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Real time voltage stabilization in microgrid

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Abstract: This study suggests a new algorithm based on a combination of fuzzy logic and genetic algorithm (GA) to improve voltage profile in a microgrid. The considered microgrid includes control variables such as onload tap changer (OLTC), active power output from distributed generators (DG) and reactive power output from feeder switched capacitors that are controlled in a microgrid controller (MGC) by communication links. The proposed method was used to obtain the optimum value of control variables to establish voltage stabilization in varying load condition as online. For establishing voltage stabilization at the microgrid, an objective function is defined and is tried to minimize it by control variables. The control variables were changed based on fuzzy logic and the GA was employed for finding the optimum shape of membership functions. In order to verify the proposed method, a 34 buses microgrid in varying load condition was analyzed and was compared with previous works.

Key words: capacitor, distributed generation (DG), onload tap changer (OLTC), voltage stabilization, microgrid

1. Introduction

Voltage stabilization is the ability of a power system to close the voltage of all buses to reference voltage under nominal conditions and after being subjected to a disturbance. Also, voltage instability problems and collapse typically occur when the power system is not able to cover the reactive power demand of power system in heavy loads and fault conditions.

Distributed generation and feeder switched capacitors and onload tap changer have an important role in a microgrid. The previous studies have showed that proper coordination between this control variables causes to loss minimization, improve the voltage profile and power factor correction. Proper coordination of control variables means that they are remotely adjusted by MGC system through communication link. The microgrid is mostly a resistive network ($R/X \geq 1$), Therefore with the proper management of active power output of DG, loss can greatly be reduced and voltage profile is improved .kumar and Selvan [1] used DGs as control variables and applied genetic algorithm to finding the optimum values of real power output of DG to improve the voltage profile and reduce the loss. The value of loss depends on the penetration of DG in distributed Systems [2]. If this penetration is greater than a particular value, the rate of loss in distribution systems with DG is greater than that in distributed system without DG. Also the effect of DG with different technology on loss was investigated and it was shown that wind turbine has the worst behavior on real loss. OLTC is a transformer with on load regulated transformation ratio that can regulate its secondary voltage by varying the transformer ratio in a specified range. In some reports [3, 4] Control variables are DG and OLTC and it was shown that not only the loss is reduced, but also DG capacity is increased by using OLTC. Viawan and Karlsson [5] considered reactive power output from DG (active power output from DG is considered constant), OLTC and feeder switched capacitor as control variables and they show that DGs operating at constant voltage are very effective in loss reduction, OLTC operation and voltage fluctuation. Voltage and reactive power control in radial and closed loop distribution systems with DG are investigated and it was shown that the feeder losses and the voltage fluctuation decrease with the reconfiguration of system from radial to closed loop operation [6]. Ref. [7] deals with the management of active and reactive power output from DG in a microgrid. The active power output was controlled based on a frequency-droop characteristic and reactive power output was controlled based on three strategies that are: 1) voltage-droop characteristic, 2) voltage regulation, and 3) load reactive power compensation.

The present work proposed a new method to coordinate the control variables to improve the voltage profile in varying load conditions at a microgrid. The considered DGs in this study can produce several levels of active power and the considered OLTC has 32 taps that can keep the substation secondary bus voltage in a specified range.

2. Impact of DG and feeder switched capacitor on voltage profile

Figure 1 shows a single line diagram of two buses of a microgrid. The voltage drop in electrical power line is in relation with the active and reactive power output of DG according to the following equation [5, 6], with reduction the voltage drop in the lines, the voltage stabilization can be established in the system.

$$U_1 - U_2 = \frac{R(P_{load} - P_{DG}) + X(Q_{load} - (\pm Q_{DG}))}{U_2}, \tag{1}$$

where U_1: primary voltage bus, U_2 : secondary voltage bus, R: the resistance of line, P_{load} : active Power consumption of load, P_{DG} : active Power output of distributed generator, Q_{load} : reaceive power consumption of load, Q_{DG} : reactive Power output of distributed generator, X: the reactance of line, $+Q_{DG}$ means that DG operates at lagging power factor and $-Q_{DG}$ means that DG operates at leading power factor. As it is shown in above equation, both of active and reactive power outputs of DG are effective in voltage regulation. It is observed that the voltage regulation by active and reactive power output of DG is highly dependent on the resistance and reactance of line, respectively. Because of in a microgrid $R \geq X$, Therefore, in voltage regulation, active power output of DG is more effective than reactive power output of DG.

