Voltage and reactive power control in distribution network considering optimal network configuration and voltage security constraints

Gholamreza Memarzadeh¹, Saeid Esmaeili²*

M.Sc., Department of Electrical Engineering, Shahid Bahonar University of Kerman,
Postal code: 7616914111, Kerman, Iran, Telephone number: +983434323334, Mobile number: +989103131394
E-mail: reza.memarzadeh@eng.uk.ac.ir

Associate Professor, Department of Electrical Engineering, Shahid Bahonar University of Kerman, Postal code: 7616914111, Kerman, Iran Telephone number: +983431322500, Mobile number: +989131915346
E-mail: s_esmaeili@uk.ac.ir

Abstract

In order to reduce energy losses and improve voltage stability index in distribution system, two different approaches have been proposed and employed including voltage and reactive power control (volt/var control) and distribution network reconfiguration. In the present paper, volt/var control and network reconfiguration in distribution system considering voltage security constraints is modelled as a multi-objective optimization problem. Total electrical energy losses, voltages deviations and voltage stability have been considered as objectives. Also, a new method for distribution network reconfiguration has been utilized for implementation of these two problems simultaneously. In this way, the two problems can be solved in less time. In addition, different nature of loads in each bus is considered in network load modelling. Non-dominated sorting genetic algorithm-II is used to solve this problem.

* corresponding author
Finally, the effectiveness of the proposed method is evaluated by implementation on the IEEE 33-bus system and a real 77-bus distribution system.

**Keywords:** Voltage and reactive power control, Distribution network reconfiguration, Distribution system, Voltage security constraints, Non-dominated sorting genetic algorithm-II (NSGA-II)

1. **Introduction**

Voltage and reactive power control and network reconfiguration have been widely used to reduce power losses and improve voltage profile in distribution networks. In some studies, only voltage and reactive power control have been used to effective operation of distribution networks [e.g. 1-15]. Meamarzadeh et al. proposed the volt/var control problem in distribution system in presence of distributed generators from the perspective of improving the voltage security index of the system [1]. Manbachi et al. presented an innovative smart grid-based Volt-VAR optimization engine, capable of minimizing system power loss cost as well as the operating cost of switched capacitor banks, while optimizing the system voltage using an improved genetic algorithm (GA) with two levels of mutation and two levels of crossover [2]. The objectives which are proposed by them are the total feeder loss, voltage profile and limitation of reactive power flow into main transformers. Besides, other researchers have studied this problem in the presence of distributed generation. Jashfar et al. presented volt/var/THD control in distribution networks in the presence of the reactive power capability of solar energy conversion [3]. 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. Resener et al. presented an optimization model for volt/var control and energy losses minimization in power distribution networks, considering the presence of distributed generation (DG)
Sayadi et al. presented two-layer control method for voltage and reactive power control in harmonic polluted distribution network with penetration of photovoltaic (PV) systems. Optimal scheduling of load tap changer and shunt capacitors for minimising energy losses and improving the power quality simultaneously are performed using perturbation-particle swarm optimisation (P-PSO) optimisation method [5]. Niknam et al. proposed a stochastic multiobjective framework for daily volt/var control, including hydroturbine, fuel cell, wind turbine, and photovoltaic powerplants. For this purpose, the uncertainty related to hourly load, wind power, and solar irradiance forecasts are modelled in a scenario-based stochastic framework [6].

In addition to the volt/var control, distribution network reconfiguration is another significant control scheme in the distribution systems, which alters the topological structure of distribution feeders by changing open/closed status of sectionalizing and ties switches. After reconfiguration the redial network which encompasses all buses is acceptable. The distribution network reconfiguration by consideration all the mentioned issues is a complicated nonlinear optimization problem. Distribution network reconfiguration has been studied by researchers [16-23]. Merlin and Back for the first time in 1975, proposed reconfiguration idea in the distribution network [16]. In the proposed method by these researchers, first all network switches are closed. Then by use the heuristic rules, each switch which has less flow is opened. Civanlar et al. suggested a heuristic algorithm, where a simple formula was developed to determine changes in power loss due to a branch exchange [17]. Zhu proposed refined genetic algorithm for loss reduction in the distribution network [18]. Gupta et al. presented an efficient Genetic Algorithms (GAs) based method to improve the reliability and power quality of distribution systems using network
for minimizing the real power losses using the new proposed technique and the ant colony optimization [20]. Two new objective functions to address power quality and reliability issues in the reconfiguration problem are formulated in this study. Distribution network reconfiguration is also being used along with other operation methods [21, 22]. For example, Farahani et al. applied reconfiguration and capacitor placement simultaneously for energy loss reduction based on a simple branch exchange method of the single loop [21]. Zhao et al. proposed reactive power control of wind farm and network reconfiguration to obtain the optimal reactive power output of wind farm and network structure simultaneously by joint optimization algorithm [22].

