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Improvement of Power Quality Using Optimized Non-Linear SAPF Controller

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Abstract: In this study the optimized fuzzy logic controlled three-phase shunt active power filters to eliminate harmonics of line current, correct power factor, balanced and unbalanced loads is given. Here for efficient operation of the system this fuzzy logic controller is optimized by Ant Colony Algorithm (ACA). The controller is customized by adding an additional tuning controller to improving filter performance for light loads this tuning controller controls the output parameter of Shunt Active Power Filter (SAPF) by tuned to an optimized value. This optimized SAPF system has very short response time delay for different complex power quality issues and various compensation purposes. The system obtains dissimilar compensating current references accurately and easily. The SAPF system can be used for different compensation purposes and it improves power quality accurately. Moreover, simulation shows that installation of this optimized controller in the SAPF system eliminates harmonics and corrects the waveform of the line current and corrected power factor. Simulation results obtained with MATLAB and testing results on an shunt APF are presented to validate the performance of the compensation system.

Key words: Shunt active power filter, harmonic elimination, ant colony algorithm, fuzzy logic controller instantaneous reactive power theory, voltage

INTRODUCTION

The current drawn by power electronics loads in power systems is degrading the power quality because of harmonics, voltage fluctuations and undesired power factor. Conventionally, the passive filters have been used to moderate the harmonics distortion and reactive power compensation. But these filters are bulky and they are resonating with the supply impedance (Li *et al.*, 2005). The active power filters is an efficient tool which is used to compensate the various problems and also current harmonics produced by non linear loads. But also of reactive power and unbalance of fluctuating loads (Mattavelli, 2001), even though it is smaller but it is more reliable, better damped and more selective. They are studied widely and great developments have taken place in theory and application of Shunt Active Power Filters (SAPFs) (Zhaoan *et al.*, 1998). Figure 1 shows the basic compensation principle of shunt active power and the main objective of the SAPF is to compensate the harmonic currents due to the non linearity of the load. The SAPF is to sense the load currents and extract the harmonic component of the load current to produce a reference current I_R. The reference current consists of the current harmonics of the load and the active filter must supply. The IRPT (pq theory) which is used to identify the injected current harmonics this IRPT theory was introduced by Akagi *et al.* (1983) in Japanese.

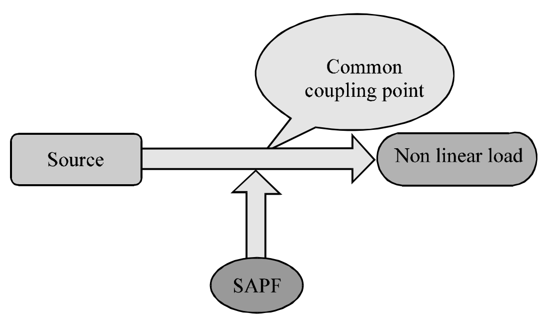

Fig. 1: Basic principle of Shunt Active Power Filter (SAPFs)

The proposed optimized non linear controller is good tool for the compensation purpose not only for the current harmonics produced by the non linear load (Mattavelli, 2001). If we adjust the DC-link voltage of

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SAPF system, the system will give the great extent and provide trouble-free control and better performance. The Fuzzy theory was investigated by Prof. Zadeh in 1965. The Mamdani fuzzy inference system was presented to control a steam engine and boiler combination by linguistic rules (Zhou and Lai, 2000). In the fuzzy logic controller is simple and more power full and the fuzzy logic controller does not require any mathematical models. Owing to its easy application, the fuzzy logic controllers are widely used in industry. However, the rules and the membership functions of a fuzzy logic controller are based on expert experience or knowledge database. The ant colony algorithm has been used to find the optimal values and parameters of the fuzzy logic controller. This algorithm was proposed by Macro and Gambardella (1997). This algorithm are strong robust and parallel processing, the algorithm has solved Task scheduling and Travelling Salesman Problems (TSP). In this study, a new approach is proposed for designing the optimized fuzzy logic controller for DC link voltage, ant colony algorithms are applied to look for globally optimal parameters of fuzzy logic. The shapes of membership functions and the best fuzzy inference rules. Moreover, the two different fuzzy logic controllers are compared and then simulations results are offered to show the efficiency of the optimized fuzzy logic controller. Finally, the harmonics of non linearity of the load has been greatly reduced and maintains the power quality as per the IEEE 519 standard.

