

SECURITY BASED VOLT/VAR CONTROL IN DISTRIBUTION SYSTEM IN THE PRESENCE OF DISTRIBUTED GENERATORS USING TEACHING-LEARNING-BASED OPTIMIZATION ALGORITHM

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Abstract: Different operation conditions along with the existence of distributed generations (DG) are of the most important characteristics of modern distribution networks. Considering this fact, it is essential to add voltage security term to the objective function of voltage and reactive power control. This paper proposed security based voltage and reactive power control in the presence of DG in the distribution network. In the formulation of the objective function of this problem three functions are provided including; minimization of total electrical energy losses, minimization of voltage deviations and maximization of voltage stability. To satisfy these conditions, optimum dispatch schedules for the on-load tap changer (OLTC) settings and all shunt capacitors switching on the network should be taken into account. In order to reduce the volume of calculations and the number of switching's, optimization algorithms are used to classify daily load curves. Furthermore, the teaching-learning-based optimization (TLBO) which is a kind of evolutionary algorithms is proposed to solve the security based volt/var control in the distribution system in the presence of distributed generators. In addition, performance of TLBO algorithm and genetic algorithm for solving this problem are compared. Finally, IEEE 33-bus test system and real-life 77-bus distribution network are considered as the case studies to demonstrate the effectiveness of the proposed method. The results of simulation have shown us: improving voltage stability, decreasing total electrical energy losses and reducing voltage deviations. In addition, the simulation results verify that the TLBO algorithm has better performances in comparison with genetic algorithm.

Key words: Voltage and reactive power control, Voltage security, Distributed generation, Multiobjective optimization, Teaching-learning-based optimization.

1. Introduction

Voltage and reactive power control in distribution networks means appropriate operational planning of an on-load tap changer and all of switching shunt capacitors installed in the network to achieve an appropriate voltage profile and reactive power flow.

The growth of distributed generation based on renewable energy sources in distribution networks, has an important influence on the

voltage and reactive power control as one of the most important duties of the distribution network operator. The radial structure of distribution network multiplies the effect of these resources on the problem of voltage and reactive power control. On the other hand, this radial structure may lead to reduce the reliability of consumers feeding, increase the power losses and voltage drop at the load points [1]. In addition, load level of this network is constantly changing. Because of the variable nature of daily load, the network can lead to voltage collapse. To prevent the occurrence of this event, the voltage stability index is formulated as one of the objective functions of this problem along with other objective functions. The main goal of the daily voltage and reactive power control problem is to find an optimal schedule of the tap position for OLTC transformers and the on/off status of switched capacitors for the next day in order to regulate the feeder's voltage profile, and reactive power at grid while minimizing the predefined objective functions.

Recently, multi-objective optimization approaches for volt/var control have become more attractive. Ramakrishna and Rao utilized volt/var control in distribution systems in order to reduce losses in the network without violating the voltage security constraint of the system [2]. Liu et al. presented the optimal control in order to find the optimal dispatch schedule for shunt capacitor and OLTC so that power losses are minimized and voltage profile is improved [3]. A method for volt/var control is presented to dispatch OLTC, substation capacitor and feeder capacitors based on hourly forecasts of the load by Liang and Cheng [4]. The objectives, which are proposed by Liang and Cheng are minimization the total feeder loss, improvement voltage profile and limitation reactive power flow into main transformers. Besides, other researchers have studied this problem in the presence of distributed generation. For example, Niknam et al. proposed a price based approach for volt/var control in distribution system using DG units [5]. Zare and Niknam suggested a multi-objective volt/var control in distribution network, including renewable energy resources for environmental and economic management [6]. The objective functions of this

model are electrical energy losses, voltages deviations, total electrical energy costs and total emissions of renewable energy sources and substations. Niknam proposed a stochastic multiobjective framework for daily volt/var control, including hydro-turbine, fuel cell, wind turbine, and photovoltaic power plants. The multiple objectives of the volt/var control problem to be minimized are the electrical energy losses, voltage deviations, total electrical energy costs, and total emissions of renewable energy sources and grid [7]. Malekpour presented a new algorithm for the multi-objective probabilistic volt/var control problem in distribution systems including renewable energy sources. The objective functions, which are investigated, are the total cost of power generated by wind farms, fuel cell power plants and the grid; the total electrical energy losses and the total emission produced by wind farms, fuel cell power plants and distribution companies. Moreover, a new optimization algorithm based on improved shuffled frog leaping algorithm is proposed to solve this problem [8]. Mohapatra presented an efficient hybrid approach for volt/var control in distribution systems, with switching limits on taps and shunts. The proposed approach combines the strengths of a gradient technique and a metaheuristic technique [9]. Borghetti presented a mixed integer linear programming model for the solution of the three-phase volt/var optimization of medium voltage unbalanced distribution feeders. The volt/var optimization of a distribution feeder is aimed at calculating the most efficient operating conditions by means of the scheduling of transformers equipped with an on-load tap changer and distributed reactive power resources [10]. Jashfar and Esmaeili presented volt/var/THD control in distribution networks in the presence of the reactive power capability of solar energy conversion [11]. The main aim of this study is to find proper dispatch schedules for the capacitors, OLTC tap positions and inverter reactive power of photovoltaic systems by considering the power quality constraints. Azimi and Esmaeili presented a multi-objective daily volt/var control in distribution systems in the presence of distributed generation units [12]. The main purpose of this study is to determine optimal dispatch for OLTC and shunt capacitors based on the day-ahead load forecast. Although most studies focus on the optimization of distribution network losses and voltage profile, few of researchers have considered the optimum performance of capacitors and transformers in their objective functions [13]. Various mathematical techniques such as dynamic programming, gradient and sensitivity analysis are proposed to solve the voltage and reactive power control problem [14].