In present study, to follow the previous work in [1], voltage and reactive power control and distribution network reconfiguration are studied simultaneously to obtain the optimal dispatch schedules for OLTC settings and all shunt capacitors on the network and to determine network structure which is a novel viewpoint for operating of distribution networks. For achieving this purpose, a new method is presented for distribution network reconfiguration in order to reduce the convergence time. In addition, the proposed Volt/var control and network reconfiguration in distribution system considering voltage security constraints is modelled as a multi-objective optimization problem. The objective functions used in this problem are total electrical energy losses, voltage deviations and voltage stability index just like using it in [1]. But in this paper, the non-dominated sorting genetic algorithm-II (NSGA-II) is used instead of old GA based weighing method to find the global optimum solution more effectively. To illustrate the effectiveness of the proposed method, it is performed in IEEE 33-bus and real 77 bus distribution systems with different nature of loads in each bus and its
Performance is compared with the multi-objective particle swarm optimization (MOPSO) algorithm. Simulation results show that the NSGA-II algorithm gives better performances than the other algorithm. The paper is outlined as follows: Section 2 presents problem formulation. The method that is applied to distribution network reconfiguration and volt/var control are introduced in section 3, 4. Volt/var control and network reconfiguration in distribution system that is utilized to save energy and improvement voltage stability is proposed in section 5. Simulation results of applying the suggested control scheme and discussion about them is demonstrated in Section 6. Finally, the major contributions and conclusions are summarized in Section 7.

2. Problem formulation

In this section, the objective function is presented and then governing constraints of this problem are introduced. This problem has been modelled as a multi-objective optimization problem. The objectives are the system real power losses and the deviation of the bus voltage minimization and voltage stability index maximization. The three objective functions are in contrast with each other, so that the improvement of voltage deviations reduces the voltage stability index and increases the power losses. On the other hand, improvement of losses leads to increase the voltage stability index, which leads to increase voltage deviations. So, all the three objective functions should be optimized simultaneously.

2.1. Objective functions

2.1.2. Minimization of the total electrical power losses

The first objective function is electrical energy losses which are expressed as follows [1]:

\[ f_1 = \sum_{i=1}^{T} P_{\text{loss},i} \]  

(1)
Where $P_{\text{loss},t}$ is the total system losses at time $t$ and $T$ is the total number of hours in a day.

### 2.1.2. Minimization of the voltage deviations

The voltage deviation of the distribution network for buses is expressed as follows [1]:

$$f_2 = \frac{\sum_{t=1}^{T} U_d^t}{T}$$  \hspace{1cm} (2)

$$U_d^t = \sum_{i=1}^{N_{\text{bus}}} \left| U_i^N - U_i^t \right|$$  \hspace{1cm} (3)

Where in these equations, $U_d^t$ is the voltage deviation from the reference value, $U_i^N$ is nominal voltage of bus $i$, and $U_i^t$ is voltage magnitude of bus $i$.

### 2.1.3. Maximization of the voltage stability

The third objective function represents an indicator for assessing the voltage stability of network which is expressed by the following equations [1]. To achieve a good stability level of network, this objective function must be maximized.

$$f_3 = \sum_{r=1}^{T} L_r$$  \hspace{1cm} (4)

$$L_r = \min(SI_1, SI_2, ..., SI_{N_{\text{bus}}})$$  \hspace{1cm} (5)

$$SI_j = \left| U_i \right|^2 - 4 \times \left\{ P_j \times X_{(jj)} - Q_j \times R_{(jj)} \right\}^2 - 4 \times \left\{ P_j \times R_{(jj)} + Q_j \times X_{(jj)} \right\} \times \left| U_i \right|^2$$  \hspace{1cm} (6)

Where $P_j, Q_j$ are active and reactive receiving end power, $U_j$ is sending end voltage, $R_{(jj)} + jX_{(jj)}$ is impedance of the line which is connected from bus $i$ to bus $j$, $N_{\text{bus}}$ is the maximum number of buses in the distribution system.
For stable operation of the system, $SI$ must be greater than zero. Thus, each bus which has the lowest index of stability ($SI_j$), is closer to voltage collapse. By the value of the $f_3$ function, the distribution network becomes more stable [24].

