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Single Phase Harmonic Mitigation Using Particle Swarm Optimization in Shunt Adaptive Power Filter

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Abstract

Purpose – These load sources are the main cause of generating harmonics, generating power loss in the transmission system and electrical equipment system, as well as reducing the life of electrical equipment, reducing the accuracy of electrical measuring devices, and reducing the signal transmission of communication devices.

Methodology/Approach – This study applies the Particle swarm optimization (PSO) algorithm to DC-link capacitor voltage control based on the Proportional-integral (PI) control algorithm to determine the reference current. MATLAB/Simulation 2019a is used to simulate research results.

Findings – The harmonic compensation performance of the SAPF circuit gives good results and meets the standard for total harmonic distortion (THD) of less than 5%.

Originality/Value of paper – Bridge rectifiers with RL load and Non-linear load with active RC are applied in a single-phase power supply. The single-phase voltage source inverter is used to shunt the adaptive power filter (SAPF) to compensate for reactive power and current harmonics.
***Keywords*— Particle Swarm Optimization, PSO, Shunt Adaptive Power Filter, SAPF, Single-Phase Power.**

INTRODUCTION

Single-phase power systems use a lot of nonlinear loads such as fluorescent lamps, computers, circuit converters, welding machines, etc. These load sources are the main cause of generating harmonics, generating power loss in the transmission system and electrical equipment system, as well as reducing the life of electrical equipment, reducing the accuracy of electrical measuring devices, and reducing the signal transmission of communication devices. The act of eliminating harmonics (Kumar et al., 2017) in the power supply is an urgent issue that researchers, manufacturers, and electricity users need to pay attention to first. There are many methods to remove harmonics or minimize harmonics in single-phase power such as using a Passive Power Filter (PPF) using an Active Power Filter (APF) (Luciano and Joan, 2020; Radek et al., 2013; Rajalakshmi and Rajasekaran, 2016) and using a Hybrid Power Filter (HPF). However, the Shunt Adaptive Power Filter (SAPF) (Radek et al., 2020; Radek et al., 2019; Martinek et al., 2019) was chosen to be used for this study because of its effective flexibility in removing harmonics, in addition, SAPF is also easy to apply in combination with existing control algorithms. such as nature optimization or inspired optimization, in this study, the combination of particle swarm optimization (PSO) algorithm with SAPF is used to control the offset current (Ic) from the reference current of the PSO algorithm to compensate for the current loss due to harmonics generated on the single-phase power supply. SAPF operates without giving rise to resonance problems in single-phase power.

The block diagram model using SAPF for harmonic control in a single-phase source is shown in Figure 1. The bridge rectifier, resistive load (R), and inductor (L) are considered for the operation of nonlinear loads connected in single-phase power systems. SAPF set of 3 elements connected and

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working together, the first part is a harmonic detector, the second part is a Hysteresis Band Current Controller which is used to calculate the reference currents to find the offset current, and the last part, the harmonic detection algorithms are presented and applied to calculate the reference current. Common algorithms used for SAPF in a single-phase source such as the PQ algorithm (Oswaldo et al., 2017), the Synchronous Reference Frame (SRF), and the Sliding Window with Fourier Analysis (SWFA) (Oswaldo et al., 2017; Hafiz et al., 2022) and SAPF also use hysteresis controllers to select offset current control in single-phase circuits (Giang et al., 2021), as these provide good, responsive performance control Fast and easy to design with y hysteresis band (HB) parameter and control DC voltage from rectifier of SAPF circuit, PI controller is applied to control DC voltage, enough for continuous regulation.
The results of applying the particle swarm optimization algorithm to the SAPF circuit in a single-phase source have several benefits such as:
1. Accelerates the convergence of the current compensating for the source current.
2. Stabilize the sine wave shape of the power supply from the stable supply of the compensating power
3. Select the best voltage level to supply to the PI controller.
4. Select the best power supply parameter to generate a suitable, stable reference current that provides rapid compensating current for single-phase power supply.
The article is structured as follows: Part 2 presents the content of modelling and its Equivalent Circuit of a Single Phase. Part 3 covers the Implementation of the Proposed Shunt Active Filter System such as Instantaneous reactive power theory, The DC regulator voltage, Synchronous reference frame, and Implementation of Particle swarm optimization (PSO). Part 4 notes the review of Hysteresis's current control. Part 5 shows results and discussion like experimental result analysis, and part 6 shows conclusion.

