Optimal Placement of Phase Shifter Transformers for Power Loss Reduction Using Artificial Bee Colony Algorithm

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Abstract- Control of power transmission and loss causes complications in the large power systems. Phase Shifter Transformers (PST) according to their capabilities can be appropriate devices for power controlling in the large power transmission systems. Various criteria such as decreasing of loss, saving of generator annual economic cost, improving system static and dynamic behaviors and reducing of congestion have been individually studied in the literature to placement problem of phase shifter transformers (PST). In this paper, loss reduction, voltage profile and congestion improvement indices are assessed and the optimal locations of PST devices evaluated by using Artificial Bee Colony (ABC) algorithm. The effectiveness of the proposed ABC based method is demonstrated on IEEE 30-Bus network through some performance indices in comparison with the genetic algorithm and particle swarm optimization. Results evaluation show that the ABC algorithm has an excellent capability in loss reduction, voltage profile and congestion improvement than the GA and PSO methods.

Keywords: PST, Allocation, ABC; Power Loss Reduction

1. Introduction

Nowadays, increment of generation quantity becomes a necessity relating to the ongoing industrials, electrical consumptions growing and consequently the consecutive load increasing. On the other hand, operating of power system must be closed to its nominal capacity considering high development costs of networks and their related devices and environmental concerns. Liberalization of the electricity market and utilities tendency in getting more profits also compel power systems to operate close to theirs rate capacities and sometimes in over load conditions. Moreover, variable distribution of load and generation resources based on their conditions make network operate in heavy congested load conditions in some parts and in light load conditions in others. Accurate evaluating of power transmission and determining its level is investigated in congestion indices concepts. Many various indices already have been represented to quantifying congestion values of transmission lines [1].

Network operation close to its nominal capacity may appear as over load state in some sections and can lead to partial outages. Continuation of this state results in blackout condition possibly. Thus, proper management of network power flow is a main necessity along with holding the operation constraints. Controlling and managing the power flow in network lines can be done by using the various methods and some controlling actions and devices such as Generation Rescheduling (GR), series capacitors, FACTS controlling device and suede-FACTS devices [2-4]. Phase Shifter Transformer (PST) is one of the suede-FACTS devices which can replace the power in related and next lines by changing the transmitting power value that may cause to relieve congestion [5-7]. Phase shifter transformer installation considering its advantages can control the value of line power flows obviously. However, because of investment limitations, the installation and usage of phase shifter transformers only based on their advantages will not be economic.

Proper location and sizing of PST should be noticed and studied because its installation at wrong places and capacities can cause various problems in the operation conditions. In this paper, an Artificial Bee Colony (ABC) algorithm is proposed for finding optimal location of PST aimed at reducing the power loss and
improving voltage profile and power congestion. The 
ABC algorithm is a typical swarm-based approach to 
optimization, in which the search algorithm is inspired 
by the intelligent foraging behavior of a honey bee 
swarm process [12] and has emerged as a useful tool for 
engineering optimization. It incorporates a flexible and 
well-balanced mechanism to adapt to the global and 
local exploration and exploitation abilities within a short 
computation time. Hence, this method is efficient in 
handling large and complex search spaces [13].

IEEE 30 Bus network has been used as a test system 
to demonstrate the effectiveness and robustness of the 
proposed ABC algorithm and their ability to provide 
efficient loss reduction and voltage profile 
 improvement. To show the superiority of the proposed 
approach, the simulations results are compared with the 
particle swarm optimization and genetic algorithm 
through some performance indices. The results 
evaluation shows that the proposed method achieves 
good robust performance and is superior to the other 
methods.

2. PST Model [10]
An ideal voltage source with voltage $V_i$ and reactance $X_i$ 
that is connected in series between nodes $i$ and $j$ is 
shown in Fig. 1.

