A Whale Optimization Algorithm Based Shunt Active Power Filter for Power Quality Improvement

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***Abstract*—In this paper, a Whale Optimization Algorithm (WOA) based PI controller is designed for Shunt Active Power Filter (SAPF). For estimating the harmonic current injected in source by non-linear load, self-tuning filter is used. To control the DC-link voltage to a constant value, a PI controller is used. The gains of the controller (K_P and K_I) are tuned using WOA such that tracking performance can be improved. While for generating gate signal a simple Pulse Width Modulation (PWM) technique has been used. To verify this control method a simulation model has been designed and simulated in MATLAB/SIMULINK. The obtained results are compared with the conventional method used for obtaining the parameter values of this controller. The result shows that this proposed method gives better results in suppressing the harmonic pollution in the system.**

***Index Terms*—power quality, Shunt Active Power Filter (SAPF), Whale Optimization Algorithm (WAO), Self Tuning Filter (STF), Proportional Integral (PI) controller**

I. Introduction

Power quality plays an important role in power system. It is always a desire to have a good power quality. A good power quality means that under steady state voltage and current stays within a prescribed range with a smooth waveform which resembles sinusoidal waveform. Due to the wide use of power electronics devices in industry and household, the harmonics issue arises in power system [1]. Commonly used power electronics devices are SMPS, adjustable speed drives, programmable logic controller etc. These power electronics de-vices have non-linear characteristics and fast switching action. During their operation, they introduce harmonics in voltage and current and thereby deteriorating the power quality. The higher order harmonics in the power result to extra loss, heating problem in machines, disturbance and malfunction of equipments, poor power factor etc. However, the use of power electronics devices cannot be avoided because of its huge advantages such as fast dynamic response compared to electromechanical converters, high efficiency and reliability, less maintenance and flexibility in operation. Therefore, a mechanism is required to be introduced to handle the harmonics issues without compromising with the use of power electronic devices in power system. Traditionally, passive LC power filters were used to solve the problems of harmonics by eliminating them from the supply [2]. But this method faced problems like series and parallel resonance. At resonance, capacitor and inductor has to face over-voltage and over-current issues which can lead to failure of filter units. To overcome these issues, passive filters are replaced by power converter based Shunt Active Power Filter (SAPF). In past few decades, SAPFs have proved to be the better solution than traditional filters in reducing the harmonics [3], [4]. SAPF not only helps in eliminating the harmonics but also helps in reactive power compensation and are therefore widely used.

To reduce harmonics, SAPF senses the harmonic current and generates a compensating current that is equal and opposite to the harmonic current sensed. For the fulfillment of this process and get best results from the SAPF different control strategy have been developed in different literatures. Control strategy for active power filter includes the generation of reference current, tracking of reference current and maintaining the voltage across DC-link. Generation of reference current can be done using a frequency domain as well as time domain approach as given in different literature [5]–[10]. In [11]–[13] frequency domain approach is used and compensation signals are generated by analyzing the distorted voltage and current signal and separating the harmonic component using Fourier transformation. But in comparison to frequency domain, time domain approach is easier for controller design. Therefore, there are many control methods in time domain approach. In [5], [14] instantaneous active and reactive power $p-q$ method is used. This method is based on stationary frame $\alpha-\beta$ transformation and harmonic powers are filtered out to generate the reference signal. In [6], [15] synchronous frame transformation $d-q$ is used in which voltage and current are transformed to synchronous rotating frame and harmonic current are filtered out to generate the reference current. These methods are commonly used for reference current generation. Other methods used are flux based controller described in [9], synchronous detection method [15] described in, PI

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controller method described in [16]–[18] and sliding mode controller described in [16], [19], [20]. Second strategy is to maintain the desired voltage level across the dc-link of the converter. For this PI controller is introduced in [21] and sliding mode controller is introduced in [8]. Once the reference current is generated converter has to generate the compensation current for which the gate signals have to be controlled. In [8], a hysteresis band current controller has been designed for the gate signal generation. In [9], a space vector pulse width modulator is developed for gate signal generation. A delta sigma sliding mode controller is developed for gate signal generation in [16].

In this article, a PI controller is used to maintain the voltage level across the capacitor in the DC-link. The coefficient of the PI controller is tuned using a well known optimization algorithm (WAO) [22]. In WAO, a shrinking mechanism is used. This mechanism helps WAO to cover the entire search space, therefore the probability of hitting the optimal parameter is high [23]. To show the effectiveness of this approach in development of control strategy the results obtained are compared with the PI controller developed using conventional method. The block diagram of SAPF is shown in Fig. 1.