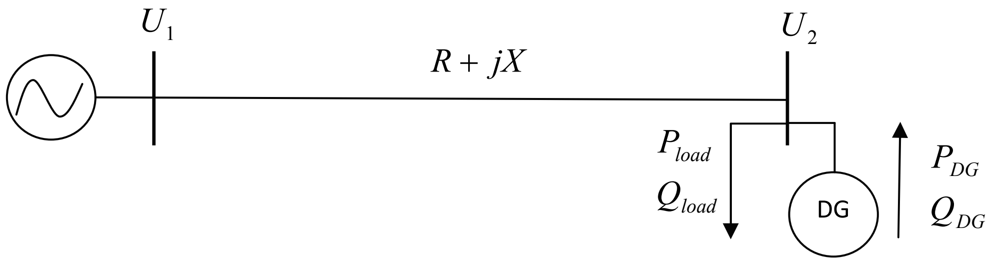

Fig. 1. One-line diagram of a simple two-bus system with DG

If in the Figure 1 DG is replaced by feeder switched capacitor, the Eq. (1) is changed to:

$$U_1 - U_2 = \frac{R(P_{load}) + X(Q_{load} - Q_C)}{U_2}. \tag{2}$$

The Equation (2) indicates that voltage regulation can be improved by the proper management of reactive power output of switched capacitors.

3. Mathematical model of the problem

In ideal conditions, it is desirable to have a constant $1^{p.u.}$ voltage on all buses. For reaching to this purpose, the proposed objective function will be as follow:

$$SDC = \sqrt{\sum_{i=1}^{N_{bus}} \frac{(V(i) - V_{ref})^2}{N_{bus}}}. \tag{3}$$

Subject to

$$V_{\min} < |V(i)| < V_{\max} \qquad \forall \text{ buses}, \tag{4}$$

$$I_l < I_l^{rat} \qquad \forall \text{ lines}, \tag{5}$$

where SDC – standard deviation criteria of the voltage buses, $V(i)$ – rms value of voltage at bus-i, V_{ref} – rated voltage of the system that is equal to $1^{p.u.}$, N_{bus} – number of buses, $V_{\min}$ – lower bound of bus voltage limits (i.e., $0.95 p.u.$), $V_{\max}$ – upper bound of bus voltage limits (i.e., 1.05 p.u.), I_l – current flowing on line-l, I_l^{rate} – line thermal capacity of line-l.

In the Equation (3) the only purpose is closing the voltage of buses to reference voltage, while it is not important sharing the input active power of system between available system resources.

The input active power of microgrid is provide by distributed generators and infinite bus. The injected active power by infinite bus to network is produced by conventional power stations. The input and output of each unit are considered as criteria for determining economic dispatch between these generation units. Power generation cost and its amount have been considered as the input and output of generator units respectively.

The cost of active power generation through the available resources in the system is formulated as:

$$f_1 = K_{in} P_{in} + \sum_{k=1}^{N_{DG}} K_{DG,k} P_{DG,k}\,, \tag{6}$$

where K_{in} – hourly cost per unit of the active power injection by grid (\$/kw.h), P_{in} – active power injection by grid, N_{DG} – number of DG in network, $K_{DG,k}$ – hourly cost per unit of the active power injection by *kth* DG (\$/kw.h), $P_{DG,k}$ – active power injection by *kth* DG.

In order to close the voltage profile of system to reference voltage with minimum cost, the objective function is formulated as follow:

$$F = f_1 + (\lambda \times SDC). \tag{7}$$

In the above equation, Lambda is balancing factor which if the amount of it is high, the voltage stabilization is more important than cost and vise versa, i.e. if the amount of it is low the cost related to input power is more important than voltage stabilization. So this value which is obtained through a trial and error process should be determined in a way that both Equations (3) and (6) have equal importance.

4. Proposed algorithm to adjust control variables

In order to establish voltage stabilization in microgrid, considered objective function should be minimized by available control variables in system. For this, optimization methods such as genetic algorithm [1], Newton [8] and the simulated annealing [9] can be used. In this paper the control variables have discrete values. Even if the active power output of DGs be continuous, we can discrete this values in a small ranges and saved them in a table as offline. If this range becomes smaller, the active power output of DGs is closing to continuous value.

