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Optimal placement of power factor correction capacitors in power systems using Teaching Learning Based Optimization

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Abstract: This paper presents a method to optimize the placement of capacitors in a distribution system to correct power factor and reduce losses and costs. The method uses the Teaching Learning Based Optimization (TLBO) method to solve the optimal capacitor placement problem. The combinatorial nature of the problem suggests the employment of a mixed binary and real valued TLBO algorithm. To validate the efficiency of the method, it was applied to various examples (different bus systems) and simulation results are discussed.

Keywords: Power factor, Capacitor placement, TLBO, Optimization.

1. INTRODUCTION

Capacitor placement in distribution systems helps improve power factor, bus voltage regulation, reduce power and energy loss, increase system capacity in addition to enhancing the power quality [1-2].

There exist two conventional strategies to deal with the problem of capacitor placement for reactive power compensation. Either a bank of capacitors is placed at each power system bus or to place the bank of capacitors at the mains to enhance the overall power factor. The effectiveness of either strategy depends on the criticality of the power factor deterioration problem. Indeed, the first strategy is economically expensive but allows the control of the individual reactive powers at each bus. The second strategy is cheaper but no control on the individual bus reactive power levels is possible [2].

To compromise between the two philosophies, one would ask how capacitors are placed and controlled under some loading conditions. This means that the capacitor placement problem turns to an optimization problem and it should be formulated with the desired objective function (such as loss minimization and cost reduction) and various technical constraints (e.g. the limits of voltage levels and power flow)[1]. The proper solution techniques should be applied to simultaneously determine the optimal number, location, type, size and control settings at different load levels of the capacitors to be installed [3-4]. Because capacitor sizes and locations are discrete variables, the capacitor placement problem has a combinatorial nature. The problem is a binary decision making problem with discrete steps of standard bank size of capacitors.

Thanks to the rapid development of computer technology, many optimization techniques such as genetic algorithm (GA), particle swarm optimization (PSO), simulated annealing (SA), artificial neural network (ANN), and gradient-based techniques have been implemented in the form of computer codes [5]. These global optimizers while more familiar, traditional techniques such as conjugate gradient and the quasi-Newtonian methods are classified as local optimizers. The distinction between local and global search of optimization techniques is that the local techniques produce results that are highly dependent on the starting point or initial guess, while the global methods are highly independent of the initial conditions [5-7]. Though they possess the characteristic of being fast in convergence, local techniques, in particular the quasi-Newtonian techniques have a direct dependence on the existence of at least the first derivative. In addition, they place constraints on the solution space such as differentiability and continuity; conditions that are hard or even impossible to deal with in practice [5]. TLBO is a teaching-learning process inspired algorithm based on the effect of influence of a teacher on the output of learners in a class. Teacher and learners are the two vital components of the algorithm and describes two basic modes of the learning, through teacher (known as teacher phase) and interacting with the other learners (known as learner phase). The output in TLBO algorithm is considered in terms of results or grades of the learners which depend on the quality of teacher. So, teacher is usually considered as a highly learned person who trains learners so that they can have better results in terms of their marks or grades. Moreover, learners also learn from the interaction among themselves which also helps in improving their results [8-12].

In this work, TLBO method is applied to the optimal placement of power factor correction capacitors with the objective to improve power factor and reduce the cost of energy losses. Various examples (different bus systems) and simulation results of the applied technique are shown and discussed.

2. BACKGROUND OF THE OPTIMAL CAPACITOR PLACEMENT PROBLEM

The power factor (PF) is a name given to the ratio of the active power being used in a circuit to the apparent power being drawn from the mains:

$$PF = \frac{\text{Active Power}}{Apparent\ Power} \quad (1)$$

The apparent power is the geometrical combination of the reactive power and the active power flow through the motor or transformer .This ratio is denoted and termed cos φ. The apparent power is greater than the active power and hence the PF is at most 1.

Low power factor causes overload phenomenon which yields to power losses and greater voltage drops besides it increases the cost due to transmitted current and reduces the load handling capability of the electrical system [4].

Power factor Correction

Power distribution system loads causes an additional load on generators, transformers, cables and switchgear [4]. A low PF increases the investment and maintenance costs for the power distribution system. The reactive current circulating between the generator and the loads converts electrical energy into heat in the power distribution system.