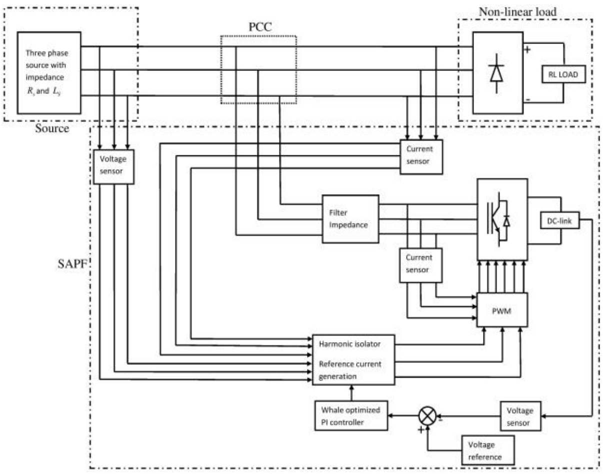

Figure 1. Block diagram of SAPF

II. Novelity

During the operation of SAPF, the DC-link voltage changes when there is change in loading condition. These changes are undesirable. Therefore, a PI controller is used to maintain the voltage. Generally the gains of the PI controller are designed using a conventional method in which overall transfer function of the voltage control loop also known as outer loop is calculated and then compared with generalized transfer function. Gains dues obtained may not be suitable for all the loading conditions. To find the ideal gain values, the PI controller is tuned using an optimization technique. Among the different optimization techniques, Whale optimization algorithm is preferred because of its capability of finding the optimal solution by means of shrinking circle mechanism which helps in covering entire search space. The results obtained using this method is compared with the conventional method. The results obtained using this method is compared with the conventional method.

III. Control Strategy for SAPF

Control strategy is the heart of shunt active power filter. To obtain the best results from the filter, it is executed in four steps. The initial step is sensing the load current and source voltage and voltage across the DC-link. In the second step, harmonic current is isolated from the sensed load current. In the next step, loss in the DC-link is calculated by comparing the link voltage with a reference voltage. Both the second and the third step combine to generate the reference current for the converter. In last step, gate signals are produced to drive the converter by comparing the filter current with the reference current. A detailed description of the complete process is discussed in the following sections. The block diagram representation of the control strategy is shown in Fig. 2.

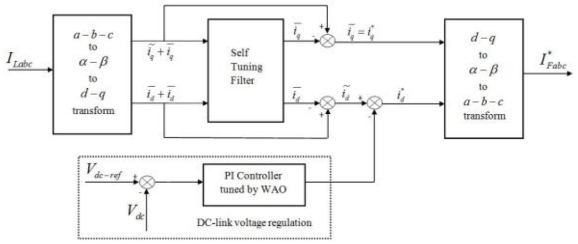

Figure 2. Control strategy for SAPF

A. Estimation of Harmonic Current

The SAPF performs well, if the reference current is accurately estimated. For this reason different estimation methods have been discussed in. It is easier to estimate harmonics current in time domain approach. Hence, among all methods synchronous rotating frame $d-q$ is used in this article. In this method, current from $a-b-c$ frame is transformed to synchronous rotating frame which rotates at a frequency θ. The transformation can be done using the equation given below:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{\sqrt{3}}{2}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

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

θ is given by $\tan^{-1}\left(\frac{v_\alpha}{v_\beta}\right)$; where $v_\alpha, v_\beta, i_\alpha, i_\beta$ are voltage and current in stationary frame $\alpha-\beta$ and i_d, i_q are current in rotating frame $d-q$. The transformed current i_d and i_q can be decomposed to oscillatory and average terms and is represented as below

$$i_d = \overline{i_d} + i_d \tag{3}$$

$$i_q = \overline{i_q} + i_q \tag{4}$$

where i_d, i_q represents the average term and $\overline{i_d}, \overline{i_q}$ represents the oscillatory term.

To separate the harmonic term, a filter can be used. In this article, a Self Tuning Filter (STF) is used [13]. The block structure of STF is shown in Fig. 3.

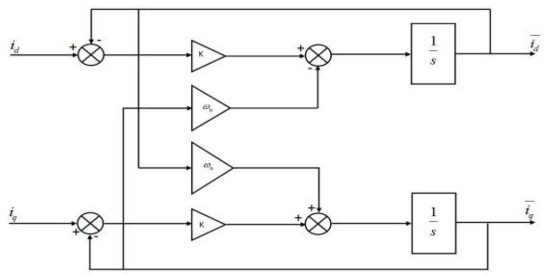

Figure 3. Block diagram of STF

The advantage of using STF is that only one filter is required to separate the average and oscillating components as compared to two different low pass filters or high pass filter for each axis. From the STF, the direct components of d-q axis currents are separated. To separate the oscillating component, dc component is subtracted from the original signal.

