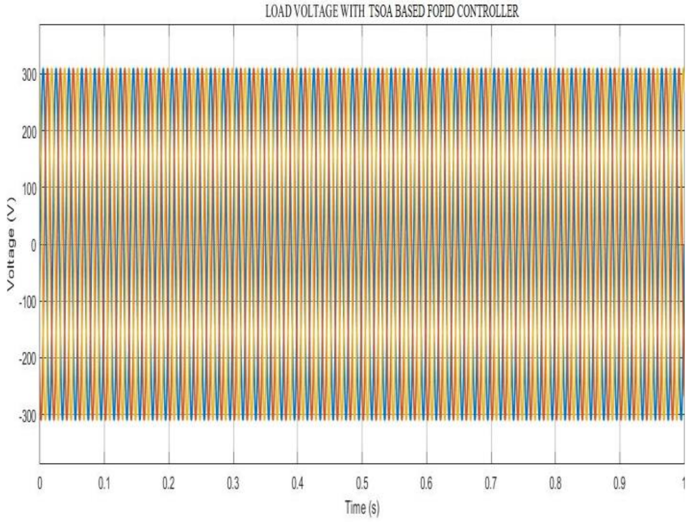


(a)

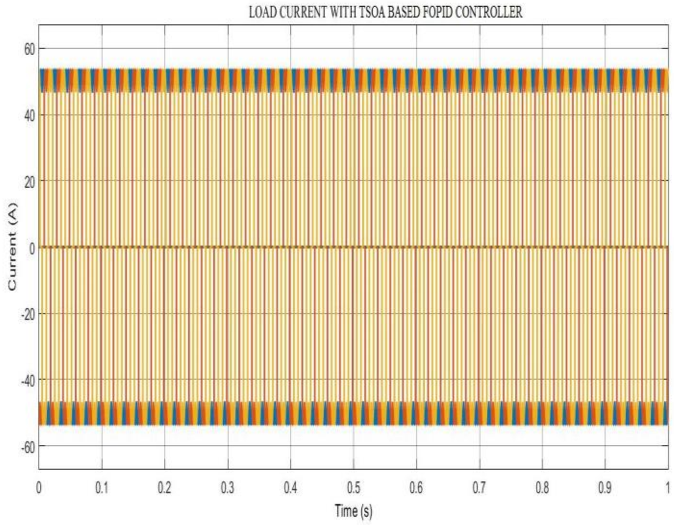


(b)

Figure 6. Source voltage and current waveform with TSOA based FOPID Controller for balanced system



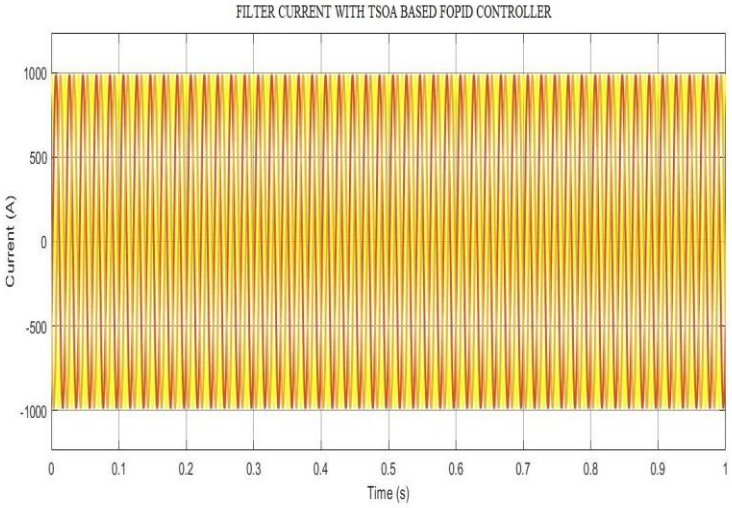
(a)