$V_i \angle \theta_i$ + $V_j \angle \theta_j$

Fig. 1. Series voltage source between buses $i$ and $j$

$V_i$ is an imaginary voltage source which can be defined as:

\[
V_i = V_S e^{j \phi} \quad \text{and} \quad 0 \leq r \leq 1
\]

Figure 2 shows a phasor diagram that is used to 
represent the voltage of Fig. 1 with regulating 
magnitude and angle.

\[
\begin{align*}
\sin \gamma & = \frac{V_i - V_j}{\sqrt{V_i^2 + V_j^2}} \\
\cos \gamma & = \frac{V_i + V_j}{\sqrt{V_i^2 + V_j^2}}
\end{align*}
\]

Fig. 2. Voltages phasor diagram of Fig. 1

Figure 3 shows the current source model of PST (the 
Norton model of voltage source) where $b_s = \frac{1}{X_S}$ and 
l $i_g = -j b_s V_s$.

\[
V_i \angle \theta_i + jX_j V_j \angle \theta_j = V_S \leq 1/b_s
\]

Fig. 3. Norton model of series voltage source

Current source is dependent on the usage of nodes $i$ and 
j for transmitting power, then $S_{is}$ and $S_{js}$ are expressed 
as follows:

\[
S_{is} = V_i(-I_s)^* \quad \text{and} \quad S_{js} = V_j(I_s)^*
\]

After replacing relations (1) and (2) to (3) and (4) 
and simplifying, the injected active and reactive powers 
are calculated using the following equations [10].

\[
\begin{align*}
P_{is} &= r b_s V_i^2 \sin \gamma \\
Q_{is} &= r b_s V_i^2 \cos \gamma \\
P_{js} &= -r b_s V_j V_i \sin(\theta_{ij} + \gamma) \\
Q_{js} &= -r b_s V_j V_i \cos(\theta_{ij} + \gamma)
\end{align*}
\]

The powers injection model of PST has been shown 
in Fig. 4 as a series voltage resource.

\[
\begin{align*}
P_{is} &= r b_s V_i^2 \sin(\theta_{ij} + \gamma) \\
Q_{is} &= -r b_s V_i V_j \cos(\theta_{ij} + \gamma) \\
P_{js} &= \cos(\theta_{ij} + \gamma) \\
Q_{js} &= -r b_s V_i V_j \sin(\theta_{ij} + \gamma)
\end{align*}
\]

Fig. 4. Injection model of series voltage source

By using Eqs. (5) through (8) and applying a phase 
shifter transformer, angle $\gamma$ can be changed and then 
the value of line power flow will be vary. If a PST is 
installed between buses $i$ and $j$, the new admittance 
matrix formed considering the impedance $X_i$ in the 
network admittance matrix. The Jacobean matrix is 
given in Table 1 [10]. Powers injection in PST model 
can be added to Jacobean matrix elements by a 
perticular sign.
3. ABC Algorithm

The ABC algorithm describes the foraging behavior of honey-bees for numerical optimization problems. The algorithm simulates the intelligent foraging behavior of honey bee swarms. It is a very simple, robust and population based stochastic optimization algorithm [11]. The ABC algorithm simulates the intelligent foraging behavior of swarms intelligence employed bees or the onlooker bees is equal to the source has only one employed bee. Thus, the number of unemployed foragers are associated with particular food quality (fitness) of the associated solution. Every food source whose nectar is abandoned by the bees is replaced with a new food source by the scouts. The food source whose nectar is abandoned by bees and send the scouts in the environment surrounding the nest for new food sources, and onlookers wait in the nest and find a food source through the information shared by employed foragers.

In the ABC algorithm, the colony of artificial bees contains of three groups of bees: employed bees, onlookers and scouts. The food source represents a possible solution of the optimization problem and the nectar amount of a food source corresponds to the quality (fitness) of the associated solution. Every food source has only one employed bee. Thus, the number of employed bees or the onlooker bees is equal to the number of food sources (solutions).

An onlooker bee chooses a food source depending on the probability value associated with that food source, \( p_i \), calculated by the following expression:

\[
p_i = \frac{fit_i}{\sum_{i=1}^{SN} fit_i}
\]  

where \( fit_i \) is the fitness value of the solution \( i \) evaluated by its employed bee, which is proportional to the nectar amount of the food source in the position \( i \) and \( SN \) is the number of employed food sources which is equal to the number of employed bees (\( BN \)). In this way, the employed bees exchange their information with the onlookers.