Therefore a method for finding the optimum values of control variables to minimization objective function is searching the entire search space of control variables which are obtained by the following algorithm.

Step 1. Obtain all combination of control variables. For example if the network has a DG that can produce K_1 active power levels and a capacitor bank that can produce K_2 reactive power levels and an onload tap changer that has K_3 taps, then the number of combinations of control variables is equal to multiplication of K_1 and K_2 and K_3.

$$NC = K_1 \times K_2 \times K_3 \tag{8}$$

Where NC: Number of combinations of control variables

Step 2. For each combination run the load flow and obtain objective function, voltage buses and lines current.

Step 3. Find a combination caused the objective function to be lowest value and voltage of all buses and line currents to be in the range

Algorithm 1

The problem of these methods is their high running time. In varying load condition, voltage stabilization should be performed as online. So the speed of algorithm is very important. This current study is looking for a new method that has a high speed and good accuracy.

4.1. Proposed method

Paying a careful attention to the structure of microgrid, it is revealed that the considered objective functions can be minimized with compensating sensitive buses by control variables. The general format of the proposed algorithm is as follow:

Step 1. Get the information of system.
Step 2. Initial the control variables (this initial values are the lowest value of the control variables that cause the load flow to be converges).
Step 3. Perform load flow in the network and determine the voltage of all buses and current of all lines
Step 4. Determine the sensitive bus with using one of the voltage stability indexes
Step 5. Find the most effective control variable to compensate sensitive bus. It is obtained as follows

(1) Find the control variables that if changed one step, cause to the sensitive bus index value at the current iteration be more than the sensitive bus index value at previous iteration and also the objective function value at the current iteration be less than the objective function value at the previous iteration.
(2) Find the optimum control variable from the obtained variables of previous step for which the sensitive bus index value to be maximum

If any control variable was found, go to step 4 and determine the next sensitive bus.
Step 6. Check the stop criterion. The stop criterion has been set as follows;

(1) All bus voltages and line currents are in the range
(2) The difference of the objective function value at the current iteration and previous iteration is lower than a specified value called ε.

If both stop criteria are true, go to the next step. Otherwise, go to the step 4
Step 7. End

Algorithm 2

The initial values are selected by trial and error method by operator of microgrid controller. However the difference between the initial values has no effect on final values of control variables.

The most important part of the above algorithm is finding sensitive bus (step 4). References [1, 10] Used line stability indicator (*SI* index) to determinate sensitive bus in accordance with Figure 2 and the following formula:

$$I_1 = \frac{|V_1|\angle\delta_1 - |V_2|\angle\delta_2}{R_1 + jX_1}, \tag{9}$$

$$P_2 + jQ_2 = V_2 I_1^*, \tag{10}$$

$$SI(N_2) = |V_1|^4 - 4|P_2R_1 + Q_2X_1||V_1|^2 - 4|P_2X_1 - Q_2R_1|^2. \tag{11}$$

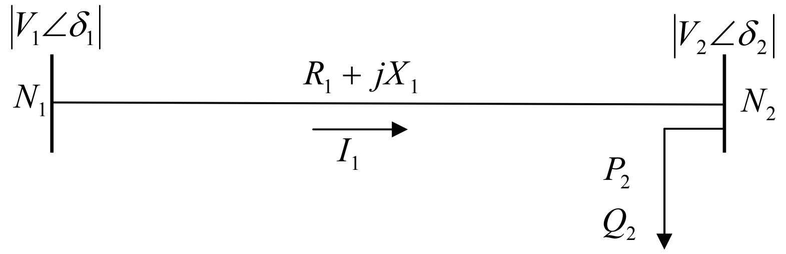

Fig. 2. One-line diagram of a simple two-bus system

In these papers, first for each bus *SI* index is determined and then bus with minimum *SI* index is recognized as sensitive bus.

In this study, proposed index for determining sensitive bus is obtained by fuzzy logic method that is more efficient than SI index.