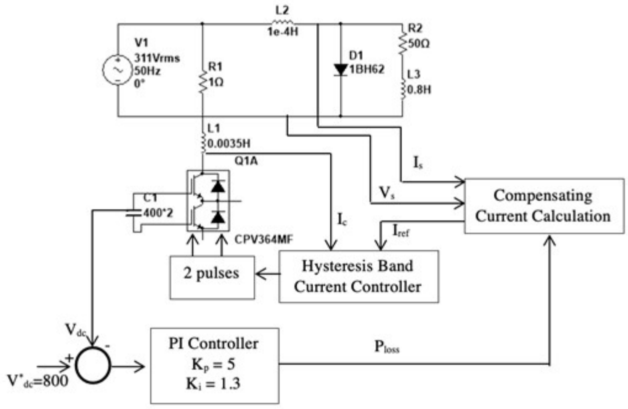

Figure 1: The considered system

Modeling and its equivalent circuit of single-phase

According to Kirchhoff's Current Law (KCL), the definition of the algebraic sum of currents meeting at a point (or intersection) is Zero (Luaciano and Joan, 2020). In particular, the Total current entering a junction is equal to the sum of the currents leaving the junction (Giang *et al.*, 2021), according to formula (1), see Figure 2 for Inductance and Resistance in Series.

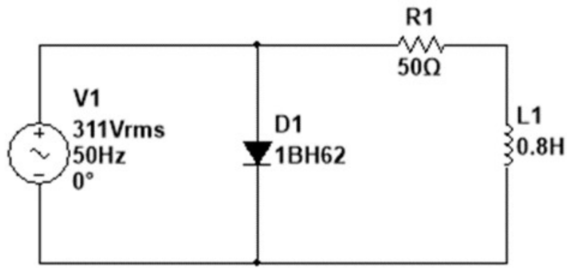

Figure 2: Inductance and resistance in series

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$I_s = (I_L) + (I_d)$ (1)

Phasors are a vector quantity, if they are of the right length and drawn in the right direction they can be plotted anywhere in the circuit. Consider Figure 1, Pythagoras Theorem may be applied, as follows:

$(V_s)^2 = (V_R)^2 + (V_L)^2$ (2)

Now, $V_R = IR;\ V_L = IX_L;\ and\ V_s = I_s Z$

$(IZ)^2 = (IR)^2 + (IX_L)^2$ (3)

And dividing through by I^2we have:

$Z = \sqrt{R^2 + (X_L)^2}$ (4)

And current through a parallel diode (A), I_{sd} - Diode reverse saturation current (A), follow formulation (5)

$I_d = I_{sd} e^{\left[\left(\frac{V_L + I_L Z}{nV_s}\right) - 1\right]}$ (5)

And

$I_{sd} = \left(\frac{V_L + I_L Z}{Z}\right)$ (6)

Substituting (4), (5) and (6) in equation (1) we get:

$I_s = I_L + \left(\frac{V_L + I_L\sqrt{R^2 + (X_L)^2}}{\sqrt{R^2 + (X_L)^2}}\right) \times e^{\left[\left(\frac{V_L + I_L\sqrt{R^2 + (X_L)^2}}{nV_s}\right) - 1\right]}$ (7)

With, the inductor value is calculated according to formula (8) and formula (9)

$X_L = \frac{V}{I_L} = 2\pi f L$ (8)

$L = \frac{V}{I_L 2\pi f}$ (9)

In addition, the value of 311V, 50Hz source voltage, and 50-ohm resistor value are selected when running the model experiment on MATLAB/Simulation.

Implementation of the proposed shunt filter system

Instantaneous reactive power theory

Liu *et al.*, (1999) proposed a PQ algorithm (Rathika and Devaraj, 2011), that has 5 steps to detect the harmonic in single-phase power systems.

Step 1: The single-phase source voltage (V_s), the single-phase source current (I_s), load current (IL) to $\alpha\beta$ by (10) and (11). with β axis is shifted from α axis by $\pi/2$ radians.