INSTANTANEOUS REACTIVE POWER THEORY

Instantaneous currents and voltages are converted to instantaneous space vectors in a three phase circuits. In IRPT, the instantaneous three-phase currents and voltages are calculated by using the Eq. 1 and 2:

$$\begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \end{pmatrix} \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \quad (1)$$

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \sqrt{\frac{3}{2}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \quad (2)$$

These space vectors are easily converted into the α and β orthogonal coordinates. In three-phase three-wire system, the three-phase currents can be expressed in terms of positive, negative and zero sequence currents (Akagi *et al.*, 1984). In Eq. 1 and 2, v_α and i_α are on α axis, v_β and i_β are on β axis. In three-phase instantaneous power is calculated as follows:

$$P = v_\alpha i_\alpha + v_\beta i_\beta \quad (3)$$

The total power is equal to the following equation:

$$P = v_a i_a + v_b i_b + v_c i_c \quad (4)$$

The real and imaginary power are calculated by:

$$\begin{pmatrix} p \\ q \end{pmatrix} = \begin{pmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{pmatrix} \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} \quad (5)$$

In Eq. 5 $v_\alpha i_\alpha$ and $v_\beta i_\beta$ are instantaneous real (p) and imaginary (q) powers:

$\bar{P}$ = The mean value of the instantaneous real power-corresponds to the energy per time unity which is transferred from the power supply to the load

$\tilde{P}$ = Alternated value of the instantaneous real power it is the energy per time unity that is exchanged between the power supply and the load through a-b-c coordinates

$\bar{Q}$ = Instantaneous imaginary power-corresponds to the power that is exchanged between the phases of the load. This component does not imply any exchange of energy between the power supply and the load but is responsible for the existence of undesirable currents which circulate between the system phases

$\tilde{Q}$ = The mean value of the instantaneous imaginary power that is equal to the conventional reactive power

The harmonic components of total power can be load power is summation of DC components are presented in the net output and harmonic component presented in the output power. Reference current can be calculated by in the coordinates α, β, Eq. 5 can be written as Eq. 6:

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{pmatrix}^{-1} \begin{pmatrix} p \\ q \end{pmatrix} \quad (6)$$

Reference compensation currents in the a-b-c coordinate the inverse of the transformation given in expression:

$$\begin{pmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & \sqrt{\frac{3}{2}} \\ -\frac{1}{2} & -\sqrt{\frac{3}{2}} \end{pmatrix} \begin{pmatrix} i_{c\alpha} \\ i_{c\beta} \end{pmatrix} \quad (7)$$

Table 1: Fuzzy inference rules

	Error E (t)				
Output U (t)	VH	H	W	C	VC
Error variation D E(t)					
VH	VH	VH	H	H	W
H	VH	H	H	W	C
W	H	H	W	C	C
C	H	W	C	C	VC
VC	W	C	C	VC	VC

FUZZY LOGIC CONTROLLER

The fuzzy logic theory was first proposed and investigated by Prof. Zadeh in 1965. The steam engine and boiler combination was controlled by Mamdani fuzzy inference system. The fuzzy system is a rule based by means of IF-THEN with the human language. The advantage of fuzzy logic system, mathematical model is not necessary. Thus, the fuzzy logic controller owns good robustness. Fuzzy controller has been widely used in industry for its easy realization. The fuzzy controller converts a linguistic control into an automatic control. However, the rules and the membership functions of a fuzzy logic controller are constructed by expert experience or knowledge database as shown in Table 1. Set the error E (t) and the error variation De (t) of the angular velocity to be the input variables of the fuzzy logic controller. The control voltage U (t) is the output variable of the fuzzy logic controller.