Individual power factor correction

In the simple case an appropriate sized capacitor is installed in parallel with each individual inductive consumer. This will eliminate the additional load on the cabling. In this method the capacitor is only utilized during the operation time and it is not always easy to install the capacitor directly adjacent to the machines that they compensate (space constraints, installation costs) [2,4].

Group power factor correction

A combination of electrical machines that are always switched on at the same time can have a joint correction capacitor.

- Applications

Group power factor correction is used for several inductive consumers provided that these are always operated together.

- Advantages

The advantages of the group power factor correction are the same as the individual power factor correction but more cost-effective.

- Disadvantages

The group power factor correction is used only for group of consumers that are always operated at the same time.

Central power factor correction

The installation of the power factor correction capacitance will be at a central point for example at the main voltage board. This system covers the total reactive power demand. An automatic reactive power control relays are used to switch in and out of service the several sections of the divided capacitance. This method widely used today because it is easy to monitor and usually the overall capacitance installed is less and better utilized [2-4].

- Applications

The central power factor correction can always be used where the user's internal power distribution system is not under dimensioned.

- Advantages

The central power factor correction has a good utilization of installed capacitance and its installation is usually simple with less expenses.

- Disadvantages

This method has additional costs for the automatic control system and reactive currents within the user's internal power distribution system are not reduced.

3. THE TEACHING LEARNING BASED OPTIMIZATION

Mechanism of TLBO

Most of the metaheuristic methods are inspired from nature i.e. they mimic the behavior of nature. For example in Genetic Algorithm inspired from Darwin's theory, the strongest is the one who survive, Particle swarm is inspired from the movement of a flock of bird, a school of fish, or a swarm of bees that are looking for food, Artificial Bee Colony (ABC) simulates the intelligent forging of honey bee swarm, Ant colony shows how ants search for food and how to find an optimal way to it,…etc. They prove their effectiveness in solving many engineering optimization problems but each one of them requires its own algorithm specific control parameters.For example, Genetic Algorithm (GA) uses mutation rate and crossover rate. Similarly ¨Particle Swarm Optimization (PSO) uses inertia weight, social and cognitive parameters. The improper tuning of algorithm specific parameters either increases the computational effort or yields the local optimal solution. Considering this fact, Rao et al. (2011, 2012), Rao & Savsani (2012) and Rao & Patel (2012) introduced recently the Teaching-Learning Based Optimization (TLBO) algorithm which does not require any algorithm specific parameters. In this way, TLBO obtain global solutions for continuous nonlinear functions with less computational effort and high consistency [8-12].
TLBO is a teaching-learning process inspired algorithm based on the effect of influence of a teacher on the output of learners in a class. Teacher and learners are the two vital components of the algorithm and describes two basic modes of the learning, through teacher (known as teacher phase) and interacting with the other learners (known as learner phase). The output in TLBO algorithm is considered in terms of results or grades of the learners which depend on the quality of teacher. So, teacher is usually considered as a highly learned person who trains learners so that they can have better results in terms of their marks or grades. Moreover, learners also learn from the interaction among themselves which also helps in improving their results [8-13].

TLBO is population based method. In this optimization algorithm, a group of learners is considered as population and different design variables are considered as different subjects offered to the learners and learners' result is analogous to the 'fitness' value of the optimization problem. In the entire population the best solution is considered as the teacher. The working of TLBO is divided into two parts, 'Teacher phase' and 'Learner phase'. Working of both the phases is explained below.

Teacher phase: in this phase the best student is chosen from the population (the class) according to the fitness function and set as a teacher. Since the teacher is the highest learned person in the class, he puts effort to disseminate knowledge among students so that he tries to bring the mean level of the class up to his level, the new mean of the class depends on two things:

- The ability of the teacher i.e. his method in teaching is good or bad and this is represented by a factor t_f called "teaching factor", it can be 1 or 2 (those values are concluded from experiments).
- The ability of the student to receive and understand concepts from his teacher.

Learner phase: as known, when a student does not understand his teacher or he wants to have more knowledge, he will interact with one of their fellow students. If he finds his friend better than himself he will learn from him otherwise he will not [13].