$\begin{pmatrix} V_{s\alpha} \\ V_{s\beta} \end{pmatrix} = \begin{pmatrix} V_s(\omega t) \\ V_s(\omega t - (\pi/2)) \end{pmatrix}$ (10)

$\begin{pmatrix} I_{L\alpha} \\ I_{L\beta} \end{pmatrix} = \begin{pmatrix} I_L(\omega t) \\ I_L(\omega t - (\pi/2)) \end{pmatrix}$ (11)

Step 2: The load instantaneous active power (p_L) and load instantaneous reactive power (q_L) are calculated by (12)

$\begin{pmatrix} p_L \\ q_L \end{pmatrix} = \begin{pmatrix} V_{s\alpha} & V_{s\beta} \\ -V_{s\beta} & V_{s\alpha} \end{pmatrix} \times \begin{pmatrix} I_{L\alpha} \\ I_{L\beta} \end{pmatrix}$ (12)

The p_L and q_L have consists of the harmonic component $(\widetilde{p_L}, \widetilde{q_L})$. The reference current (I_{ref}) of SAPF are calculated by $\widetilde{p_L}\ and\ \widetilde{q_L}$ for harmonic elimination and power factor improvement.

$p_L = \overline{q_L} + \widetilde{q_L}$ (13)

$q_L = \overline{q_L} + \widetilde{q_L}$ (14)

Step 3: A low pass filter (LPF) is used to determine PL, in the QP Theory algorithm, See Figure 3 The diagram of the PQ Algorithm and MATLAB/Simulink of the PQ Algorithm circuit are shown in Figure 4.

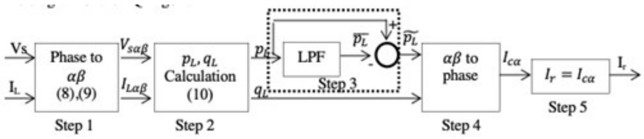

Figure 3: The diagram of the PQ algorithm

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Step 4: The reference current on αβ axis is calculated by (15).

$$\begin{pmatrix} I_{c\alpha} \\ I_{c\beta} \end{pmatrix} = \begin{pmatrix} V_{s\alpha} & V_{s\beta} \\ -V_{s\beta} & V_{s\alpha} \end{pmatrix}^{-1} \times \begin{pmatrix} p_L \\ q_L \end{pmatrix} \qquad (15)$$

Step 5: The single-phase reference current (I_r) is equal to the current value on α axis.

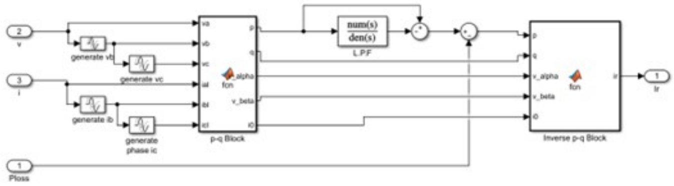

Figure 4: The Simulink diagram of the PQ algorithm

This method PQ works with instantaneous values in a system phase. This method is based on the Clark transform to convert a 1-phase system into a stationary αβ coordinate. The instantaneous active power pL and reactive power qL are calculated as follows (12). The instantaneous active power pL is divided into the fundamental active power part pL and the harmonic part. Then the Basic part is ignored. The reference current in coordinates α and β is calculated backwards qL and the offset current is obtained by performing the Clark inverse transform. The whole process is shown in Figure 3. The advantage of this method is that it is easy to implement and gives excellent results when supplying the ideal voltage to the system under static conditions. However, the PQ method has the disadvantage that the results will be skewed when the system is not supplied with an ideal voltage. This method is very sensitive to imbalance and high harmonic distortion in voltage signals.

The DC voltage regulator

The control signal (Ploss) is issued from the DC voltage from the voltage regulator (Figure 5). It forces the Shunt adaptive power filter to draw current from the network, The PI regulator is used with the transfer function of G(s) = KP + KI/s. The DC voltage regulator is a slower feedback control loop. The low-pass filters create a controller that introduces temporary compensation errors that affect the DC voltage. If the nonlinear load is unbalanced, it consumes fundamental negative current and is compensated by the SAPF unit. The SAPF unit provides negative power to the load and tends to discharge the DC capacitor. The voltage regulator recognizes this voltage change and adjusts the Ploss to adjust the SAPF generating positive current to the network. The SAPF unit provides the average negative string power to the network forward source load and discharge with the same magnitude of the DC voltage regulated around the reference value.