In the proposed research Mamdani fuzzy inference engine is used. The linguistic variables are defined as (VH, H, W, C and VC) which mean cool, very cool, warm, hot and very hot, respectively. The membership functions of the fuzzy logic controller. The fuzzy inference mechanism in this study follows as:

$$\mu_B(u(t)) = \max_{j=1}^{m}[\mu_{A1j}(e(t)), \mu_{A2j}(\Delta e(t))\mu_{Bj}u(t)] \quad (8)$$

The control voltage can be calculated by given equation whether inferring concerned i is the output rule:

$$U(t) = \frac{\sum_{i=1}^{m}\mu_B(U_i(t)U_i}{\sum_{i=1}^{m}\mu_B(U_i(t))} \quad (9)$$

ANT COLONY ALGORITHM

Origin of ant colony: The ant colony algorithm was introduced by Marco Dorigo and colleagues in the year of 1990. The development of algorithms was inspired by the observation of ant colonies. They are in line in colonies and their behavior is governed by the goal of colony survival rather than being focused on the survival of individuals. The colony is how to find the shortest paths between food beverages and their nest. The ants are initially exploring the area surrounding in a random manner while searching food. When moving, ants are leaving a chemical pheromone trail on the ground. Ants can smell pheromone. When ants find food beverages, it evaluates quantity and the quality of the food and carries some of it back to the nest. During the return trip, the quantity of pheromone that an ant leaves on the ground may depend on the quantity and quality of the food. The indirect communication between the ants via pheromone trails this is known as stigmergy. It enables them to find shortest path between their nest and food beverages.

Figure 2 shows colony find the shortest path finding capability of ant colonies between the ants nest and the only food beverages exist two paths of different lengths, the pheromone trails are shown in the dashed lines, the thickness of dashes which indicated as trail strengths. The artificial pheromone value can be calculated as:

$$\tau_i \leftarrow \tau_i + \frac{Q}{l_i} \quad (10)$$

Where:

Q = The positive constant

l_i = The differential length

Ant colony simulation: All the ants are initially placed in node v_s ants are moved from v_d:

$$\tau_i \leftarrow (1-\rho)\tau_i \quad i = 1, 2, 3...... \quad (11)$$

ρ is the parameter regulates the pheromone evaporation. All the ants their return trip and reinforce their chosen path as outlined. The ant system simply iterates the main loop where m is the ants construct the parallel solution and updating the trail levels. The parameters are α, β relative importance of trail attractiveness. ρ is the trail persistence, τ_{ij} (0) initial trail level and no of ants:

Step 1:
{Initialization }
Initialize τ, Ψ and ηΨ, Λ(Ψ)

Step 2:
{Construction}
For each ant K (currently in state l) do repeat

Step 3:
{Trail updation}
Ant mov (Ψ) do
Compute $\Delta\tau_{i\Psi}$ update trail matrix
End for

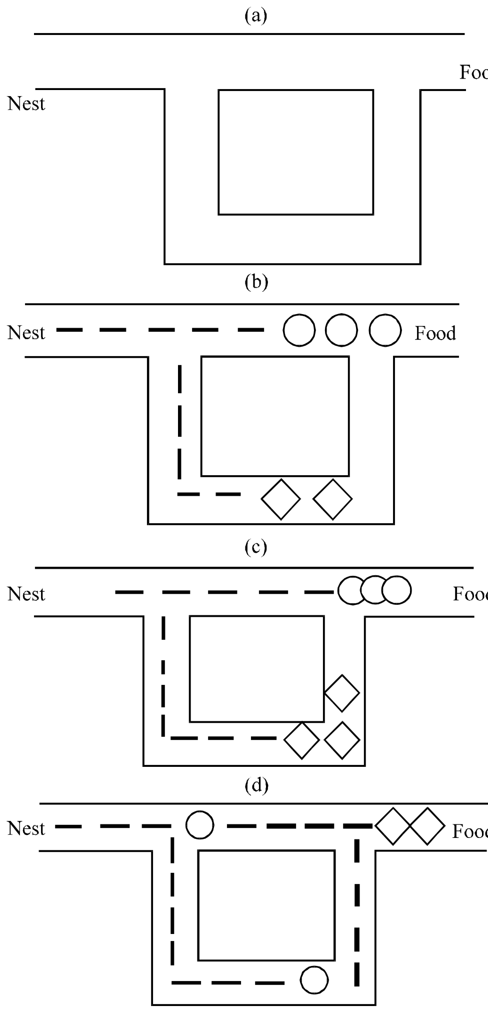

Fig. 2: a) Ants are in nest; b) 50% of ants take the shortest path (indicated in circle) 50% of ants take the longest path); c) the ants are reached earlier at the food source when returning, the probability to take again shortest path higher; d) due to evaporation of the pheromone on the long path whole ants will select the shortest path