Implementation of TLBO Algorithm for optimization:

Step1: formulate the optimization problem, the objective function and the side constraints:

Minimize (objective function) $y = f(x_1, x_2, \ldots, x_{n-1}, x_n)$ such that: $x_j^{min} \le x_j \le x_j^{max}$ Where j=1, 2, 3,……,D those are the side constraint which specify the limit of each design variable i.e. the maximum and minimum level in each course of any student.

The variables $x_1, x_2, \ldots, x_{n-1}, x_n$ represent the level of student $\mathbf{X}$ in each course so x_1 is the level of $\mathbf{X}$ in the first course.

Decide how many student you will use or the population size, also the number of generation. Here a minimization problem is considered; the maximization is similar.

Step 2: initialization: suggest a population (that will be developed to reach the final solution) or students randomly according to the following equation:

$$x_{(i,j)}^1 = x_j^{min} + rand_{(i,j)} \times \left(x_j^{max} - x_j^{min}\right) \quad (2)$$

i:refer to student number, so this is the ith student, *i*=1, 2, …,P

j:refer to the course number, $x_{(i,j)}$ is the level of the ith student at the jth course, *j*=1, 2,…,D

The small number 1 refer to the generation number, it's the first generation.

After manipulating the above equation $P \times D$ times, a $P \times D$ matrix which represents the population is obtained:

$$population^1 = \begin{bmatrix} x_{(1,1)}^1 & \cdots & x_{(1,D)}^1 \\ x_{(2,1)}^1 & & x_{(2,D)}^1 \\ \vdots & \ddots & \vdots \\ x_{(P,1)}^1 & \cdots & x_{(P,D)}^1 \end{bmatrix} \quad (3)$$

So $X_1^1 = (x_{(1,1)}^1, \quad x_{(1,2)}^1, \ldots, x_{(1,D)}^1)$ is student number 1 in the first generation.

Choose the teacher: the best student is the one which has the minimum fitness function.

Step 3: teacher phase

Mathematically, how the best student teaches the others:

$$X_{i,new} = X_i + (X_{teacher} - t_f \times mean) \quad (4)$$

t_f is the teaching factor, it can be 0 or 1.

A comparison between the new student $X_{i,new}$ and the old one X_i should be made, if $X_{i,new}$ is better than X_i, replace the old by the new one otherwise keep the old one. $i = 1, 2, \ldots, P$.

$$if\ f(X_{i,new}) < f(X_i)\ then\ X_i = X_{i,new}\ else\ do\ nothing \quad (5)$$

Step 4: learner phase

This phase shows the interaction between students.

For each student i we pick another student j randomly and compare their level (fitness function), the first student i will learn from the second j (get close to him) if he is better than him otherwise he will go far from him, according to the formula: $if\ f(X_{i,new}) < f(X_i)\ then\ X_i = X_{i,new}\ else\ do\ nothing$

$$X_{i,new}^g = \begin{cases} X_i^g + rand_i^g \times \left(X_j^g - X_i^g\right), & iff(X_i^g) < f\left(X_j^g\right)\ better \\ X_i^g + rand_i^g \times \left(X_i^g - X_j^g\right), & iff(X_i^g) \ge f\left(X_j^g\right)\ worst \end{cases} \quad (6)$$

After completing the process for all the population, the fittest student is set as teacher.

Step 5: if $g \neq numberofgeneration$ go to step 3 else stop.

The flowchart of the TLBO algorithm is shown in Fig. 1.

4. RESULTS AND DISCUSSIONS

Mathematical formulation

Two objectives have been set: cost reduction and power factor improvement.

- *Loss reduction*

The problem is defined as:

$$\text{Minimize: } Lt = \sum_{i=1}^{n} Li \quad (7)$$

Where:

Lt: the total losses.

N: is the number of lines.
Li: is the active losses in line i.

$$\text{Li} = \frac{\text{Ri}(\text{P}^2\,\Sigma\text{,i}+\text{Q}^2\,\Sigma\text{,i})}{|\text{Vi}|^2} \tag{8}$$

Where:
Ri = resistance of the line i.
$P^2\Sigma$,i = the square of active power summation of the downstream systemfrom node i (W).
$Q^2\Sigma$,i = the square of reactive power summation of the downstreamSystem from node i (VAr).
Vi = voltage at node i (Volts).