Due to the multi-phase nature of volt/var problem and the non-linearity of the objective functions, utilize the mathematical methods for this problem are complex and require heavy computational capacity. Hence, evolutionary algorithms have been used to solve this problem. For example, Ulinuha et al. presented a hybrid genetic-fuzzy algorithm (GA-Fuzzy) for optimal volt/var/total harmonic distortion control of a distorted distribution system serving non-linear loads [15]. Niknam used HBMO algorithm for multi-objective daily volt/var control in distribution system including distributed generators [16]. In this study, the objectives of problem are reduction of the costs of energy generation by DGs and distribution companies, electrical energy losses and the voltage deviation for the next day.

In this paper, we proposed the security based volt/var control problem in distribution system in presence of distributed generators. The volt/var control is formulated as a multi-objective optimization problem in which the objective functions are: 1) total electrical energy losses, 2) voltage deviations, 3) voltage security index. Therefore, two topics are discussed:

1) The new multi-objective function presented to solve the volt/var control problem in distribution system in the presence of distributed generators. In other words, the voltage security index, along with total electrical energy losses and voltage deviations, are added to the objective function to improve voltage stability in distribution network

2) This problem has been solved with TLBO algorithm. In order to validate the proposed model, simulation of volt/var control problem on IEEE 33-bus test system and real-life 77-bus distribution network is implemented.

2. Problem formulation

This section divides the volt/var control problem into two separate sections. In the first section, the objective function is presented and then the second section is devoted to define the related constraints. In this paper, the problem of controlling the security-based volt/var in distribution systems in the presence of distributed generators is defined as a multi-objective function. This function consists of three parts: i) total electrical energy losses, ii) voltage deviations, iii) voltage security index. These objectives are weighted and described as follow.

$$F = \omega_1 f_1 + \omega_2 f_2 + \omega_3 f_3 \quad (1)$$

where ω_i is the weighting factor of f_i .

2.1. Objective functions

As mentioned in the above section, three objectives are used to establish the multi-objective function, which will be described in the following subsections.

2.1.1. Minimizing the total electrical energy losses

The first objective function used to minimize the total electrical energy losses is expressed as follows:

$$f_1 = \sum_{t=1}^T P_{loss,t} \quad (2)$$

where $P_{loss,t}$ is the total energy losses and T is total number of hours in the time period of simulations.

2.1.2. Minimizing the voltages deviations

The voltage deviation of the distribution network is expressed as follows:

$$f_2 = \frac{\sum_{t=1}^T V_d^t}{T} \quad (3)$$

where

$$V_d^t = \sum_{i=1}^{N_{bus}} \left| \frac{V_i^N - V_i^t}{V_i^N} \right| \quad (4)$$

In the above formula, V_d^t is the voltage deviation from the reference value, V_i^N is the nominal voltage value of bus i (V) and, V_i^t is the voltage magnitude of bus i (V).

2.1.3. Maximizing the voltage stability

The third objective function represents an indicator to assess the voltage stability of the network. It should be noted that, unlike the objective functions described earlier, here the objective function that exploits the voltage stability index should be maximized.

$$f_3 = \sum_{t=1}^T L_t \quad (5)$$

where

$$L_t = \min(SI_1, SI_2, \dots, SI_{N_{bus}}) \quad (6)$$

Where [16] give the voltage stability index:

$$SI_j = \left\{ |V_i|^4 \right\} - 4 \times \left\{ P_j \times X(jj) - Q_j \times R(jj) \right\}^2 - 4 \times \left\{ P_j \times R(jj) + Q_j \times X(jj) \right\} \times |V_i|^2 \quad (7)$$

In (5)-(7), P_j , Q_j are the active and reactive powers at the receiving end respectively, V_i is the sending end voltage, $R(jj) + jX(jj)$ is the line impedance connected from bus i to bus j

and, N_{bus} is the number of buses in distribution system.

Eq. (6) shows that the stable operation of the system must be greater than zero. Considering this issue, the bus associated with the lowest stability index (SI) is more susceptible to voltage collapse. Then, the more the value of the objective function f_3 increases, the more the distribution network from the perspective of stability indices improves [17].

2.2. Constraints

In an optimization problem, it is reasonable to solve the objective functions along with some constraints, which are utilized to apply limits on the variables. In this paper, the constraints including voltage and reactive power control are as follows:

- Magnitude of bus voltage

$$V_{\min} < V_{t,i} < V_{\max} \quad (8)$$

where V_{\min} and V_{\max} are respectively the minimum and maximum amount of voltages and $V_{t,i}$ is the voltage of ith bus at time t.

- Limits of distribution lines

$$|P_{ij}^{br}| \leq P_{ij}^{br,max} \quad (9)$$

where $|P_{ij}^{br}|$ is the active power flows through the line from bus i to bus j during the time interval T (kW). Furthermore, $P_{ij}^{br,max}$ is the active power limit of line from i to j (kW).

- The limits on the daily number of OLTC operations:

$$\sum_{t=1}^T |TAP_t - TAP_{t-1}| \leq TAP_{\max} \quad (10)$$

where TAP_t is the tap position of OLTC at time t, and TAP_{\max} , is the maximum allowed switching operation for the OLTC during time interval T.