Step 4:

{Terminating condition}

If not (end test) go to step 2

Implementing ant colony algorithm in fuzzy logic system: Visibility (η_{ij}) is related to the specific problem as the inverse of the cost function. This heuristic factor does not change while the algorithm execution; instead the heuristic factor is updated after each iteration. The parameters α and β enable the user to direct the algorithm search in favor of the heuristic or the pheromone factor. These two factors are dedicated to every edge between two nodes and weight the solution graph. The pheromones are updated after a tour is built in two ways: firstly, the pheromones are subject to an evaporation factor which allows the ants to forget their past and avoid being trapped in a local minimum (Eq. 2). Secondly, they are updated in relation to the quality of their tour (Eq. 12). The pheromones can be updated by this equation:

$$P_{ij}(t) = \frac{[\tau_{ij}(t)][\eta_{iu}]^{\beta}}{\sum_{h\epsilon s}[\tau_{ij}]^{\alpha}[\eta_{ih}]^{\beta}} \quad (12)$$

The heuristic factor η_{ij} or visibility is related to the specific problem as the inverse of the cost function. This factor does not change during algorithm execution; instead the heuristic factor (related to pheromone which has an initial value) is updated for after the each iteration. The parameters α and β enable the user to direct the algorithm search in favor of the heuristic or the pheromone factor. These two factors are dedicated to every edge between two nodes and weight the solution graph.

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Heuristic information which measures the heuristic preference of moving from node i to node j, i.e., of traveling the edge of α_{ij}, it is denoted by η_{ij}, $\rho \in (0, 1)$ is the evaporation rate:

$$\tau_{ij}(t=0) = \frac{1}{\sum_{i=1}^{a} bi} \quad (13)$$

A = The total no of attributes

bi = The number of values in the domain attributes

Ant modifies environment in two ways. When each ant passes the node, the node pheromone can be updated by the help of this equation:

$$T_{ij} \leftarrow (1-\rho)\ \tau_{ij}(t) + \rho\tau_0 \quad (14)$$

ρ = Being the pheromone evaporation rate

τ_0 = Initial pheromone value

η = Referring to the heuristic information

$$\tau_{ij} \rightarrow \tau_{ij} + \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \quad (15)$$

$$\Delta\tau_{ij} = \frac{1}{c^k}$$

If (i, j) belong to T^k; 0 Otherwise

M = The aunt number
C^K = The cost function

PROPOSED METHOD

Figure 3 shows the internal structure of the control circuit. In the control circuit have three major part which are PI and current limiter, sine wave generator. The peak reference current can be estimated by adjusting the DC link voltage. The actual capacitor voltage is compared with a set value (V_{dc}). The output of the comparator is estimated with the help of PI controller and tracing the reference current signal. The output of the PI controller which consists of two component fundamental active power component of load current and loss component of active power filter. The capacitor voltage is maintained constant. Peak value of the current so obtained is multiplied by the unit sine vectors in phase with the respective source voltages to obtain the reference compensating currents.

The calculated reference current and actual current is compared at a hysteresis band which gives the error signal for the modulation technique. This error signal decides the operation of the converter switches. The DC link capacitor voltage is kept constant throughout the operating range of the converter. The FLC controller which its output is multiplied by the mains voltage waveform Vs1-Vs3 in order to obtain the supply reference currents found. In this study, all parameters of FLC controller such as the range of the membership functions Ke and Kde, the shape of the membership functions (e1-e5, de1-de5 and u1-u5) are hinted by 150 nodes, respectively and there is resolution 0.0001 among each node.

The more accuracy trails are updated after having constructed a complete path and the solution. In this study, there are 2552 nodes including the start node and the end node to form a graph representation. Each path defines the performance indexes on the load disturbance response and transient response for a set of Ke, Kde, e1…..e5, de1….de5 and u1……u5. Finally, the optimal membership functions found using ACO algorithm of fuzzy controller are shown in Fig. 4-6.