4.2. Proposed index

4.2.1. Fuzzy modeling

In the fuzzy set each member *x* from global set is defined by its membership function accordance to the flowing relation.

$$\mu_f : U \rightarrow \{0,1\}. \tag{12}$$

If the membership degree of member x was zero, this member is completely out of set and if it was one, it means that it is completely inside the set and if it was a value between zero and one, it gradually represents the membership function. In fact, the membership degree is a criterion for assessing the similarity of x compared to the members of global set [11, 12]. In this paper three membership functions are used.

The sensitive bus is a bus that the deviation voltage of it from $V_{ref} = 1^{\text{p.u}}$ is more than other buses, or the active or reactive power loss of it is more than other buses. The ideal bus is a bus that the voltage of it is $1^{\text{p.u}}$ and the active and reactive power loss of it is zero. Accordingly, for voltage of buses the maximum value of membership function is attributed to 1 p.u voltage. The deviation of this value is causing the membership function be less. The best membership functions that can be proposed for the voltage of each bus bar are the Gaussian or triangular membership function. The shape of these membership functions are shown in Figures 3, 4.

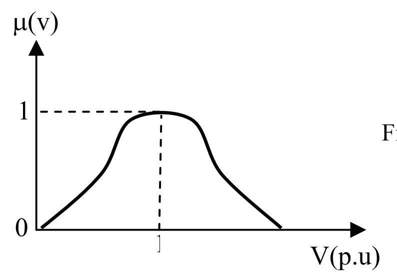

Fig. 3. Gaussian membership function system

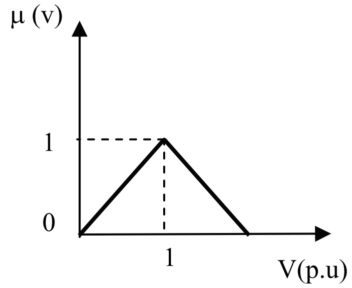

Fig. 4. triangular membership function system

Both of mentioned membership function is tested in the proposed algorithm and the result shown that Gaussian membership function has better performance than triangular membership function. The Gaussian membership function is formulated as (13) Equation.

In the case of loss, when the loss of lines is increased, the membership function should be reduced. The best membership function that can be proposed is trapezoidal membership function that is shown in Figures 5 and 6. Trapezoidal membership function for active and reactive power loss are formulated as (14) and (15) equations.

$$\mu_v(i) = e^{-w_V.(\frac{(V(i)-1)}{V_{\max}-V_{\min}})^2}, \tag{13}$$

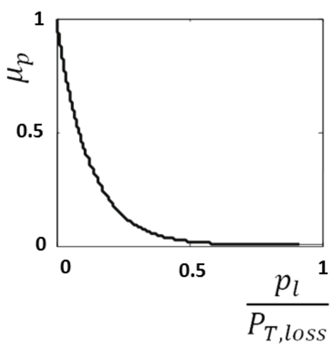

Fig. 5. Trapezoidal membership function

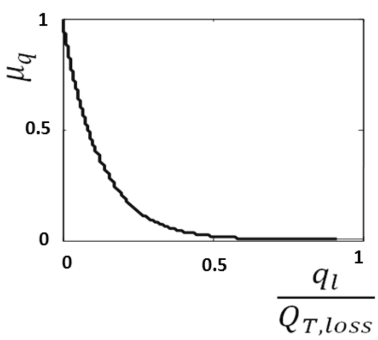

Fig. 6. Trapezoidal membership function

$$\mu_q(i) = e^{\frac{-w_q \cdot ql(i)}{Q_{loss}}}, \tag{14}$$

$$\mu_p(i) = e^{\frac{-w_p \cdot pl(i)}{P_{loss}}}, \tag{15}$$

where μ_v – membership function for voltage bus; w_v – weighting factor of voltage membership function; μ_q – membership function for reactive power loss between lines; w_q – weighting factor of reactive power loss membership function; $q_l(i)$ – reactive power loss for line between i and i + 1 buses; Q_{loss} – total reactive power loss; μ_p – membership function for active power loss between lines; w_p – weighting factor of real loss membership function; $p_l(i)$ – real loss for line between i and i + 1 buses.