B. Dc Voltage Regulation

The performance of SAPF not only depends on reference current generation but also on DC-link voltage. It is therefore important to maintain a constant DC-link voltage. Whenever, there is change in demand, the active power flow in the system changes, thereby changing the DC-link voltage. To regulate and maintain a constant DC-link capacitor voltage, the active power flow into the shunt active power filter has to be regulated. This is possible, if the active power flow into the filter is made equal to the switching losses of the filter. In order to control the active current flow, a PI controller is introduced to inject equivalent current (i_{max}) of the switching losses in d axis. To achieve proper control, a reference voltage (V_{dcref}) is set. The PI controller gets an error signal which is the difference of the reference voltage set and actual voltage of the DC-link. The output of this PI control is considered as the peak value of the supply current which comprises of loss component of active power filter and fundamental active power component of load current. Hence, by the proper designing of the PI controller, a good regulation of the voltage can be achieved. To design the controller gains of PI controller, a Whale optimization algorithm (WAO) is used. The controller design is described in the section IV-B. The output of the controller is added to the isolated d-axis current to get the reference current as:

$$i_d^* = i_d + i_{max} \tag{9}$$

where i_{max} is the equivalent current comprising of loss component of active power filter. Finally, equation 8 and 9 gives the reference current which is transformed back to $a-b-c$ frame using the inverse transformation as show below

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \tag{11}$$

This generated reference current is used in the last step for generating the gate signal for the Voltage Source Inverter (VSI) of active power filter.

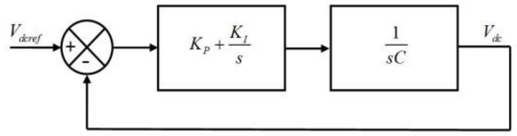

Figure 4. Voltage control loop

C. Gate Signal Generation

The last stage of control strategy is to control the gate signals for the converter (Voltage Source Inverter (VSI)) in shunt active power filter. The reference current generated from the harmonic current extraction is used for controlling the gate signals in such a way that the filter currents always track their reference current. Different methods like Pulse Width Modulation (PWM), hysteresis band controller etc can be used. In the article, PWM based technique is used because of its simplicity in implementation and fast current control response. In this technique, the filter current is compared with the reference current using a comparator. If the filter current is less than the reference current then a positive signal pulse is generated else no signal is generated. These generated pulses are fed to the terminals of VSI. To avoid the situation of short circuit only one switch on each terminal should be turned on. For this reason, pulses given to the terminals of VSI are complemented to each other so the high pulses become low and visa-verse. Under this condition, only one switch gate on each terminal gets positive pulse to be turned on. According to these gate signals, the compensating currents for all the three phases are generated which compensates the harmonic currents from the system.

IV. Design of PI Controller

To regulate the DC-link voltage, a PI controller is used. The controller gains are tuned using a conventional approach and Whale optimization algorithm based approach. The structure of PI controller been used is given as

$$C(s) = K_P + \frac{K_I}{s} \tag{12}$$

where K_P is the proportional gain which helps is providing a better dynamic response to the system and K_I is the integral gain for the control which eliminates the steady state error to the system.

A. Using the Conventional Method

In conventional method, coefficients of the controller are calculated by comparing the overall transfer function of the system with the generalized second order transfer function model. The overall transfer function of the system can be obtained by solving the outer control loop of the DC-link with the controller as shown in Fig. 4 and is given as

$$T(s) = \frac{(\frac{sK_P + K_I}{C})}{s^2 + \frac{sK_P}{C} + \frac{K_I}{C}} \tag{13}$$

The gain of the controllers is given as K_P equal to $2\delta\omega_n C$ and K_I equal $\omega_n^2 C$ [9].

B. Using WAO Approach

In this article, a Whale optimization algorithm (WAO) is used to optimize the PI controller gains. We have considered Integral Time Square Error (ITSE) as the objective function of the defined problem.

$$F = ITES = \int_0^t (te^2)dt \tag{14}$$

where $e = V_{dcref} - V_{dc}$ is the error generated after comparing the DC-link voltage with the reference voltage.