- *Cost reduction*

The formal definition of this problem is as follows:

Given two sets, c ("capacitors") and L ("buses locations"), of equal size, together with a weight function w : P × P → R and a distance function d : L × L → R. Find the bijection f: P → L ("assignment") such that the cost function:

$$\sum_{a,b\in P} w(a,b)\cdot d(f(a),f(b)) \tag{9}$$

is minimized , the losses are decreased and the power factor is enhanced [14-15]. The function ω will be the flow (the voltage between capacitors)

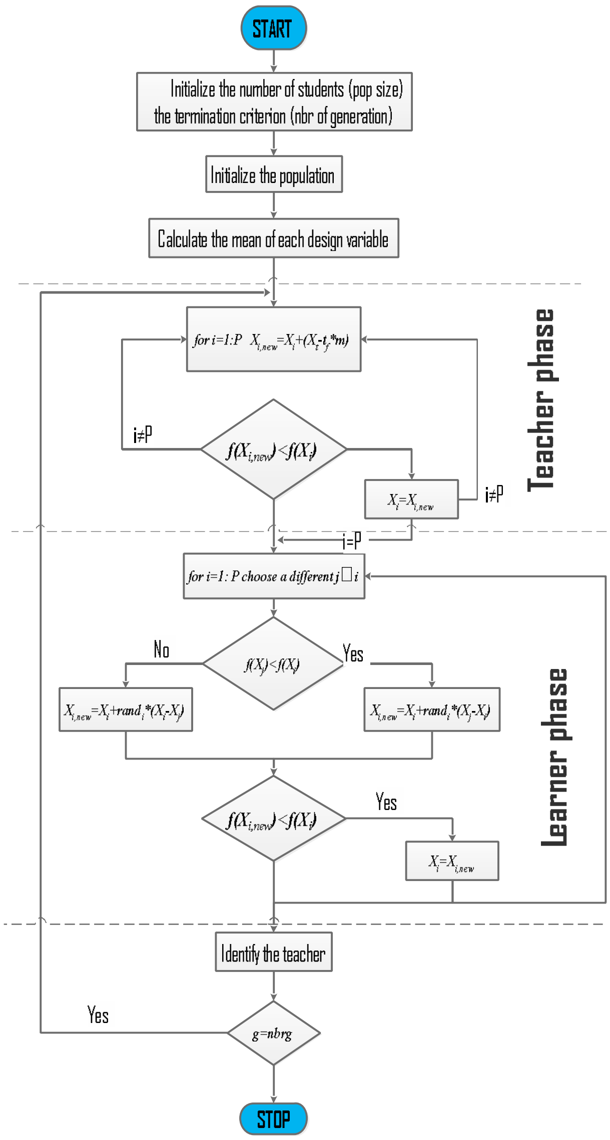

Fig. 1 Flowchart of TLBO Algorithm

Simulation Results and Discussions

- **The14-bus system**

- *Bus locations*

The bus system is represented by these two vectors to denote bus locations:
x= [67 80 62 34 54 22 36 90 95 15 40 23 75 46];
y= [9 81 9 43 89 55 63 42 58 95 64 51 52 58];

- *The voltage between any two capacitors:*

These are specified as shown in the table below:

TABLE 1 the flow between capacitors in 14-bus system

	C1	C2	C3	C4	C5	C6
C1	0	6	6	3	5	5
C2	6	0	6	4	-10	3
C3	6	6	0	4	5	8
C4	3	4	4	0	4	4
C5	5	-10	5	4	0	3
C6	5	3	8	4	3	0

- *The optimal placement of capacitors*

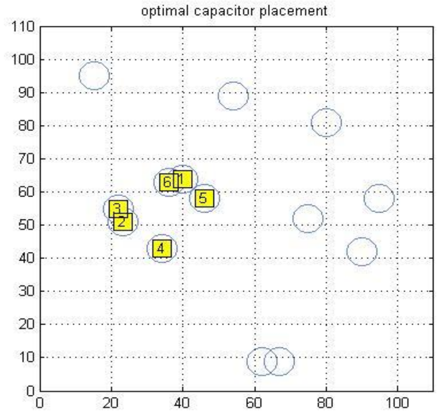

Fig. 2 the optimal capacitor placement of a 14-bus system

Figure 2 shows the ideal placement of the used capacitors performed by ACO algorithm for obtaining the best solution. In all cases simulated, the solution was found with 500 iterations. The figure shows the positioning of capacitors C3, C2, C4, C6, C1 and C5 on buses 6, 12,4,7,11,14 respectively. It is found that the cost values tend to settle exactly around 42 iterations with a best cost = 778.1096.

- **The 30-bus system**

Bus locations
This is represented by these two matrices:
x=[67 80 62 34 54 22 36 90 95 15 40 23 75 46 9 81 9 43 89 55 63 42 58 95 64 51 52 58 33 25];
y=[9 81 9 43 89 55 63 42 58 95 64 51 52 58 67 80 62 34 54 22 36 90 95 15 40 23 75 46 25 33];
Similar to the 14-bus system, the following table specifies the voltages between the capacitors as constraints to the problem:

TABLE 2 the flow between capacitors in 30-bus system

	C1	C2	C3	C4	C5	C6	C7	C8
C1	0	6	6	3	5	5	2	4
C2	6	0	6	4	-10	3	3	2
C3	6	6	0	4	5	8	2	3
C4	3	4	4	0	4	4	2	1
C5	5	-10	5	4	0	3	1	1
C6	5	3	8	4	3	0	6	4
C7	2	3	2	2	1	6	0	-3
C8	4	2	3	1	1	4	-3	0

- *The optimal placement of capacitors*

Figure 3 shows the ideal placement of the used capacitors performed by ACO algorithm for obtaining the best solution. In all cases simulated, the solution was found with 500 iterations. The positioning of capacitors C7, C8, C5, C6, C1, C4, C3, and C2 on buses 29, 4,7,18,20,28,21 and 3, respectively. The graph of the optimization evolution shows a decreasing in the total cost of the system. It can be clearly noticed that the cost values tend to settle exactly around 270 iterations with a best cost = 1777.8338.

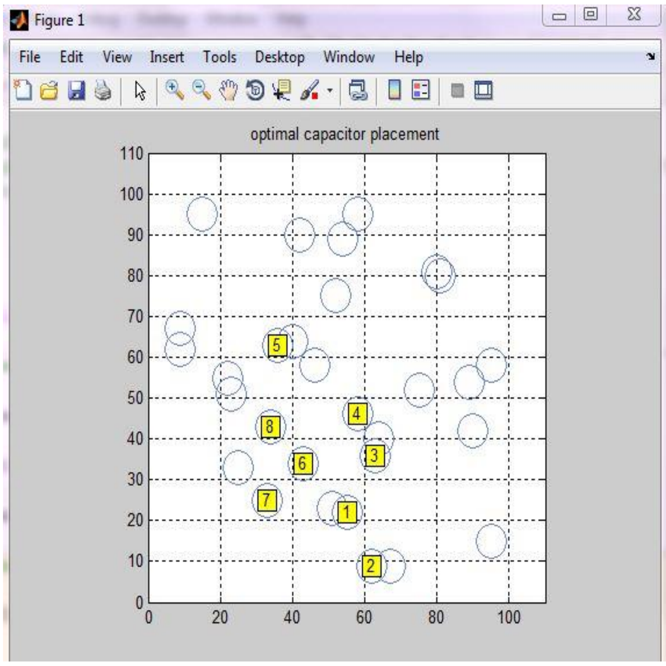

Fig. 3 the optimal capacitor placement of a 30-bus system

5. CONCLUSIONS

The placement of power factor correction capacitors using ant colony optimization has been addressed in this work. Optimal capacitor placement allows to strategically place capacitor for voltage support and power factor correction while minimizing installation and long-term operation costs. TLBO approach has been used to determine optimal placement of capacitors in a real 14-bus and 30-bus network. The approach determines simultaneously the capacitor sizing and locations as well as the voltage between capacitors.

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