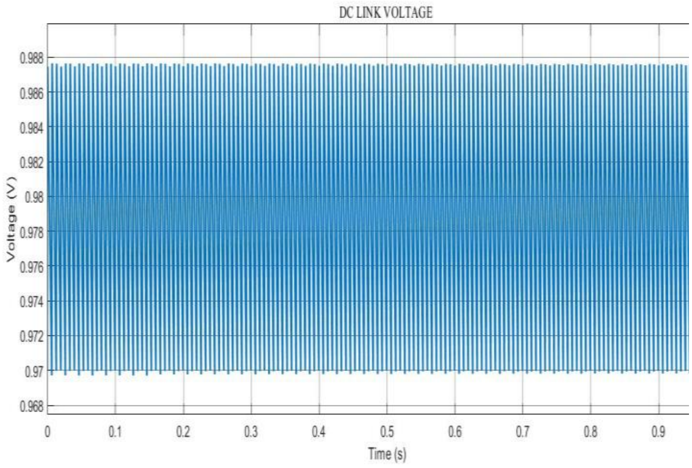
(b)

Figure 7: Load voltage and current waveform with TSOA based FOPID Controller for balanced system

The Source voltage and current waveform with the TSOA-based FOPID Controller for a balanced load is shown in Figure 6, where the values of current and voltage are respectively -1200 to 1200A and 300V. Figure 7 shows a load voltage and current waveform with a TSOA-based FOPID controller for a balanced load. The values of the current and voltage are -50 to 50 A and 300V, respectively.



(a)



(b)

Figure 8: DC link voltage and Filter current waveform with TSOA based FOPID Controller for balanced system

The waveforms of the DC link voltage and filter current with the TSOA-based FOPID Controller are shown in Figure 8 for a balanced load. The filter current is 1000 A, and the dc link voltage is 0.98V.

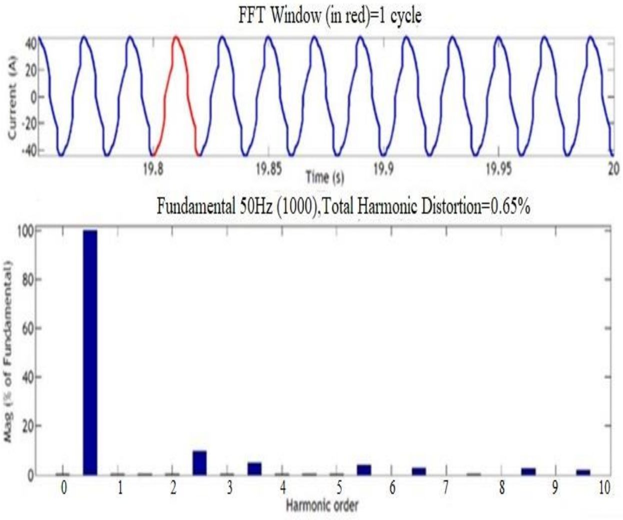


Figure 9. Total Harmonic Distortion Waveform of balanced load with TSOA based FOPID Controller

Figure 9 displays the total harmonic distortion waveform under a balanced load with a FOPID controller that is based on TSOA, with a THD value of 0.65%. With a source current of 1000A, one cycle of harmonic distortion is measured. Balanced systems have a smaller THD range than unbalanced systems.

V. CONCLUSIONS

A variety of techniques were used in this study to demonstrate their usefulness and provide the best results for SAPF device control. The current reference generating techniques for the speculative current computations utilised the PQ theory. Studies on power quality aim to keep the current and voltage in three-phase power systems as pure sinusoidal waves with a phase shift of 120 degrees between adjacent phases and a magnitude of 1 p.u. at a frequency of 1 p.u. One of the power quality issues brought on by nonlinear loads, which draw non-sinusoidal currents and degrade power quality, is harmonic distortion. The MATLAB/Simulink platform has been used to model the design of a three-phase, three-wire shunt active power filter, which is based on the instantaneous reactive power theory and the FOPID control algorithm, which is based on hysteresis-TSOA. Both balanced and unbalanced nonlinear load scenarios have been used to test how well the filter reduces current harmonics.

ACKNOWLEDGMENT

The authors would like to thank Arunachala College of Engineering for supporting this research.

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