To design a robust controller, we have considered three loading conditions. They are added up to get a proper Therefore, different loading condition are evaluated and added up to get a proper objective function that has to be optimized. Hence the overall objective function to be minimized is given as

$$F_{equ} = F_1 + F_2 + F_3 \tag{15}$$

To minimize the objective function, WOA is used. WAO is inspired from the unique bubble-net hunting behaviour of humpback whales. In the process of hunting, whale starts searching the prey according to the position of other whales. Once the position of prey is defined, it starts encircling the location of prey using two different movements which is chosen simultaneously. These movements are linear motion along shrinking circle and circular motion along a spiral shaded path. Finally, when it is close to the prey, it hunts. This process is structured and mathematically modelled in three stages which are searching of prey. This is termed as exploration followed by encircling of prey. Finally, the hunting behaviour is termed as exploitation. For more details on WOA one can [24]. This algorithm is used to optimize the unknown parameters K_P and K_I of PI controller by minimizing the objective function.

In this article, the objective function that is the error generated by comparing a reference V_{dc} and voltage across the capacitor of DC-link represents the prey location while the unknown parameter K_P and K_I of the PI controller represents the whale position. Now, the aim is to find a value of K_P and K_I so that the square of the error generated should be minimized. According to the whale optimization algorithm, first step is to initialize the whale population (number of sets for parameter K_P and K_I) and initialize the random position of whales (random values of parameter for K_P and K_I each sets). Each movement of Whale towards the prey is done by calculating their fitness (distance from the prey) and each whale update their position towards the best one. Therefore, before updating the position of each search agents, their fitness is calculated and an agent with the smallest fitness is chosen as the best search agent. As described before, once the position of prey is defined whales update their position towards them using two movements. If $p \geq 0.5$ then circular path is defined by calculating the distance from the best agent and the equation for the same is given by

$$\overrightarrow{X(t+1)} = \overrightarrow{D'}.e^{bL}.\cos(2\pi L) + \overrightarrow{X^*(t)} \tag{16}$$

where $\overrightarrow{D'} = |\overrightarrow{X}^*(t) - \overrightarrow{X}(t)|$ b is a shape constant, L is random number between [-1, 1], $\overrightarrow{X^*(t)}$ is the best search agent.

If $p < 0.5$ then linear path is defined. To define the linear path a coefficient a is defied whose value is linearly decreased from 2 to 0. If the coefficient $A > 1$ the random whale position is selected as best and the updated position is given by

$$\vec{D} = |\vec{C}.\overrightarrow{X_{rand}(t)} - \overrightarrow{X(t)}|, \tag{17}$$

$$\overrightarrow{X}(t+1) = \overrightarrow{X_{rand}(t)} - \vec{A}.\vec{D}. \tag{18}$$

where $\overrightarrow{X_{rand}}$ is a random search agent chosen from the current population $\vec{X}$ and $\vec{C}$ is a coefficient and is given as $\vec{C} = 2 * rand$. The value of coefficient A is calculated using

$$\vec{A} = 2 * \vec{a} * \overrightarrow{rand} - \vec{a} \tag{19}$$

where $rand$ is a random number.

If the coefficient $A < 1$ the best minimum error agent is used to update the position and is given by

$$\vec{D} = |\vec{C}.\overrightarrow{X_{rand}(t)} - \overrightarrow{X(t)}|, \tag{20}$$

$$\overrightarrow{X}(t+1) = \overrightarrow{X_{rand}(t)} - \vec{A}.\vec{D}. \tag{21}$$

After each update the fitness is calculated and if some other search agent has less error then it is chosen as the best search agent. But before this happens, each update agent's position is checked. If any updated agent is beyond the search space then they remains at their earlier position. When the value of coefficient a is 0, the whale hunts the prey (WOA converges to the optimal solution for PI controller).

V. Simulation and Result

For optimizing the PI controller coefficients by minimizing the objective function, a model of outer control loop of the voltage control loop has been modelled in LabVIEW. Whale optimization algorithm is also implemented in LabVIEW Here the objective function is minimized using the WAO. It is important to set the search space for the parameter to be optimized. The search space for the coefficient K_P is set as $0.1 \le K_P \le 10$ and for coefficient K_I is set as $10 \le K_I \le 200$. We have done fifty different simulations to obtain the optimal value of coefficients as K_P and K_I is obtained as 0.89045 equal to 196.572.

To check the effectiveness of the designed PI controller in maintaining the DC-link voltage, a model of SAPF with balance loading condition is implemented in the MATLAB/SIMULINK. The specifications used for designing the SAPF model are given in the Table I. To check the dynamic response of the DC-link, load resistance is changed to half after 0.3 seconds of the simulation. Fast Fourier analysis of the source current obtained from the simulation shows that for an uncompensated source current has a total harmonic distortion of 28.25 % which is reduced to 4.61 % for a compensated source current for the PI controller designed using the conventional approach and 3.07 % for a compensated source current for the PI controller designed using the optimization technique. A comparison of some harmonic frequency for compensated and uncompensated current has been given in the Table II. The response of DC-link voltage presented in Fig. 5 shows better dynamic response for the PI controller designed using the optimization technique than that of conventional method. Fig. 6 presents the uncompensated source current. Compensated filter current is shown in Fig. 7 and the overall compensated source current is shown in Fig. 8.