2.2. Constraints

Proper operating conditions of the network are achieved when initially the governing constraints of network are satisfied and then the objective functions will be optimized. Constraints of the volt/var control and distribution network reconfiguration problems are different. Therefore, in the first section, the constraints of the volt/var control problem are proposed and then the constraints for distribution network reconfiguration will be investigated.

2.2.1. Constraints of volt/var control problem

The constraints of volt/var control problem are:

1. Magnitude of bus voltage

$$U_{\text{min}} < U_{i,j} < U_{\text{max}}$$

(7)

Which $U_{\text{min}}$ and $U_{\text{max}}$ are the minimum and maximum voltages at each bus, respectively.

2. Line flow limit

$$S_{TX,i} \leq S_{TX,\text{rat}}$$

(8)

Which $S_{TX,i}$ is the apparent power flow on the substation transformer at time i, $S_{TX,\text{rat}}$ is the substation transformer rating.

3. The daily number of OLTC operations limit:

$$\sum_{t=1}^{T} |TAP_t - TAP_{t-1}| \leq TAP_{\text{max}}$$

(9)
In equation (9), \( TAP_t \) is the tap position of OLTC at time \( t \) and \( TAP_{\text{max}} \) is the maximum switching operation for the OLTC.

4. Daily number of switching operations for shunt capacitors limit:

\[
\sum_{t=1}^{T} (C_{k,j} \oplus C_{K,j-1}) = CM_k
\]  

(10)

Where \( C_{k,j} \) is the status of capacitor \( k \) (on or off) at time \( t \), \( CM_k \) is the maximum switching operation for capacitor \( k \) and \( \oplus \) is the exclusive OR operation.

2.2.2. Constraints of distribution network reconfiguration problem

The constraints of distribution network reconfiguration problem are:

1. Magnitude of bus voltage

\[
U_{\text{min}} < U_n < U_{\text{max}}
\]  

(11)

Which \( U_{\text{min}} \) and \( U_{\text{max}} \) are the minimum and maximum voltages at each bus, respectively.

2. Line current for each line of the system

\[
I_n < I_{n}^{\text{max}}
\]  

(12)

Here, \( I_n \) is the line capacity of the \( n \text{th} \) line and \( I_{n}^{\text{max}} \) is the maximum capacity of the \( n \text{th} \) line of the distribution network.

3. After reconfiguration, the network must be radial.

4. Lines current, voltage of buses and all networking equipment must be in the permitted range.

5. The configured network must encompass all buses.

3. Distribution network reconfiguration

Distribution networks, which have the ability to perform reconfiguration, must have tie lines. If tie lines are closed, the network structure became ring. Therefore, for
preservation the radial structure of the network, number of tie line must be opened.

So, solution structure for distribution network reconfiguration problem includes network switches which must be opened. The main point in this problem is the selection of switches which must be opened. In order to solve distribution network reconfiguration problem properly, first governing constraints of the network must be satisfied and then the objective functions should be optimized which in the present study this method has been used.

In the mentioned method, the following steps are considered:

1. The minimum number of distribution network rings is equal to the number of tie lines. For example, in a network with five tie lines, there must be at least five rings. Thus, in the first step of this method, the rings which created by tie lines should be identified.

2. Some of the switches are shared between two or more rings. These switches must be identified and considered in one of the rings. With this method, some of the rings in the network converted to branches without a way back. Therefore, two constraints of the problem including radial structure of distribution network and considering all buses of the network are satisfied.

3. To make voltage of buses and lines current in permitted range, configurations of network which not meet these constraints removed by introducing penalties factor in power flow.

4. **Volt/var control in distribution system**

Volt/var control in the distribution network is a multi-objective optimization problem. To solve this problem, evolutionary algorithms can be used. In this paper, NSGA-II is used to solve the optimization problem. This algorithm is capable to find the global optimum solution, effectively. The structure of a feasible solution which is
considered in the present study is shown in Fig. 1. As it is shown, solution is composed
of two parts. The first part is related to the capacitor ‘on/off’ switching modes and
second part is related to the OLTC tap position.