- The limit on the daily number of switching operations of shunt capacitors:

$$\sum_{t=1}^T (C_{k,t} \oplus C_{k,t-1}) = CM_k \quad (11)$$

Where $C_{k,t}$ is the state of capacitor k (1 = on ; 0 = off) at time t, CM_k is the maximum allowed switching operation for capacitor k and \oplus is the exclusive OR operation.

3. Teaching-learning-based optimization algorithm (TLBO)

Recently, Rao et al. [18, 19] has introduced an optimization algorithm based on teaching-learning process, which does not require any special parameters. In fact, TLBO algorithm only needs control parameters such as population size and generation that makes this algorithm more simple in comparison with the other traditional optimization methods. The process of TLBO is divided into two steps: 1) teacher phase and 2) learner phase. In this algorithm, in a group of students the highest learned one is assumed to be the teacher. Then the teacher will share his knowledge with the other learners. Therefore, it is obvious that the teaching quality of teachers affects learner's output; i.e. the class member's grades are directly related to how teachers teach. On the other hand, the learners can interact with each other to improve the learning process.

3.1. Teacher phase

A good teacher is one who brings his learners up to his level in terms of knowledge [7]. However, in practice, this is not possible and a teacher can only move the mean of a class up to some extent depending on the capability of the class. Let M_i be the mean value of variations of the class and T_i be the teacher at any iteration i . T_i will try to move M_i towards its own level (M_{new}). The solution is updated according to the difference between the existing and the new mean value given by [18]:

$$\text{Difference_Mean}_i = r_i (M_{new} - T_F M_i) \quad (12)$$

In the above formula, T_F is a teaching factor used to decide where the mean value change or not, and r_i is a random number in the range [0, 1]. The value of T_F can be 1 or 2 and is calculated randomly using (13) [18].

$$T_F = \text{round}[1 + \text{rand}(0,1)] \quad (13)$$

This difference modifies the existing solution according to the following expression [18]:

$$X_{new,i} = X_{old,i} + \text{Difference_Mean}_i \quad (14)$$

3.2. Learner phase

Learners increase their knowledge in two different ways: one through the input from the teacher and the other through the interaction between themselves. A learner randomly interacts with the other students to improve his knowledge and, will learn something new if the other learners have more knowledge than he does. Learner modification is expressed as [18]:

$$X_{new,i} = X_{old,i} + r_i (X_i - X_j) \quad (15)$$

if $f(X_i) > f(X_j)$

$$X_{new,i} = X_{old,i} + r_i (X_j - X_i) \quad (16)$$

if $f(X_j) > f(X_i)$

3.3. Implementation of TLBO for optimization

The steps of TLBO algorithm are as follows:

Step 1: Define the optimization problem and initialize the optimization parameters.

In this step, the optimization problem with an objective function can be modeled mathematically as in (17) [18]:

$$\text{Minimize } f(X) \Leftrightarrow \text{Subject to } X_i \in x_i = 1, 2, \dots, D_n \quad (17)$$

$$L_{L,i} \leq x_i \leq U_{L,i}$$

Where X is a vector for design variables such that $L_{L,i} \leq x_i \leq U_{L,i}$.

Initialize the population size (P_n), number of generations (G_n), number of design variables (D_n), and limits on the design variables (U_L, L_L) [18].

Step 2: Initialize the population.

Generate a random population, according to the population size and the number of design variables. For TLBO, the population size indicates the number of learners and, the design variables indicate the subjects (i.e. courses) offered. This population is expressed as [18]:

$$\text{Population} = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,D} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,D} \\ \vdots & \vdots & \ddots & \vdots \\ x_{Pn,1} & x_{Pn,2} & \cdots & x_{Pn,D} \end{bmatrix} \quad (18)$$

Step 3: Teacher phase.

Calculate the mean of the population column-wise, which will give the mean for the particular subject as [18]:

$$M_{,D} = [m_1, m_2, \dots, m_D] \quad (19)$$

The best solution will act as a teacher for that iteration [18]:

$$X_{teacher} = X_{f(x)=\min} \quad (20)$$

$$M_{,new,D} = X_{teacher,D} \quad (21)$$

As explained above, a good teacher is one who brings his or her learners up to his or her level in terms of knowledge. The mathematical expression is explained in Section 3.1.

Step 4: Learner phase.

As explained above, learners increase their knowledge with the help of their mutual interaction. The mathematical expression is explained in Section 3.2.

Step 5: Ending.

Stop if the maximum generation number is achieved; otherwise repeat from Step 3.

The flow chart of the Teaching–learning-based optimization algorithm is shown in Fig. 1.

4. The proposed algorithm for volt/var control

The multi-objective security based volt/var control in the presence of distributed generators can be converted into a single objective optimization problem by weighting each of the objective functions. The weighting factors for each objective must be smaller than 1. In addition, the sum of the factors must be one. In this paper, TLBO algorithm is used to solve the optimization problem. This algorithm is capable to effectively find global optimum learner which is related to the best answer for this problem. A schematic flowchart of the computational procedure is also shown in Fig. 2.

4.1 Load interval using GA

The idea of load interval division is based on the reality that several apparent load levels exist during a day. These intervals can therefore be used to determine the OLTC tap position, which remains constant during a load interval and may differ at a different load interval. It should also be noted that, because of the probabilistic nature of load forecasting, it could be construed as inaccurate to determine a dispatch schedule of the OLTC settings based only on load forecasting [11].