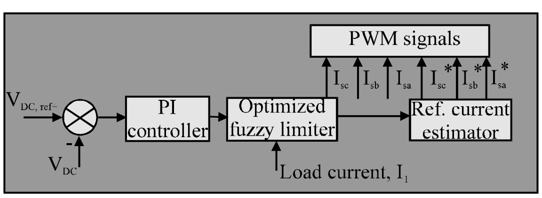

Fig. 3: Proposed controller

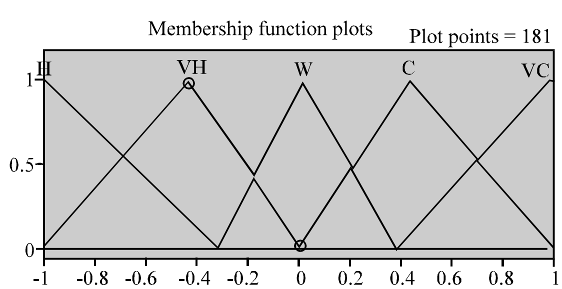

Fig. 4: Input variable E (t)

Optimal membership function

Design parameter of ant colony algorithm: The design parameters for the proposed method are initialized in the ant colony algorithm as shown in the Table 2.

Table 2: Value initialization of ant colony algorithm

Parameters	Values
Ant number	30.0
Maximum cycle time	200.0
Total trail of each ant	200.0
Trail intensity α	1.5
Coefficient ρ	0.4
Relative important parameter visibility β	2.0

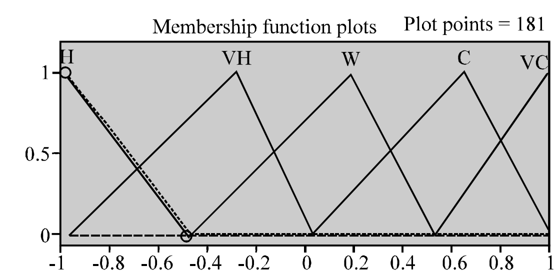

Fig. 5: Input variable DE (t)

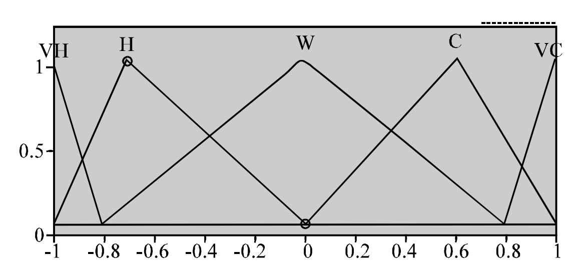

Fig. 6: Output variable U (t)

SIMULATION RESULTS

The optimized non linear controller designed by ant colony algorithm of dc capacitor voltage is set in the MATLAP environment and predict proposed method performance (Table 3). Here the two different controllers are implanted for the simulation. The conventional fuzzy controller is based on the expert experience has been used on the system SAPF which is connected in parallel with nonlinear load. The proposed optimized fuzzy logic controller with ACO has been examined to see its effect for damping harmonics current and reducing Total Harmonic (THD). The main objective is to minimize the fitness function that is shown Fig. 7-11. The regulation time and rise is comparatively shorter response. After optimization the peak over shoot is greatly reduced. The source voltage and source current are in phase with each other at that time the DC link voltage is maintained constant. The optimized non linear controller can meet the requirement of harmonic cancellation and the reactive power compensation.

Table 3: System parameter

Parameters	Values
Source voltage	220 V
System frequency	50 Hz
Source impedance	R_s 0.9 Ω; L_s 2 mH
Filter impedance	Rc-0.1 Ω; 0.6 nH
DC capacitor value	11 μF

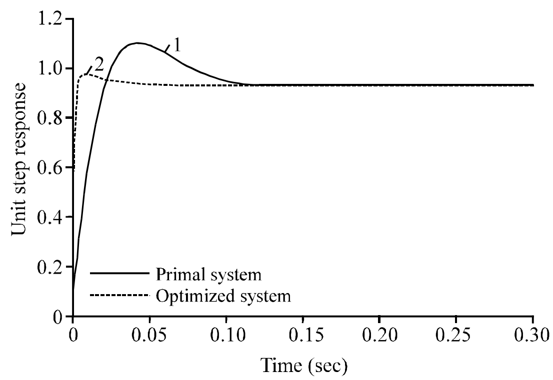

Fig. 7: Step response of SAPF system optimized and non -optimized the ant colony algorithm