TABLE I. SIMULATION PARAMETER

Source Voltage	120 Volts
Frequency	50 Hz
Load Resistance	45 Ω
Load Inductance	1.3 mH
Source Resistance	0.43 Ω
Source Inductance	0.1 mH
DC-Link Voltage	420volts
DC-Link Capacitance	1100 μF
Filter Inductance	3 mH
KP (using conventional method)	0.4883956
KI (using conventional method)	108.4556
KP (using proposed method)	0.89045
KI (using proposed method)	196.572

TABLE II. HARMONIC DISTORTION

Order of harmonics	Before compensation	After compensation
5^{th} harmonics	21.91%	1.67%
7^{th} harmonics	10.70%	1.41%
11^{th} harmonics	8.18%	0.16%
13^{th} harmonics	5.58%	0.21%
17^{th} harmonics	4.73%	0.08%
19^{th} harmonics	3.57%	0.10%
Total harmonic distortion	28.25%	3.07%

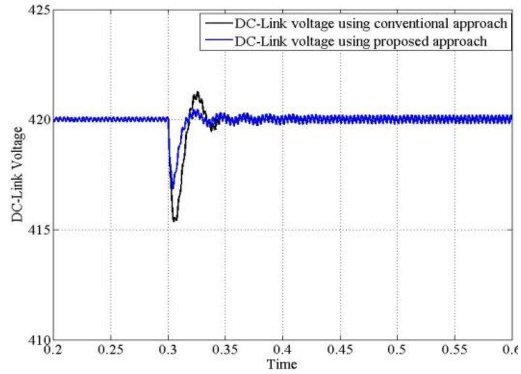

Figure 5. DC-Link voltage

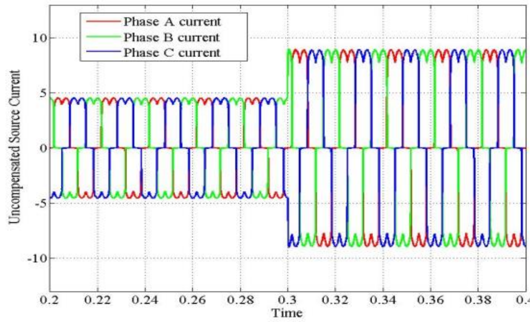

Figure 6. Uncompensated source current

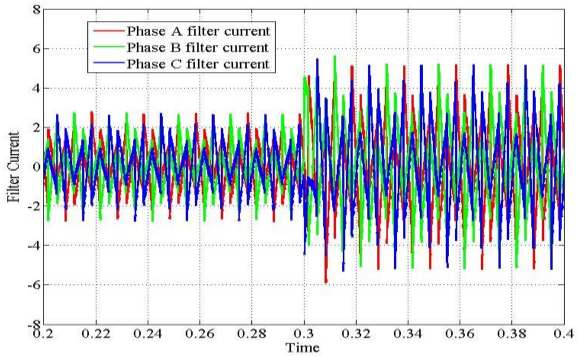

Figure 7. Filter current

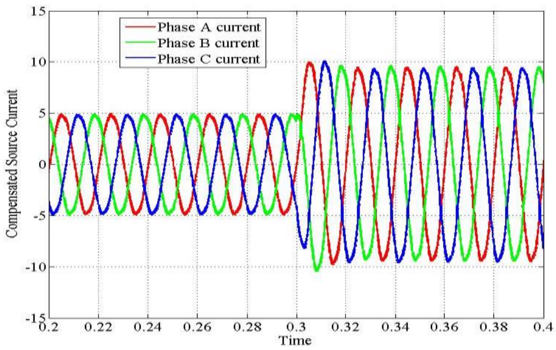

Figure 8. Compensated source current

VI. CONCLUSION

In this article, a PI controller is designed using Whale Optimization algorithm has been presented such that DC-link voltage will remain constant for different loading conditions. This controller is used to regulate the DC link voltage during change of loading condition. The results obtained using this tuned controller is compared with a PI controller designed using the conventional method. From the simulation results, it can be inferred that this tuned PI controller not only has a better regulating ability with less overshoot but also compensates the harmonics from the source current more effectively. Further, this tuned PI controller can be used in hardware for real time implementation.

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