In order to determine the optimal load intervals, at first the number of intervals should be defined. A GA is then employed to determine the beginning and the end of each interval. The fitness function is as the one described in [20]:

$$F = F_{\max} - \text{Min} \sum_{i=1}^M \sum_{j=1}^{K_i} [(P_{ij} - PA_i)^2 + (Q_{ij} - QA_i)^2] \quad (22)$$

Where F_{\max} is a constant parameter used to convert the fitness function into a standard form; P_{ij} and Q_{ij} are the active and reactive load power at i th hour of the j th load interval respectively; PA_i and QA_i are the average amount of active and reactive load powers for the i th load interval; K_i is the number of hours at the i th load interval.

4.2 Dispatch of shunt capacitors

The utilization of shunt capacitors in distribution networks is essential for many reasons, including power flow control, loss

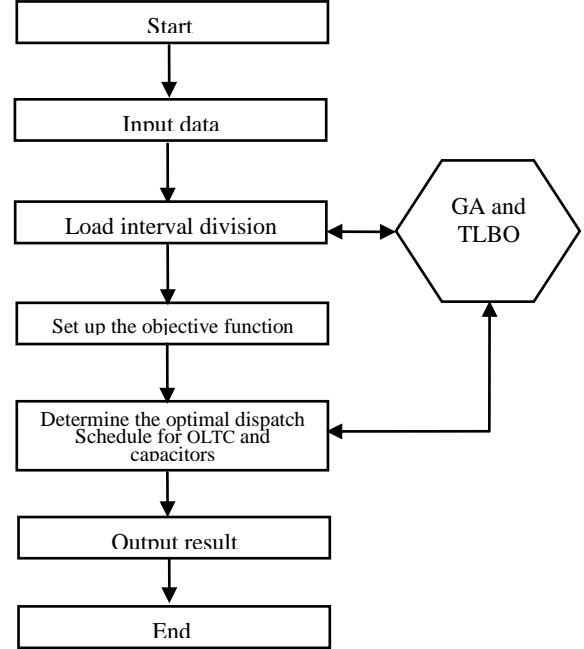


Fig. 2. Flowchart of the proposed volt/var control algorithm

minimization, power factor correction, voltage profile management, and system stability improvement [21]. At each hour, power quality improvement greatly depends on the location and size of the switched capacitors [15]. In addition, the continuous switching of capacitor banks will reduce their lifetime. In this paper, a method is utilized to guarantee the suppression of maximum allowable daily capacitors along feeder and substation's capacitor switching and, effectively correct the convergence process.

4.2.1 Capacitors along feeder

These capacitors are normally allowed to be switched 'on' and 'off' once a day. Therefore, each capacitor occupies two segments in the genome. The first segment represents the time at which the capacitor is switched on, while the second one represents the time duration in which the capacitor remains on. For example, assume that the initial state of the capacitor is off and, the first variable in the genome is 4 and the second variable in the genome is 9, so this means that the

capacitor will be switched on at 4:00 and switched off at 13:00.

4.2.2 Substation's capacitor

Considering the limitation of capacitors daily operation, these capacitors should be programmed in a way that the constraints in switching capacitors become implicit [15]. This programming procedure has appropriate convergence. However, it requires large computational volume.

If the maximum number of switching operations for substation's capacitor is considered 6, using this method, 24 hours per day should be divided into 6 parts. Then the minimum and maximum amounts of time intervals are considered to be 0 and 4 respectively. The values zero or one represent 'on/off' state of the capacitor.