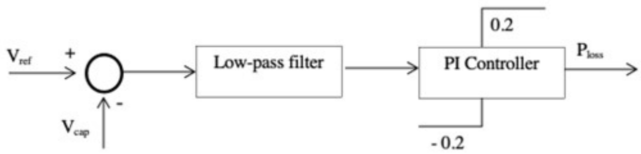

Figure 5: The DC voltage regulator

Synchronous reference frame

Gonzalez *et al.*, (2004) proposed an SRF algorithm (Kumar *et al.*, 2017) or the synchronous reference frame for a single-phase power system that uses the rotational frame (DQ axis) technique by the angular velocity at the fundamental frequency of the Point of Common Coupling (PCC) voltage. The algorithm has 5 steps.

Step 1: The single-phase load current (I_L) to αβ axis I_{Ld}, I_{lq} using (11).

Step 2: The load current on the αβ axis to the DQ axis I_{Ld}, I_{lq} by (16). Where cos(θ) and sin(θ) are rotated by phase angular of PCC voltage (PCC) which is obtained by using the Phase-Locked Loop (PLL) technique.

$$\begin{pmatrix} I_{Ld} \\ I_{Lq} \end{pmatrix} = \begin{pmatrix} cos(\theta) & sin(\theta) \\ -sin(\theta) & cos(\theta) \end{pmatrix} \times \begin{pmatrix} I_{L\alpha} \\ I_{L\beta} \end{pmatrix} \qquad (16)$$

The fundamental current $\overline{I_{Ld}}, \overline{I_{Lq}}$ and the harmonic current $\widetilde{I_{Ld}}, \widetilde{I_{Lq}}$ was shown in (17), (18)

$$I_{Ld} = \overline{I_{Ld}} + \widetilde{I_{Ld}} \quad (17)$$

$$I_{Lq} = \overline{I_{Lq}} + \widetilde{I_{Lq}} \quad (18)$$

Step 3: The LPF issued $\widetilde{I_{Ld}}$, , see Figure 6

Step 4: Calculate the reference current on αβ axis

$$\begin{pmatrix} I_{c\alpha} \\ I_{c\beta} \end{pmatrix} = \begin{pmatrix} cos(\theta) & sin(\theta) \\ -sin(\theta) & cos(\theta) \end{pmatrix}^{-1} \times \begin{pmatrix} \widetilde{I_{Ld}} \\ I_{Lq} \end{pmatrix} \quad (19)$$

Step 5: The single-phase reference current (I_r) of SAPF to the same the current value on α axis ($I_r = I_{c\alpha}$)

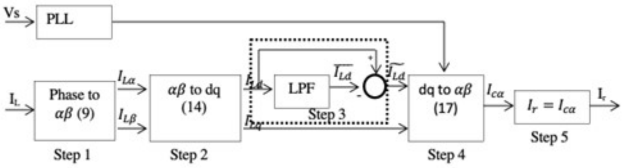

Figure 6: SRF algorithm

Implementation of particle swarm optimization (PSO)

Some parameters in SAPF need to be optimized, such as inductor L_f, Direct current (DC) link capacitor (C_{dc}) DC link voltage V_{dc}^*, K_{pc} and $K_{ic}$of the DC link with the DC voltage compensator and K_p, K_i of the PI line controller to store the minimum value Total Harmonic Distortion (THD).

The Particle Swarm Optimization (PSO) is a search technique used in computer engineering to find the optimal solution to an optimization problem. The swarm optimization method is swarm intelligence inspired by natural social behavior and moves with the communication of insects, birds, and fish. The Particle Swarm Optimization (PSO) uses several swarming particles that move around the search space to find the optimal solution in that space. Each particle in the search space adjusts its flight speed; it follows its own flight experience and the flight experience of other particles. Essential properties of PSO to note, particle *i* represents a possible solution. The group N population of particle *i* searches for possible solutions in the search space [a,b], and each particle *i* is assumed to have two properties: (1) position x_i and (2) velocity V_i. Meanwhile, each county is tracked using the parameters as (1) individual best $P_{best,i}$ and (2) global best value G_{best}. The steps of PSO implementation are presented as follows:

Step 1: Initialize the initial population with the number of seeds N.