In order to produce a candidate food position from the old one, the ABC uses the following expression:

\[
v_{ij} = x_{ij} + \phi_{ij} (x_{ij} - x_{kj})
\]  

Where, \( k \in \{1,2,...,BN\} \) and \( j \in \{1,2,...,D\} \) are randomly chosen indexes. Although \( k \) is determined randomly, it has to be different from \( i \). \( \phi_{ij} \) is a random number between [0, 1]. It controls the production of a neighbor food source position around \( x_{ij} \) and the modification represents the comparison of the neighbor food positions visually by the bee. Equation (10) shows that as the difference between the parameters of the \( x_{ij} \) and \( x_{kj} \) decreases, the perturbation on the position \( x_{ij} \) decreases, too. Thus, as the search approaches to the optimum solution in the search space, the step length is adaptively reduced.

The food source whose nectar is abandoned by the bees is replaced with a new food source by the scouts. In the ABC algorithm this is simulated by randomly producing a position and replacing it with the abandoned one. If a position cannot be improved further through a predetermined number of cycles called limit then that food source is assumed to be abandoned.

After each candidate source position \( v_{ij} \) is produced and then evaluated by the artificial bee, its performance is compared with that of \( x_{ij} \). If the new food has equal or better nectar than the old source, it is replaced with the old one in the memory. Otherwise, the old one is retained. In other words, a greedy selection mechanism is employed as the selection operation between the old and the current food sources.

The main steps of the algorithm are given by [13, 14]:

\( i \) Initialize the population of solutions and evaluate them.

\( ii \) Produce new solutions for the employed bees, evaluate them and apply the greedy selection mechanism.

\( iii \) Calculate the probabilities of the current sources with which they are preferred by the onlookers.

\( iv \) Assign onlooker bees to employed bees according to probabilities, produce new solutions and apply the greedy selection mechanism.

\( v \) Stop the exploitation process of the sources abandoned by bees and send the scouts in the search area for discovering new food sources, randomly.

\( vi \) Memorize the best food source found so far.

\( vii \) If the termination condition is not satisfied, go to step 2, otherwise stop the algorithm.

It is clear from the above explanation that there are three control parameters used in the basic ABC: The
number of the food sources which is equal to the number of employed or onlooker bees (SN), the value of limit and the Maximum Cycle Number (MCN).

4. Problem Formulation

The main goal of this paper is loss reduction, voltage profile and congestion improvements via optimal allocation of PST. Decreasing the amount of loss and boosting the voltage profile are serious issues in new and modern power networks, but the necessity of having an acceptable security margin in network operation is also very important. For obtaining these purposes, utilizing of phase shifter transformers is essentially required. Thus, for balancing lines power flow, it is necessary to assess congestion problem in relevant indices firstly. To investigating the congestion parameter of test system, the \( P_{\text{Il}} \) index proposed in reference [15] has been used which is expressed as follows:

\[
P_{\text{Il}} = 1 - \frac{1}{N} \sum_{i=1}^{N} \frac{w_i}{\sqrt{2\pi\sigma}} \exp \left( -\frac{1}{2} \left( \frac{P_{\text{Il}} - \mu_i}{\sigma} \right)^2 \right)
\]  

(11)

Where,
- \( \sigma \): Lines power standard deviation from nominal values
- \( \mu_i \): Equals 70 percent of line nominal power (P.U)
- \( w_i \): Weight factor of line \( i \)
- \( N \): Number of lines \( N \)
- \( P_i \): Power of each line (p.u.)

For calculating \( P_{\text{Il}} \): \( w_i \) and \( \sigma \) is considered 1 and 0.3, respectively.