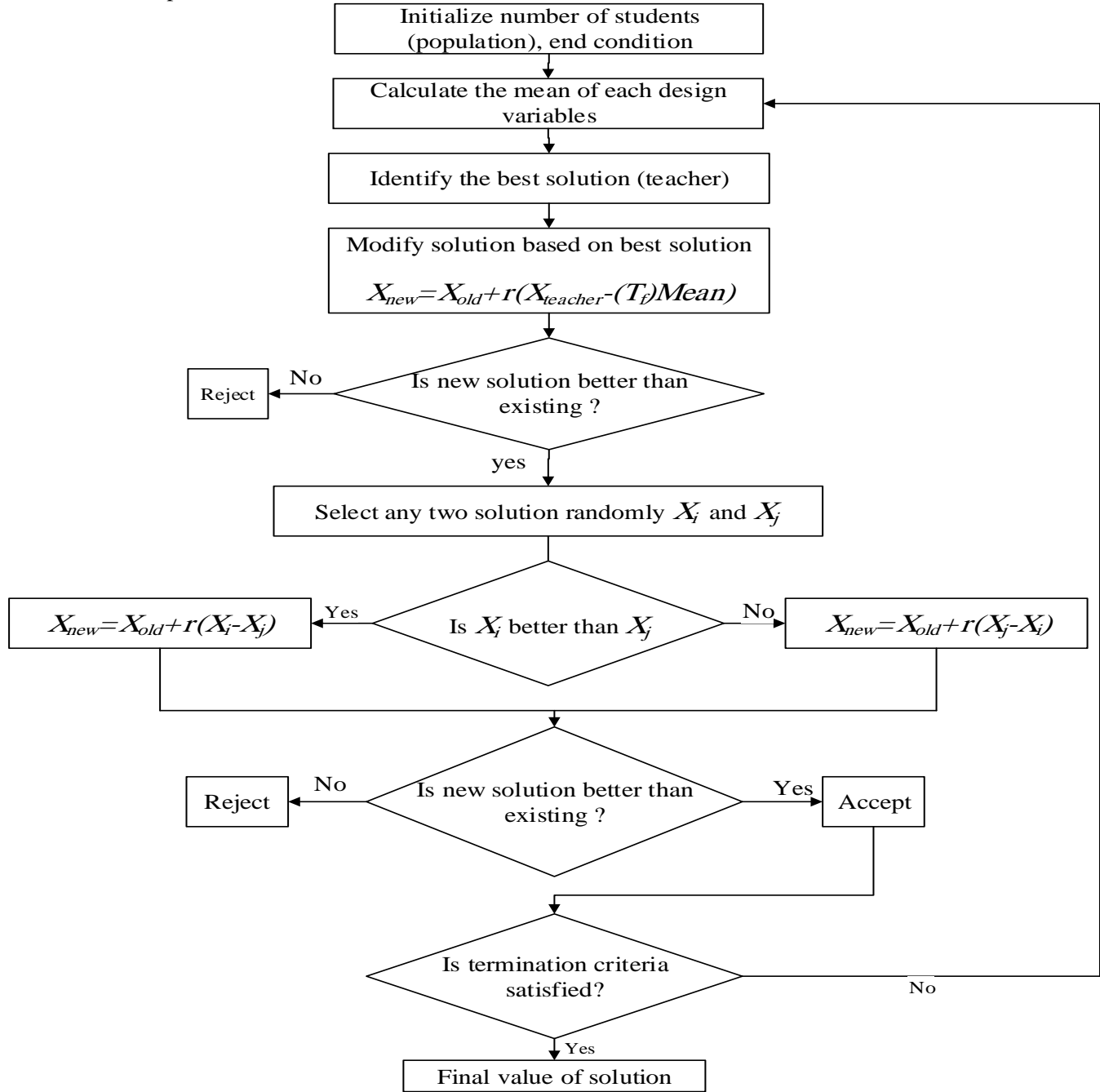


Fig. 1. Flow chart for teaching-learning-based optimization (TLBO)

For example, Fig. 3 shows the sample data of a chromosome representing the scheduling of a starting the simulation related to a daily time period. Since d2 is assigned by 0, 'on/off' state is

substation's capacitor. Fig. 3 implies that the capacitor would remain 'on' for three hours from not determined in this interval. In this case, it can be concluded that the switching operation of

capacitor is reduced. The capacitor is switched 'off' at hour 4 and remains off for two hours. Then the 'on' state is scheduled for two consecutive periods of three and four hours i.e. d_4 and d_5 . In the same way as the one stated above, here another switching reduction can be seen. After that, the capacitor remains off for the rest of the day.

Time duration for each interval						'on/off' state of the capacitor				
d_1	d_2	d_3	d_4	d_5	d_6	s_1	s_2	s_3	s_4	s_5
3	0	2	3	4	1	1	0	1	1	0

Fig. 3. Presents the sample data of a chromosome representing the scheduling of a substation's capacitor

5. Simulation results and discussion

In this paper, to demonstrate the effectiveness of the proposed approach for solving security based volt/var control in distribution system in the presence of distributed generators, the algorithm is tested on the IEEE 33-bus and real-life 77-bus distribution network.

5.1. IEEE 33-bus distribution system

Fig. 4 shows the test system with capacitors installed on buses 1, 8, 13, 17 and 28. The detailed data of the capacitors is described in Table 1. In this system the total real power and reactive power loads are 3.72 MW and 2.3 MVar . The line data and power of loads at the time of peak load of this network are presented in [22]. The OLTC has 17 tap positions ($[-8...0...8]$) and is able to change the voltage level from 0.95 to 1.05 per unit. The voltage on the primary bus of a substation is 1.0 per unit. We assume that the loads are constant power loads and their daily variation is in accordance with the load profile shown in Fig. 5. For this load profile, 4 intervals (M) have been considered. Information about the parameters of the TLBO algorithm is given in Table 2.

In order to permit a better evaluation of the security based volt/var control in the distribution system in the presence of distributed generators, the results of the algorithm are presented in four

different cases. In addition, the DG considered in this paper is a synchronous machine-based one. These cases are as follow:

Case1) there is no DG in the system.

Case2) DGs are installed on selected buses with unity power factor. These buses are modeled as PQ buses.

Case3) DGs are installed on selected buses and each of them delivers a fixed amount of reactive power ($Q_{DG} = 0.3MVar$). These buses are modeled as PQ buses.

Case4) DGs are installed on selected buses and operated in the voltage control mode. In this case the reactive power limit is $Q_{DG,max} = 0.3MVar$ and $Q_{DG,min} = -0.3MVar$.

Table 1

Capacitor data for the IEEE 33-bus distribution system

Capacitor number	C_1	C_2	C_3	C_4	C_5	C_6
Capacity (kVar)	300	200	250	300	250	200
Location	1	1	8	13	17	28