Step 2: Initialize initial position x_i and initial velocity V_i.

Step 3: Assign $P_{best,i}$ and G_{best} based on the objective functions.

Step 4: Update position x_i and velocity V_i of each particle according to the formula.

$$V_i(+) = \theta V_i(t-1) + C_1V_1(P_{best,i} - x_i(t-1)) + C_2V_2(G_{best} - x_i(t-1)) \quad (20)$$

$$x_i(t)=x_i(t-1)+V_i(t) \quad (21)$$

Step 5: The variables of the PSO algorithm are iterated until the maximum number of iterations is reached, or the termination criterion is met, Figure.7. Shunt Adaptive Power filter (SAPF) control PSO model and parameters of the PSO method was shown in Table I.

The model of applying PSO to the control of the SAPF unit, see Figure 7, consists of four main blocks: (1) harmonic extraction block, (2) DC-link capacitor voltage regulation, (3) current control, and (4) synchronizer algorithms and an inverter voltage source including a transformer the voltage source frequency contains 2 IGBT semiconductor switches connected in a single-phase system.

TABLE I

Parameters	**Values**
Population size	30
No of iterations	300
w	0.4

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C_1	1.2
C_2	2

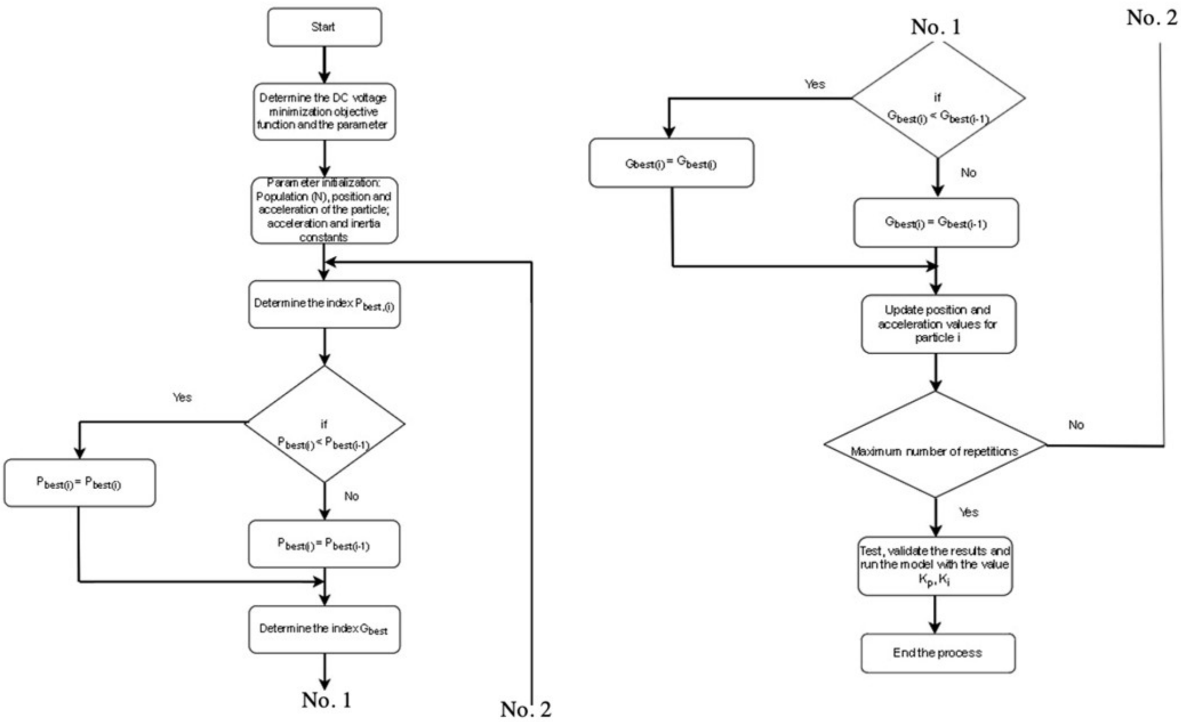

Figure 7: Flow of chart of PSO method and parameter optimization for SAPF controller to choose optimal parameter K_p, K_i.