4.1. Time interval method considering the time varying nature of loads

In the distribution networks, a variety of loads, including residential, office and
commercial using network to supply their own needs. On the other hand, each of the
loads in the distribution systems in order to use network has its particular nature. Hence,
in this study different nature of loads is considered in the network. The contribution of
each of the buses in the network from any nature of loads is specified. In order to
determine the optimal load intervals, following equation has been used. A GA is then
employed to determine the beginning and the end of each interval.

\[
F = F_{\text{max}} - Min \left( \sum_{i=1}^{M} \sum_{j=1}^{K_i} \left[ (P_{\text{Res},ij} - P_{A_{\text{Res},ij}})^2 + (Q_{\text{Res},ij} - Q_{A_{\text{Res},ij}})^2 \right] \right)
\]

\[
+ \sum_{i=1}^{M} \sum_{j=1}^{K_i} \left[ (P_{\text{Com},ij} - P_{A_{\text{Com},ij}})^2 + (Q_{\text{Com},ij} - Q_{A_{\text{Com},ij}})^2 \right]
\]

\[
+ \sum_{i=1}^{M} \sum_{j=1}^{K_i} \left[ (P_{\text{Off},ij} - P_{A_{\text{Off},ij}})^2 + (Q_{\text{Off},ij} - Q_{A_{\text{Off},ij}})^2 \right]
\]

(12)

Where \( M \), the number of load interval in a day; \( K_i \), number of hour at \( i \)th load
interval; \( P_{\text{Res},ij}, Q_{\text{Res},ij}, P_{\text{Com},ij}, Q_{\text{Com},ij}, P_{\text{Off},ij}, Q_{\text{Off},ij} \) respectively are active and
reactive power of residential, commercial and office load at \( j \)th load point of \( i \)th load
interval; \( P_{A_{\text{Res},ij}}, Q_{A_{\text{Res},ij}}, P_{A_{\text{Com},ij}}, Q_{A_{\text{Com},ij}}, P_{A_{\text{Off},ij}}, Q_{A_{\text{Off},ij}} \) respectively are average
active and reactive of residential load at \( i \)th load interval.

4.2. Dispatch of shunt capacitors

At each hour, power quality improvement greatly depends on the location and size of
the switched capacitors [10]. Furthermore, 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 corrects 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 and second variable in the genome are 4 and 9 respectively, 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 [3, 25]. 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 six parts. Then the minimum and maximum amounts of time intervals are considered to be 0 and 4 respectively.

5. Volt/var control and network reconfiguration in distribution system

In this paper, volt/var control and network reconfiguration in distribution system is employed to reduce energy losses and improves voltage stability index. The state variable vector is \( \mathbf{X} = [VVC, REC] \). \( VVC \) is variable, which represents the voltage and reactive power control. \( REC \) is variable, which represents the status of switches in distribution network. Fig. 2 represents a solution structure of the volt/var control
and network reconfiguration in distribution system which is solved by NSGA-II. The stopping criterion of the algorithm is the maximum number of iteration is reached. A schematic diagram of the computational procedure is shown in Fig. 3.

6. Simulation results and discussion

In this paper, to demonstrate the performance of the proposed optimization algorithm, the following five cases are studied.

- **Case 1**: Original network without any action.
- **Case 2**: Only perform distribution network reconfiguration.
- **Case 3**: Only perform voltage and reactive power control in the distribution network.
- **Case 4**: Perform distribution network reconfiguration first, and then perform voltage and reactive power control.
- **Case 5**: Perform volt/var control and network reconfiguration in distribution system.

6.1. IEEE 33-bus distribution system

Fig. 4 shows the test system with capacitors installed on buses 1, 8, 14, 24, 25 and 30. The detailed data of the capacitors is described in Table 1. 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.

Different nature of loads is considered in the network is shown in Fig. 5. Fig. 6 shows the contribution of each of the buses in the network from any nature of the load. For this load profiles, the number of intervals (M) has been considered 4. Information about the parameters of the algorithm is given in Table 2.

For comparison purposes, the NSGA-II and MOPSO algorithms have been applied to the IEEE 33-bus distribution system with the same conditions and system data. The results of the simulation for these cases are provided in
Table 3. In this table, the (*) represent the initial state of the network switches.