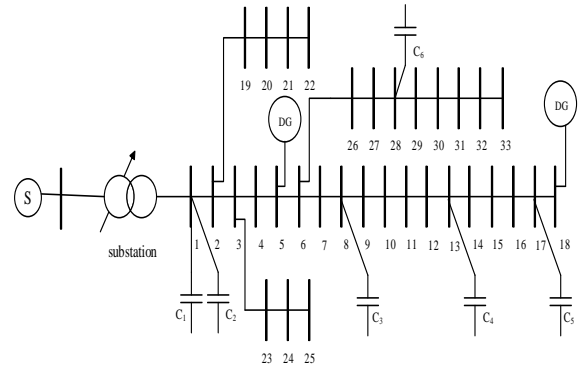


Fig. 4. One-line diagram of the IEEE 33-bus distribution system

Table 2

Information about TLBO algorithm parameters

Population size (P_n)	30
Maximum generation (G_n)	100

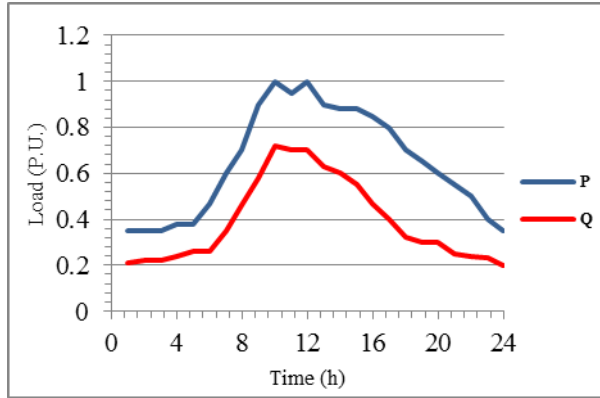


Fig. 5. Typical daily load curve

The rated capacity for each DG installed at bus 5, 18 is 0.3715 MW. Table 3 provides the results of the simulation for several scenarios including: without control, cases 1, 2, 3, 4 and case 1 with $\omega_3=0$. To simulate cases 1, 2, 3 and 4, the weighting coefficients ω_1 to ω_3 are used for functions f_1 to f_3 respectively. Therefore, the weighting factor values are 0.33 for all four cases. The third column of Table 3 shows that without considering voltage stability in the objective function, the total electrical energy losses and voltage deviations will decrease in comparison with case 1. However, the voltage stability index has also increased which shows that for better operation of distribution system, voltage stability must also be entered into the objective function. From Table 3, it can be seen that total electrical energy losses, voltage deviations and voltage stability after connecting DGs in all cases have improved compared to the cases where no DGs are installed. Furthermore, among all three cases in which DG installation is considered the best answers for voltage deviations and voltage stability are related to case 4, whereas using case 2 has led to the best value for total electrical energy losses. It should be noted that because of the nature of the optimization problem used in this paper, the best answer will improve when the value of the first and second objective functions decrease and the value of the third objective function increases.

The voltage deviations for all cases are shown in Fig. 6. Fig. 7 also shows voltage stability index. From Fig. 7 it can be seen that the voltage stability index has improved after performing the volt/var control. In addition, this improvement continues after installation of DGs.

In order to demonstrate the effectiveness of the proposed algorithm, the results are compared to the one obtained using GA to solve the optimization problem. The average results of 100 trials using TLBO and GA algorithm are presented in Table 4.

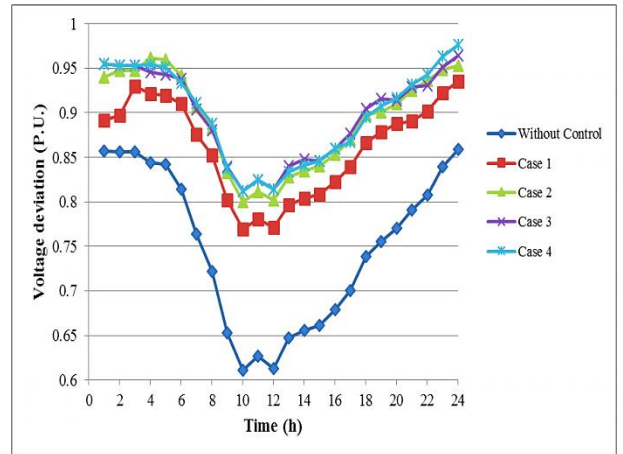


Fig. 6. Voltage deviation for four cases and without control in the 33-bus IEEE distribution system

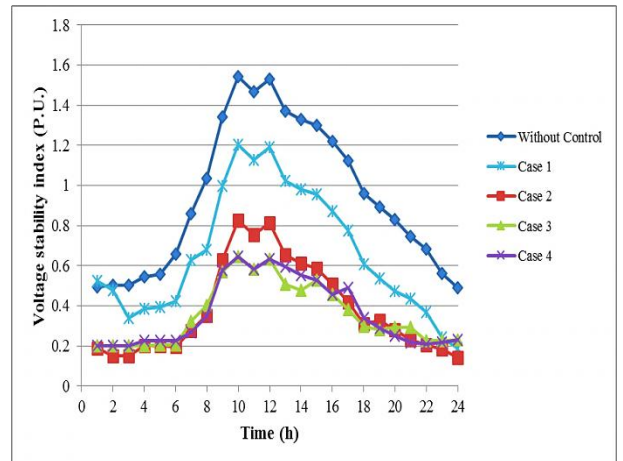


Fig. 7. Voltage stability index for four cases and without control in the 33-bus IEEE distribution system

The results indicate that the proposed TLBO algorithm based approach outperforms the GA algorithm. It is clear that solving the optimization problem using TLBO algorithm is more desirable where voltage stability function is considered. Furthermore, according to Table 4, the average computing time for the TLBO and GA algorithm is 18.53 and 20.34 respectively, which shows that using TLBO leads to less computational time.

The convergence characteristics for the best solution of the total energy losses in case 2 achieved by the TLBO and GA algorithm are presented in Fig. 8.

Table 3

The best results for different cases using TLBO in the 33-bus distribution system.