If the load flow is done in the network, then voltage and losses are calculated for all buses and lines. The membership functions corresponding to voltage of each bus and loss of each line are calculated by using Equations.13-15. Now, using fuzzy subscribe operator (Eq. 16), minimum membership function corresponding to each bus is determined and then minimum value of values obtained by Equation 16 is calculated using Equation 17. The obtained bus by Equation 17, (i^*) is known as the most sensitive bus that needs to compensate [12].

$$\mu_l(i) = \mu_{v \cap p \cap q}(i) = \min(\mu_v(i), \mu_p(i), \mu_q(i)) \qquad i = 1, 2, \cdots, n, \tag{16}$$

$$\mu_s(i^*) = \min(\mu_l(1), \mu_l(2), \cdots, \mu_l(n)), \tag{17}$$

where n – number of network buses; i^* – sensitive bus; μ_s : Sensitive bus index. Equation 17 indicates that either the voltage of sensitive bus is lower than other buses or the loss of sensitive bus is higher than other buses.

As described above, by closing bus to ideal bus the membership functions are increased and with respect to formula (17), the voltage stability index is increased too. In the other words by increasing the voltage stability index, the voltage drop between lines can be decreased. This reduction of voltage drop between lines cause the voltage stabilization is established in system and objective function be less.

4.2.2. Proposed algorithm

In the previous section, the sensitive bus is determined by fuzzy logic method. Now, algorithm 2 can be modified as follow:

Step 1. Get the information of system.

Step 2. Initial the control variables (this initial values are the lowest value of the control variables that cause the load flow to be converges).

Step 3. Perform load flow in the network and determine the membership functions μ_v and μ_q and μ_p with setting w_v and w_q and w_p by using Equations 13-15.

Step 4. Determine the sensitive bus with using Equations 16, 17 for compensate it by control variables.

Step 5. Find the most effective control variable to compensate sensitive bus. It is obtained as follows

(1) Find the control variables that if changed one step, cause to the $\mu_s(i^*)$ value at the current iteration be more than the $\mu_s(i^*)$ value at previous iteration and also the objective function value at the current iteration be less than the objective function value at the previous iteration.

(2) Find the optimum control variable from the obtained variable of previous step for which the $\mu_s(i^*)$ is maximum.

If any control variable was found, go to step 4 and determine the next sensitive bus.

Step 6. Check the stop criterion. The stop criterion has been set as follows;

(1) All bus voltages and line currents are in the range

(2) The difference of the objective function value at the current iteration and previous iteration is lower than a specified value called ε.

If both stop criteria are true, go to the next step. Otherwise, go to the step 4

Step 7. End

5. Varying load condition

For varying load condition, two scenarios can be considered as follow:

5.1. Scenario 1

In this scenario, it is assumed that the loads on all buses are constant during a day and control variables operate at their optimum values. But a heavy load is suddenly added to or removed from the network. It can damage end user and disturb voltage stabilization on buses because the voltage of buses exceeds from allowed range and the values of control variables are not optimal. In order to protect sensitive equipment such as computers, TVs etc, the proposed algorithm can be used.

By running proposed algorithm, the optimum values of control variables are obtained to minimize the objective function for specific weighting factors (w_v , w_q , w_p). Also by running a sensitivity analysis between the weighting factor parameters, and the value of objective function, it is understood that by changing weighting factors, the sensitive buses and so the objective function are changed. Therefore, it is interesting to find the optimum values of weighting factors to minimize the objective function. The optimum values of weighting factors can be found for nominal loads by genetic algorithm as offline and they are used for all load levels. The weighting factors are optimized by MATLAB optimization toolbox.

GA is one of the optimization tools that generate a set of hypotheses called population and replaces them with new hypotheses alternately. Each of these hypotheses is evaluated by a fitness function at any iteration. Then a number of best hypotheses is selected by using a probability function and constitute the new population. So search space will evolve in direction to reach the optimal solutions. A number of hypotheses selected are used without change and others are used to generate children by using genetic operators such as crossover and mutation. Crossover operator generates two chromosomes of children using two chromosomes of parent. It is done with coping a part of parent's bit to children's bits using methods such as single-point crossover, Two-point crossover and Uniform crossover. Mutation operator uses only one parent to generate children. By using Uniform distribution, a bit is randomly selected and will change its value.