If all lines are loaded at their nominal value, \( P_{\text{Il}} \) index has a low value and if overload condition occurs in networks, \( P_{\text{Il}} \) will be have a large value. Thus, optimal location of PST will be evaluated to reduce lines loss and improve congestion and voltage profile indices by ABC algorithm. The objective function used for phase shifter transformers placement is given by:

\[
P_{\text{Il}} = w_1 P_{\text{Il}} + w_2 P_{\text{loss}} + w_3 \frac{1}{m} \sum_{i=1}^{m} (V_i - 1)
\]

(12)

Where,
- \( m \): Total number of buses
- \( V_i \): \( i \)th bus voltage in p.u.
- \( P_{\text{Il}} \): Congestion indices in p.u.
- \( P_{\text{loss}} \): Total value of system losses in p.u.
- \( w_1, w_2, w_3 \): Weight coefficients related to congestion, loss and bus voltage indices, respectively

Minimizing the objective function that is composed of loss, congestion and voltage profile indices will leads to finding PST optimal location. Thus, the allocation problem can be formulated as the following optimization problem, where the constraints are the buses voltage magnitude limits, lines active power transmitting capabilities and generated active and reactive power of generators limitations [12]:

Minimize \( P_{\text{Il}} \)  

(13)

The proposed approach employs ABC algorithm to solve this optimization problem and search for optimal placement of PST by evaluating the objective cost function as given in Eq. (13) using load flow of power system. The goal is determining the installation place and angle setting of phase shifter transformers. The weight factors \( w_1, w_2 \) and \( w_3 \) are included in objective function according the importance and effects of \( P_{\text{Il}} \), congestion index \( P_{\text{Il}} \) and buses voltage magnitudes. It is necessary to mention that in this paper they have set to 20, 1 and 1, respectively.

5. Simulation Results

The proposed method is applied to the electrical network on IEEE 30 bus including six thermal generating units as shown in Fig. 5 to assess the suitability of the algorithm. The system data extracted from [15]. The MARTPOWER-4 toolbox of MATLAB software is used for load flow running.

![Fig. 5. IEEE 30 bus power system](image)

The goal is determining the installation place and angle setting of phase shifter transformers. The obtained results using ABC is compared with PSO and GA methods in order to illustrate its robust performance and effectiveness for the solution of optimal allocation of PST problem.

Results of the PST placement based on the objective function \( P_{\text{Il}} \) by applying AC power flow using the proposed ABC, PSO and GA algorithms are given in Table 2. Figure 6 shows the minimum fitness functions evaluating process.
It can be seen that from Table 1 installing a phase shifter transformer in line 14 between buses 9 and 10 can be reduced loss and improved voltage profile and congestion indices of network clearly than the GA method. Table 3 presents the lines and network loss, \( P_l \) index values before and after installing of PST using three methods. It is evident that the ABC and PSO based solution is identical. Using the GA the reduction at total loss of network is 7.5%, whereas it is 8.5 % using the proposed ABC algorithm.

<table>
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<tr>
<th>Algorithm</th>
<th>Optimized Place of PST</th>
<th>Angle of PST</th>
<th>Function Angle of PST Optimized Place</th>
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Table 2. Optimal PST parameters

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<th>NO</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Power loss (MW) Without PST</th>
<th>Power loss (MW) With PST</th>
<th>Power loss (MW) Without PST</th>
<th>Power loss (MW) With PST</th>
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TOTAL 2.395 2.215 2.193

Table 3. The lines and network loss, \( P_l \) index values before and after installing of PST
Figure 7 and 8 show the power loss of network lines and PI\textsubscript{l} index. It can be seen that the proposed ABC method has good performance and power loss reduction and PI\textsubscript{l} index improvement is significantly occurred after PST placement using ABC and PSO techniques. Voltage profile of network before and after PST installation is shown in Fig. 9. Using the proposed ABC algorithm voltage profile is considerably improved. Moreover, it is superior to the GA method.

6. Conclusions
This paper presents an appropriate method based on ABC algorithm to improve line loss, voltage profile and congestion indices through optimal sitting of a phase shifter transformers. Due to consideration to some practical issues and by defining a new performance index, the optimum allocation of a single PST and its controlling phase angles can be determined. The proposed ABC algorithm is easy to implement without additional computational complexity. Thereby experiments this algorithm gives quite promising results. The ability to jump out the local optima, the convergence precision and speed are remarkably enhanced and thus the high precision and efficiency are achieved. The performance of the proposed ABC based method is tested on IEEE 30-Bus network and the proper location for installing phase shifter transformers is obtained by minimizing the objective function in short evaluating time. Results evaluation show significant reduction in power loss in addition to voltage profile and congestion improvement than the GA method one.

References


Biographies

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