Review of hysteresis current control

The Hysteresis current control (HCC) in combination with the pulse generator, PWM to open the valves of the IGBTs bridge rectifiers to adjust the offset current that the inverter can generate. The conversion matrix block diagram for the process of finding reference current according to instantaneous reactive power theory (p-q) using Clarke transform, (Figure 3). Block diagram of the Shunt Adaptive Power Filter (SAPF) control structure using a PI controller. The PI controller applied to the voltage V_{dc} is used in the control structure (Figure 8.

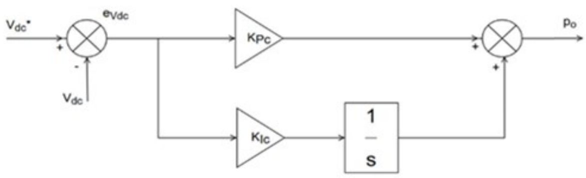

Figure 8: Structure of the controller applying PI to the voltage V_{dc}.

The triangle wave channel (TWC) is used in conjunction with a PI controller that performs PWM width modulation to switching in an IGBT bridge rectifier. The triangular carrier has a normalized to amplitude of 1 and a frequency of 50 kHz. The control signal at the output of the harmonic compensating current controller is also normalized from 0 to 1. In combination with the single-phase control signal, the pulse logic switch produces 2 PWM switching on and off for the IGBT bridge inverter (Figure 9).

Active filter design based on PI control needs to build an accurate mathematical model of a single-phase power system. Calculating parameters for the PI controller and various parameters like L_f, C_{dc}, V_{dc}^* is very complicated.

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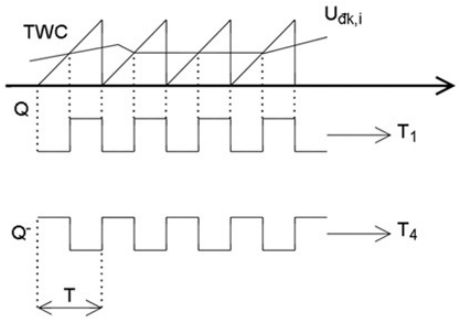

Figure 9: Effect of $U_{dk,i}$ opening and closing signal of IGBT bridge rectifier.

Result and discussion

Total Harmonic Distortion (THD) is a sinusoidal signal distortion with a percentage display value. THD is calculated as the ratio between the RMS current values of all harmony components.

$$THD = \frac{\sqrt{I_2^2+I_3^2+\cdots+I_N^2}}{I_1} x\, 100 \qquad (22)$$

With I_i the RMS current value of the fundamental harmonies $I_2, I_3, \ldots, I_N$ the RMS current value of harmonies. Signal-to-noise (SNR) is the signal-to-noise expressed to decibels.

$$SNR_{out} = 10 \times \log_{10}\left[\frac{\sum_{i=1}^{n-1}(sig_{ideal}(i))^2}{\sum_{i=1}^{n-1}(sig_{out}(i) - sig_{ideal}(i))^2}\right] \qquad (23)$$

An efficient PSO algorithm with Shunt adaptive power filter (SAPF) is proposed to find the optimal parameter of harmonies reduction in the power distribution system. The model is modeled and simulated on the bases of MATLAB/Simulation 2019a, see Figure 10. Test the proposed method by running the model test with 3 methods (PQ algorithm, SRF algorithm and Proposed PSO+PQ), the specification parameter is shown in Table II.