Objective function	Without control	Case 1 with $\omega_1=0.5$ & $\omega_2=0.5$ and $\omega_3=0$	Case 1	Case 2	Case 3	Case 4
$f_1(MWh)$	1.7482	1.2655	1.3983	0.9965	1.1780	1.1108
$f_2(pu)$	0.9398	0.6019	0.6594	0.3829	0.3569	0.3514
$f_3(pu)$	17.9647	19.1667	20.6721	21.4323	21.5400	21.5694

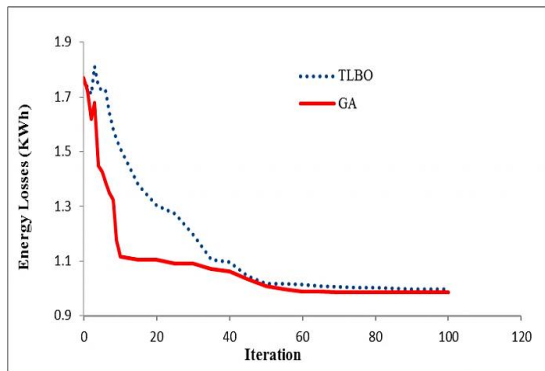


Fig. 8. Convergence characteristics of the TLBO and GA for the best solutions in case 2

5.2. Real-life 77-bus distribution network

The proposed algorithm is tested on two feeders of a real-life 77-bus distribution network of the city of Sirjan in Iran (see Fig. 9) and satisfactory results are obtained. Capacitors of this network are installed on buses 10, 21, 33, 43, 56, 67 and 74. The detailed data of the capacitors is described in Table 5. This system has 114 sectionalizing branches and 10 tie branches which have been named by Line1, Line2... Line10. The line data and power of loads at the time of peak load of this network are presented in [23]. The OLTC has 17 tap positions ($[-8...0...8]$) and is able to change the voltage level from 0.95 to 1.05 per unit. The rated capacity for each DG installed at bus 33, 50, 62, 70 is 0.6, 0.7, 0.7, 0.8 MW respectively. The other conditions of this system are the same as those considered for the IEEE 33-bus distribution test

system. Similar to the last section, 4 different cases are used to demonstrate the effectiveness of the proposed method, except that the rated reactive power of all DGs in case 3 is 0.5 and, in case 4 the limits on reactive power are between -0.5 and 0.5 MVAR. Table 6 provides the results of the simulation for several scenarios including: without control, cases 1, 2, 3, 4 and case 1 with $\omega_3=0$. Comparing the third and fourth columns of Table 6, shows that without considering voltage stability in the objective function, total electrical energy losses and voltage deviations will improve. However, the voltage stability has provided the worst value compared with case 1. It can be concluded that for better operation of distribution system, voltage stability must also be entered into the objective function. Fig. 10 shows the voltage stability index. This result shows that voltage stability index is improved after implementing control strategies. In addition, the improvement continues after connecting DG. In these cases, the fewest amount of voltage stability index is owned by case 1.

Table 5

Capacitor data for real-life 77-bus distribution system

Capacitor number	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇
Capacity (kVAR)	54	62	62	42	54	51	26
Location	10	21	33	43	56	67	74

Table 4

Average results of 100 trials for case 4 from TLBO and GA algorithm for the 33-bus distribution system

Optimization method	$f_1(MWh)$	$f_2(pu)$	$f_3(pu)$	Initial population	Calculated time (min)
TLBO	1.1639	0.3624	21.1132	30	18.53
GA	1.2359	0.3913	20.8315	50	20.34