In this network before making any network optimization process, including voltage and reactive power control and distribution network reconfiguration, the bus 18 and 33 have the lowest voltage and voltage stability index (VSI). Therefore, the voltage and voltage stability index for all cases are shown in Fig. 7 and Fig. 8. Summary of voltage, voltage stability index and energy saving in system with different cases are visible in Table 4.

6.2. Real 77-bus distribution network

The proposed algorithm is tested on two feeders of a real 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 [21]. 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. Fig. 10 shows the contribution of each of the buses in the network from any nature of loads. Information about the parameters of the algorithm for this system is the same as previous test case. The results of cases obtained using the two procedures are presented in Table 6 and the results confirm the effectiveness of the proposed method. Summary of voltage, voltage stability index and energy saving in system with different cases (2-5)
are shown in Table 7. These results represent the advantage of each of the scenarios 2 to 5 in each of the indicators is expressed.

6.3. Discussion of results

Considering the results of the previous sections shows that although the energy losses in case 2 are improved appropriately, but voltage stability index and voltage deviations did not significantly improve. Similarly, in case 3 there is improvement in indicators related to bus voltages, but not significant improvement in energy losses. The results are listed in tables 3, 4, 6 and 7 also confirm this fact. With the implementation of case 4 and 5, both energy losses and voltage indicators are improved. Fig. 7 and Fig. 8 are shown that the voltage of the bus 18 and 33 of IEEE 33 bus test system are improved to their allowable value in case 4 and 5. Furthermore, Fig. 7 and Fig. 8 are shown that the voltage stability index of the bus 18 and 33 are improved in these cases. In case 2, by changing the configuration of the network, energy losses are reduced, but due to lack of OLTC and capacitors operations, there is no possibility to control reactive power and improve voltage profiles. In case 3, using the OLTC of transformer and capacitors, all specifications of voltage are improved. However, the network configuration is not optimum, energy losses improvement is not appropriate. Total OLTC and capacitors switching operation's numbers per day satisfy the constraints. The results show that the capacitor's switching and daily load curves are dependent. In other words, considering the daily load curve, the capacitors are prevented from unnecessary switching.

7. Conclusion

The secure and economic operation of power systems is immense importance. Voltage and reactive power control and distribution network reconfiguration are used to improve these conditions in the distribution network. So, in this paper, volt/var control and network reconfiguration in distribution system and voltage security constraints are
proposed to improve network security and economic limitations. This problem is modeled as a multi-objective optimization problem. Objectives have been studied in this paper are total electrical energy losses, voltage's deviations and voltage stability. NSGA-II is used to solve the optimization problem. The results using the proposed method are compared to that reported in the literature. The results confirm the potential of the proposed approach and show its effectiveness and superiority over the MOPSO algorithm. The results obtained from the simulations show network reconfiguration and volt/var control can reduce energy losses and improve voltage stability but the best solution for these two objective functions does not happen separately. Hence these two problems should be considered simultaneously. After the implementation of volt/var control and network reconfiguration in distribution system, all objective function has been improved. Considering the daily nature of the load curve, the capacitors are prevented from unnecessary switching.

References


Saeid Esmaeili was born in Rafsanjan, Iran, in 1976. He received the B.Sc. degree in power electrical engineering from K.N.Toosi University of Technology, Tehran, Iran, in 1999 and the M.Sc. degree in power electrical engineering from Iran University of Science and Technology, Tehran, Iran, in 2002. He also received the Ph.D. degree in electrical engineering from Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran in 2007. He is currently an associate professor in the department of electrical engineering at the Shahid Bahonar University of Kerman, Kerman, Iran. His research interests include analysis and optimization of electrical power system, power quality and dynamics of electrical power system.

Gholamreza Memarzadeh was born in Rafsanjan, Iran, in 1990. He received the B.Sc. degree in power electrical engineering from Shahid Bahonar University, Kerman, Iran, in 2012 and the M.Sc. degree in power electrical engineering from Shahid Bahonar University, Kerman, Iran, in 2015. His main fields of research are Voltage and reactive power control, distribution system analysis and optimization, and distribution network reconfiguration.