TABLE II

SYSTEM SPECIFICATION

Parameter	Value
Source	Supply Voltage: 311V, 50Hz L_s: 3.5mH, R_s: 1Ω
Shunt adaptive power filter	DC link capacitor (C_{dc}): 5μF Reference DC link voltage (V_{dc}): 400V Filter L_f: 0.8H, R_f: 50 Ω
Load	Three phase rectifiers with DC Load Unbalanced RL Load

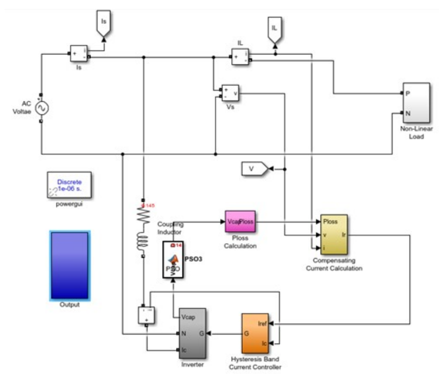

Figure 10: Experimental simulation diagram.

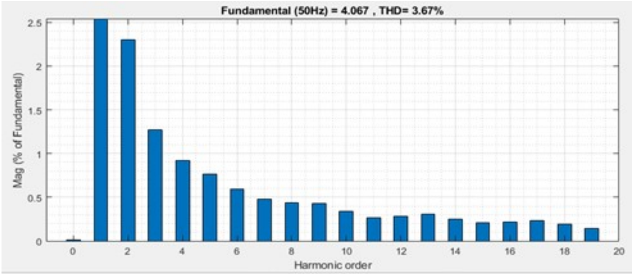

Figure 11: PSO algorithm harmonic analysis.

Simulation results of voltage source waveforms (Vs), load current waveforms (IL), offset voltage current waveforms (Ic) and source current waveforms (Is) from the experimental model are obtained by applying the PQ algorithm, the particle swarm optimization (PSO) algorithm, shown in Figure 11. The waveform of the power supply (Is) in time before compensation ($0<t<0.3$ s) is assumed to be equal to the waveform of the load current (IL) and is distorted compared to the original slurry waveform, total original harmonic distortion (THD%) is 46.58%. However, the experimental single-phase circuit diagram applies SAPF, with a delay controller and a PI controller to bring the offset current (Ic) to the reference current (Iref) from the PQ algorithm models., the particle swarm optimization (PSO) algorithm, it is possible to see that the power supply waveform (Is) after being compensated by each algorithm gradually becomes a sine shape. Although, the load current on the source changes from 5 A to 7 A at time $t>0.2$, the wave shape of the power source (Is) still maintains the sine wave shape.

Specifically, the wave shape of the power source (Is) after being compensated by the PQ algorithm, starting from $t>0.2$ s, the sine wave shape of the power source is clearly shaped time $t<0.2$, compensating current has not been generated and response to noise compensation on the power supply. The slow convergence of the PQ algorithm and the total harmonic distortion (THD%) is 3.67%. To improve the convergence and speed up the noise current compensation for the source, the particle swarm optimization algorithm is applied, and the results show significant efficiency compared to the PQ algorithm, $t>0.02$ s is the sine wave shape of the source has been profiled and total harmonic distortion (THD%) is 1.3%, see Table III. Experimental results show that the convergence and improvement of noise generated by harmonics on the power supply are better than the PQ algorithm.

TABLE III
COMPARISON OF THD WITH 3 TECHNIQUES

Solution techniques	**THD %**
PSO	1.3
PQ (Maneerat *et al.*, 2018)	3.67
SRF (Maneerat *et al.*, 2018)	3.61

Conclusion and future work

The particle swarm optimization (PSO) algorithm is used in combination with the PQ algorithm along with the Shunt adaptive power filter, to reduce the distribution power harmonic distortion. PSO is used to find the lower and upper limit parameters of the PI controller that feed the shunt adaptive power filter. Simulation results of the source current shape (Is), offset current waveform (Ic) and load current waveform (IL) of the experimental model shunt adaptive power filter, PSO provides the convergence rate Faster capacitors, increased filtering, and power compensation compensate for faster power, for results that outperform other methods. With a nonlinear load of R and L, the total harmonic distortion (THD%) value applying the PSO algorithm is 1.3% and the sine wave shape of the power source (Is) has a converging shaping rate from $t=0.02$s compared with

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THD of 3.67%, applying PQ algorithm and sine wave shape of power source (Is) with converging shaping speed from t=0.3s. The simulation results show a suitable choice for estimating the gain of the shunt adaptive power filter based on the PI controller.

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