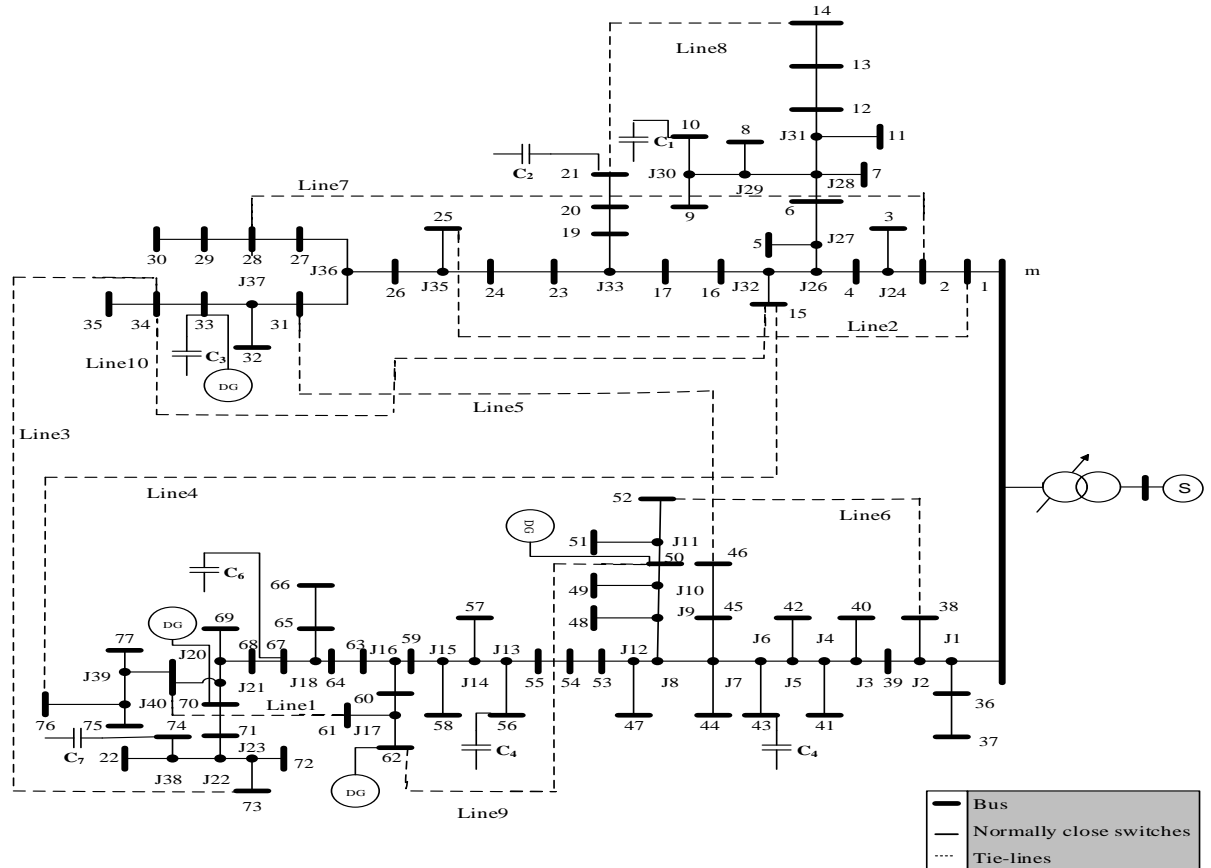


Fig. 9. Real-life 77-bus distribution system

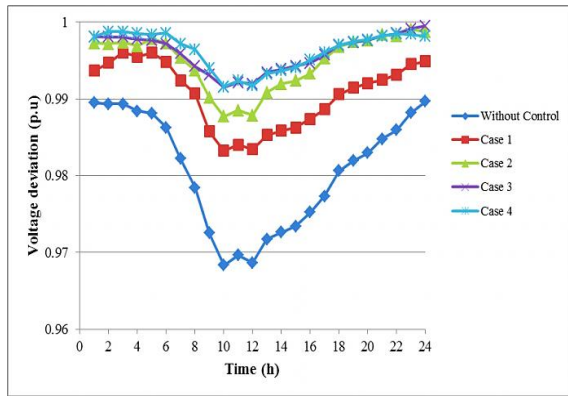


Fig. 10. Voltage stability index for four cases and without control in the real-life 77-bus distribution network

Table 7. also shows the average results of 100 trials for security based volt/var control in the distribution system in the presence of distributed generators using TLBO and GA algorithm.

Table 7

Average results of 100 trials for case 4 from TLBO and GA algorithm for the real-life 77-bus distribution system

Optimization method	$f_1(MWh)$	$f_2(pu)$	$f_3(pu)$	Initial population
TLBO	0.1263	0.0785	23.9001	30
GA	0.1273	0.0794	23.8893	50

Table 6

The best results for different cases using TLBO in the real-life 77-bus distribution network

	Without control	Case 1 with $\omega_1=0.5$ & $\omega_2=0.5$ and $\omega_3=0$	Case 1	Case 2	Case 3	Case 4
$f_1(MWh)$	0.3659	0.2610	0.2598	0.1253	0.1214	0.1258
$f_2(pu)$	0.2224	0.1544	0.1503	0.0941	0.0708	0.0771
$f_3(pu)$	23.5350	23.7804	23.7729	23.8770	23.9049	23.9120

5.3 Discussion of results

Considering the results of the previous sections, shows that the maximum amount of voltage stability belong to case 4. In other words, the most stable operation is belonged case4. However, about the other objective functions, the best operating conditions are belonged with case 2 and 3. This difference is due to type of DGs that is used in distribution system. For example, for IEEE 33 bus test system, case 2 has the minimum losses. That in this case, DGs is used as PQ buses with unity power factor. While this condition for real-life 77-bus distribution network is resulted from case 3. In this case, DGs is used as PQ buses. Furthermore, from the results are listed in table 4 and 7, indicate that the proposed TLBO algorithm based approach outperforms the GA algorithm. It is clear that solving the optimization problem using TLBO algorithm is more desirable where voltage stability function is considered. In addition, computing time of security based volt/var control problem has been reduced. Fig.8 that is presented the convergence characteristics achieved by the TLBO and GA algorithm, is shown this fact, that TLBO algorithm is more capable to converge best solution.

6. Conclusion

In this paper, TLBO algorithm is proposed to solve security based volt/var control in distribution system in the presence of distributed generators. In the formulation of the objective function of this problem three functions are provided including; minimization of total electrical energy losses, minimization of voltage deviations and maximization of voltage stability. In order to permit a better evaluation of the security based volt/var control in the distribution system in the presence of distributed generators, the results of the algorithm are presented in four different cases. By considering voltage security index as one of the objective functions, the network security situation has improved without additional cost and the most stable operation is resulted from case 4. In this paper, all of objective functions including: total electrical energy losses, voltage deviations, and voltage stability are improved. It can be resulted that best operating condition for all of objectives function in both distribution network is related to case 4. By defining the number of OLTC and capacitor operations as the constraints of these problems, unnecessary switching of these devices is prevented. This will also speed up the volt/var control problem solving procedure.

TLBO algorithm is more capable than the GA to solve this problem. The results of this comparison showed that performance of the of the TLBO algorithm in computing time and convergence procedure is better than GA. By using the method presented in this paper, the convergence of the problem is effectively improved.

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