Table:

Table 1. Capacitor data for the IEEE 33-bus distribution system

<table>
<thead>
<tr>
<th>Capacitor number</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (kVar)</td>
<td>350</td>
<td>200</td>
<td>100</td>
<td>200</td>
<td>200</td>
<td>350</td>
</tr>
<tr>
<td>Location</td>
<td>1</td>
<td>8</td>
<td>14</td>
<td>24</td>
<td>25</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2. Optimization parameters used in the dispatch problem

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum generation</td>
<td>200</td>
</tr>
<tr>
<td>Population size</td>
<td>100</td>
</tr>
<tr>
<td>Probability of crossover</td>
<td>0.7</td>
</tr>
<tr>
<td>Probability of mutation</td>
<td>0.3</td>
</tr>
<tr>
<td>Mutation rate</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

Table 3. Result from proposed cases in the IEEE 33 bus test system
<table>
<thead>
<tr>
<th>Case</th>
<th>Optimization algorithm</th>
<th>Power losses (Kw)</th>
<th>Voltage deviation (P.U)</th>
<th>Voltage stability index (P.U)</th>
<th>Open switches</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NSGA-II</td>
<td>1.0023</td>
<td>0.7161</td>
<td>19.0491</td>
<td>33, 34, 35, 36, 37 *</td>
</tr>
<tr>
<td></td>
<td>MOPSO</td>
<td>1.0023</td>
<td>0.7161</td>
<td>19.0491</td>
<td>33, 34, 35, 36, 37 *</td>
</tr>
<tr>
<td>2</td>
<td>NSGA-II</td>
<td>0.6972</td>
<td>0.4850</td>
<td>20.5166</td>
<td>7, 9, 14, 32, 33</td>
</tr>
<tr>
<td></td>
<td>MOPSO</td>
<td>1.2040</td>
<td>0.6114</td>
<td>19.3791</td>
<td>9, 14, 28, 32, 34</td>
</tr>
<tr>
<td>3</td>
<td>NSGA-II</td>
<td>0.8691</td>
<td>0.4083</td>
<td>23.6000</td>
<td>33, 34, 35, 36, 37 *</td>
</tr>
<tr>
<td></td>
<td>MOPSO</td>
<td>0.8801</td>
<td>0.4630</td>
<td>23.5543</td>
<td>33, 34, 35, 36, 37 *</td>
</tr>
<tr>
<td>4</td>
<td>NSGA-II</td>
<td>0.6586</td>
<td>0.3995</td>
<td>24.3231</td>
<td>7, 9, 14, 32, 33</td>
</tr>
<tr>
<td></td>
<td>MOPSO</td>
<td>0.7443</td>
<td>0.5466</td>
<td>23.8911</td>
<td>9, 14, 28, 32, 34</td>
</tr>
<tr>
<td>5</td>
<td>NSGA-II</td>
<td>0.6428</td>
<td>0.3943</td>
<td>24.3364</td>
<td>7, 9, 14, 28, 33</td>
</tr>
<tr>
<td></td>
<td>MOPSO</td>
<td>0.6777</td>
<td>0.4881</td>
<td>23.9906</td>
<td>10, 26, 32, 34, 36</td>
</tr>
</tbody>
</table>

Table 4. Summary results of approaches

<table>
<thead>
<tr>
<th>Case</th>
<th>Power saving (%)</th>
<th>Average system voltage (pu)</th>
<th>Maximum voltage (pu)</th>
<th>Minimum voltage (pu)</th>
<th>Average system VSI (pu)</th>
<th>Maximum VSI (pu)</th>
<th>Minimum VSI (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>30.44</td>
<td>0.9860</td>
<td>1</td>
<td>0.9595</td>
<td>0.9211</td>
<td>1</td>
<td>0.9595</td>
</tr>
<tr>
<td>3</td>
<td>13.29</td>
<td>1.0098</td>
<td>1.0327</td>
<td>0.9849</td>
<td>1.0630</td>
<td>1.0327</td>
<td>0.9849</td>
</tr>
<tr>
<td>4</td>
<td>34.3</td>
<td>1.0104</td>
<td>1.0329</td>
<td>0.9881</td>
<td>1.0693</td>
<td>1.2110</td>
<td>0.9358</td>
</tr>
<tr>
<td>5</td>
<td>35.87</td>
<td>1.0109</td>
<td>1.0329</td>
<td>0.9886</td>
<td>1.0698</td>
<td>1.2560</td>
<td>0.9509</td>
</tr>
</tbody>
</table>