5.2. Scenario 2

In this scenario, it is assumed that at each bus bar the forecasted daily load curve has previously been predicted by electrical company for duration in years (for example one month in year) and the power system loads that is named practical load level are constantly changing around the forecasted load level as online. We can consider any time interval for practical load levels but the time interval for forecasted load level is determined by electrical company. The forecasted load curve was shown in Figure 7. Parameters n_1 – n_8 given in this Figure, are normalized integers that are multiplied in loads peak at each bus bar. These loads peak have been forecasted by electrical company at each bus bar.

As it was described in the previous scenario, the objective function is related to weighting factors. Therefore because of the difference between the practical load level and the forecasted load level is little, the optimum values of weighting factors can be found for forecasted load levels by genetic algorithm as offline and they are used for practical load levels as online.

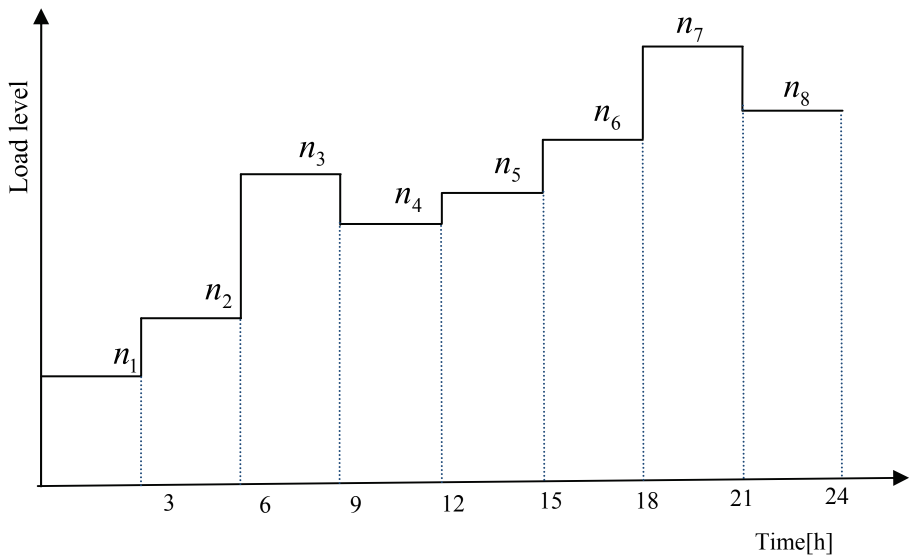

Fig. 7. Daily load Curve

6. Case study

In order to investigate the performance of the proposed algorithm, it is applied to 34 buses microgrid that its rated voltage is 11^{kv}. The single line diagram of this system is given in Figure 8. The lines data and the loads data of this system has been given in [13]. The control variables data are presented in table 1. K_{DG1}, K_{DG2} and K_{in} are equal to 0.1 \$/kw.h, 0.079 \$/kw.h and 0.173 \$/kw.h respectively [14]. DG1 and DG2 operate at 0.95 lagging power factor and 0.9 leading power factor respectively. The voltage limits are $0.95^{p.u.}$ and $1.05^{p.u.}$.

6.1. Voltage stabilization without attention to sharing the input active power of system between available system resources

In this section the objective function is as Equation (3). For varying load condition two scenarios are considered as follow:

6.1.1. Scenario 1.

The optimum values of weighting factors and control variables when the nominal loads are connected to the network are $W_v = 6.291$, $W_p = 15.397$, $W_q = 14.51$, $P_{DG1} = 1250$ kw, $P_{DG2} = 1950$ kw, $Q_{cap1} = 5100$ k var, $Q_{cap2} = 3100$ k var and $V_{OLTC} = 1$ p.u, respectively.

The standard deviation criteria and the cost of input active power to the network for these control variables are 0.0011 and 619\$ respectively.