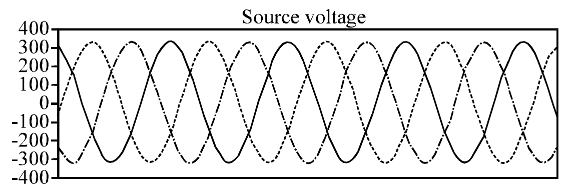

Fig. 8: Source voltage wave form

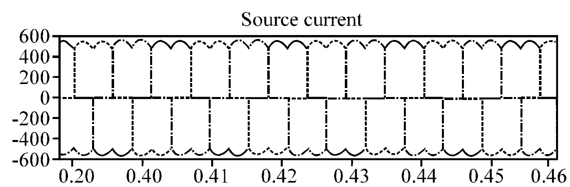

Fig. 9: Source current before compensation

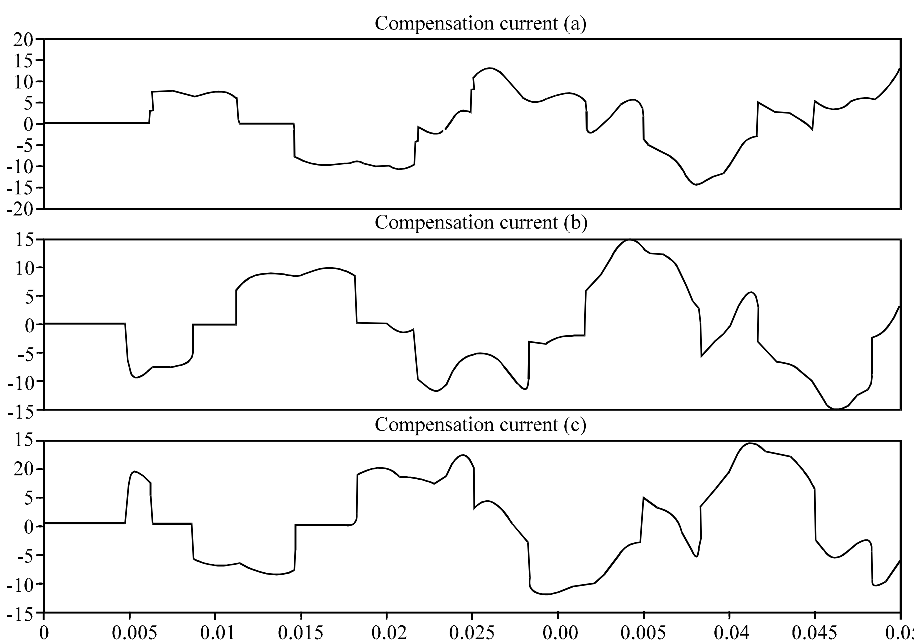

Fig. 10: Compensation current

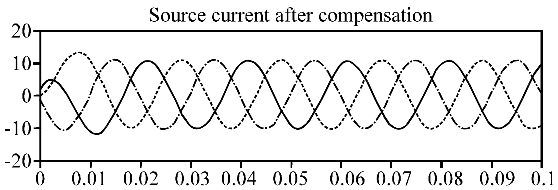

Fig. 11: Compensated source current

Table 4: Performance comparison analysis of proposed method

Parameter indexes	Non optimized	Optimized
Proportional gain K_e	0.9	0.99
Integral gain K_{de}	1.66 e^{-8}	1.69 e^{-9}
Gain U	35 e^4	32 e^4
Overshoot in percentage	16.77	4.4
Regulation time	0.096 s	0.026 s

Performance comparison results: The simulation results are shown the optimized value of PI parameters. The Fig. 6. shows the Dc link performance curve of system used in conventional fuzzy controller optimized fuzzy parameter. The comparison between the existing and proposed system shown in Table 4.

CONCLUSION

The ant colony optimization is applied to the fuzzy parameter of SAPF system is power balance principle in this study. The compensating performance of SAPF can meet the requirements of power system. Through the simulation, the optimized fuzzy logic controller is better than the existing fuzzy logic controller and then we can say that the optimized fuzzy logic controller is the best controller and performance of the controller is good one.

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