Table 5. Capacitor data for real 77-bus distribution system

<table>
<thead>
<tr>
<th>Capacitor number</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (kVAR)</td>
<td>545</td>
<td>625</td>
<td>625</td>
<td>420</td>
<td>545</td>
<td>515</td>
<td>265</td>
</tr>
<tr>
<td>Location</td>
<td>10</td>
<td>21</td>
<td>33</td>
<td>43</td>
<td>56</td>
<td>67</td>
<td>74</td>
</tr>
</tbody>
</table>
Table 6. Result from proposed cases in the real 77-bus distribution system

<table>
<thead>
<tr>
<th>Case</th>
<th>Optimization algorithm</th>
<th>Power losses(Kw)</th>
<th>Voltage deviation (P.U)</th>
<th>Voltage stability index (P.U)</th>
<th>Open switches</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NSGA-II</td>
<td>0.1095</td>
<td>0.3546</td>
<td>23.4845</td>
<td>Line1, Line2, …, Line10 *</td>
</tr>
<tr>
<td></td>
<td>MOPSO</td>
<td>0.1095</td>
<td>0.3546</td>
<td>23.4845</td>
<td>Line1, Line2, …, Line10 *</td>
</tr>
<tr>
<td>2</td>
<td>NSGA-II</td>
<td>0.0858</td>
<td>0.3162</td>
<td>23.5710</td>
<td>13-14, 17-33, 36-27, J8-J9, 59-J16, J17-62, 63-64, 70-J39, 31-46, 15-36</td>
</tr>
<tr>
<td></td>
<td>MOPSO</td>
<td>0.0864</td>
<td>0.3169</td>
<td>23.5725</td>
<td>13-14, 20-21, 36-27, J8-J9, 59-J16, J17-62, 63-64, 70-J39, 31-46, 15-36</td>
</tr>
<tr>
<td>3</td>
<td>NSGA-II</td>
<td>0.1014</td>
<td>0.3435</td>
<td>24.0919</td>
<td>Line1, Line2, …, Line10 *</td>
</tr>
<tr>
<td></td>
<td>MOPSO</td>
<td>0.1018</td>
<td>1.7634</td>
<td>23.7191</td>
<td>Line1, Line2, …, Line10 *</td>
</tr>
<tr>
<td>4</td>
<td>NSGA-II</td>
<td>0.0802</td>
<td>0.3476</td>
<td>24.1851</td>
<td>13-14, 17-33, 36-27, J8-J9, 59-J16, J17-62, 63-64, 70-J39, 31-46, 15-36</td>
</tr>
</tbody>
</table>
## Table 7. Summary results of approaches

<table>
<thead>
<tr>
<th>Case</th>
<th>Power saving (%)</th>
<th>Average system voltage (pu)</th>
<th>Maximum voltage (pu)</th>
<th>Minimum voltage (pu)</th>
<th>Average system VSI (pu)</th>
<th>Maximum VSI (pu)</th>
<th>Minimum VSI (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>21.64</td>
<td>0.9973</td>
<td>0.9952</td>
<td>0.9837</td>
<td>0.9717</td>
<td>0.9940</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>7.4</td>
<td>1.0015</td>
<td>1.0079</td>
<td>0.9973</td>
<td>1.0096</td>
<td>1.0484</td>
<td>0.9841</td>
</tr>
<tr>
<td>4</td>
<td>26.76</td>
<td>1.0019</td>
<td>1.0081</td>
<td>0.9978</td>
<td>1.0115</td>
<td>1.0494</td>
<td>0.9867</td>
</tr>
<tr>
<td>5</td>
<td>27.76</td>
<td>1.0038</td>
<td>1.0200</td>
<td>0.9977</td>
<td>1.0241</td>
<td>1.1263</td>
<td>0.9865</td>
</tr>
</tbody>
</table>

Fig. 1. Solution structure for voltage and reactive power control problem

Fig. 2. Solution structure of the voltage and reactive power control in distribution network considering optimal network configuration problem
Fig. 3. Flowchart of the proposed voltage and reactive power control in distribution network considering optimal network configuration
Fig. 4. One-line diagram of the IEEE 33-bus distribution system

Fig. 5. Different nature of loads is considered in the network
Fig. 6. Contribution of each of the buses in the network from any nature of load.

Fig. 7. Voltage and voltage stability index improvement of the bus 18.
Fig. 8. Voltage and voltage stability index improvement of the bus 33
Fig. 9. Real 77-bus distribution system
Fig. 10. Contributions buses 1 to 77 of real 77-bus distribution system from any nature of loads