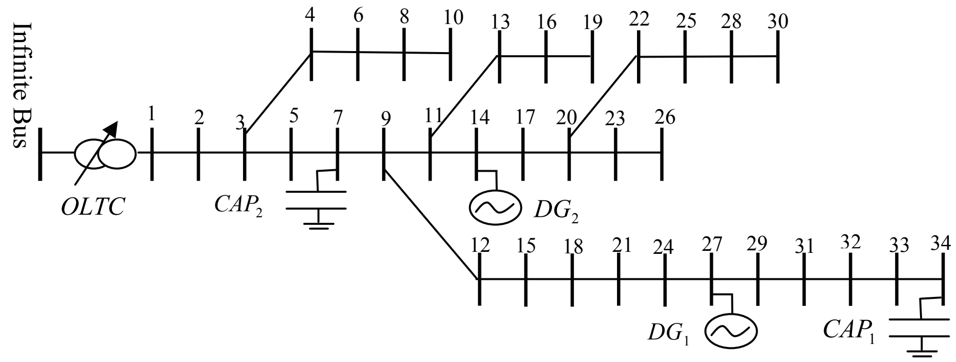

Fig. 8. Single line diagram of 34 buses microgrid

Now it is assumed that the line between bus 14 and bus 17 is removed from the network. This event causes the loads on buses 17, 20, 22, 23, 25, 26, 28, 30 removed from the network. In this case, the above control variables are not optimum for new network. The standard deviation criteria and the cost of input active power to the network for above control variables are 0.0076 and 478 \$ respectively. Figure 9 shows the voltage of buses before and after disturbance.

For finding the optimum values of control variables to minimization the Equation 3 for new network, one of the below methods are used.

Table 1. Control variables data of 34 bases system

Step	P_{DG1} (kW)	P_{DG2} (kW)	V_{OLTC} (p.u.)	Q_{cap1} (kvar)	Q_{cap2} (kvar)
0	0	0	0.9000	0	0
1	100	100	0.9063	300	300
2	150	150	0.9125	600	700
3	200	200	0.9188	900	1100
4	250	250	0.9250	1200	1500
5	300	300	0.9313	1500	1900
6	350	350	0.9375	1800	2300
7	400	400	0.9437	2100	2700
8	450	450	0.9500	2400	3100
9	500	500	0.9563	2700	
10	550	550	0.9625	3000	
11	600	600	0.9688	3300	
12	650	650	0.9750	3600	
13	700	700	0.9813	3900	
14	750	750	0.9875	4200	
15	800	800	0.9938	4500	
16	850	850	1.0000	4800	
17	900	900	1.0063	5100	
18	950	950	1.0125		
19	1000	1000	1.0188		
20	1050	1050	1.0250		
21	1100	1100	1.0313		
22	1150	1150	1.0375		
23	1200	1200	1.0438		
24	1250	1250	1.0500		
25	1300	1300	1.0562		
26	1350	1350	1.0625		
27	1400	1400	1.0688		
28	1450	1450	1.0750		
29	1500	1500	1.0813		
30	1550	1550	1.0875		
31	1600	1600	1.0938		
32	1650	1650	1.1000		
33	1700	1700			
34	1750	1750			
35	1800	1800			
36	1850	1850			
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39	2000	2000			
40	2050				
41	2100				
42	2150				
43	2200				
44	2250				

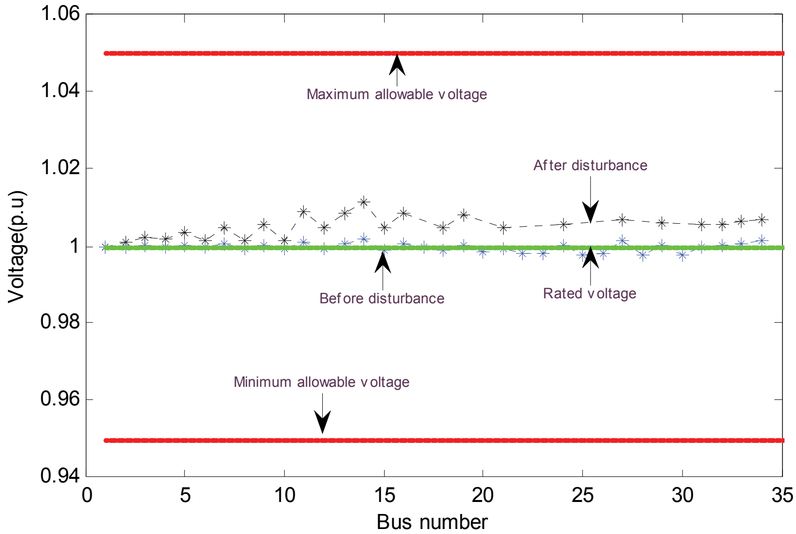

Fig. 9. Voltage profile of 34 buses system before and after disturbance

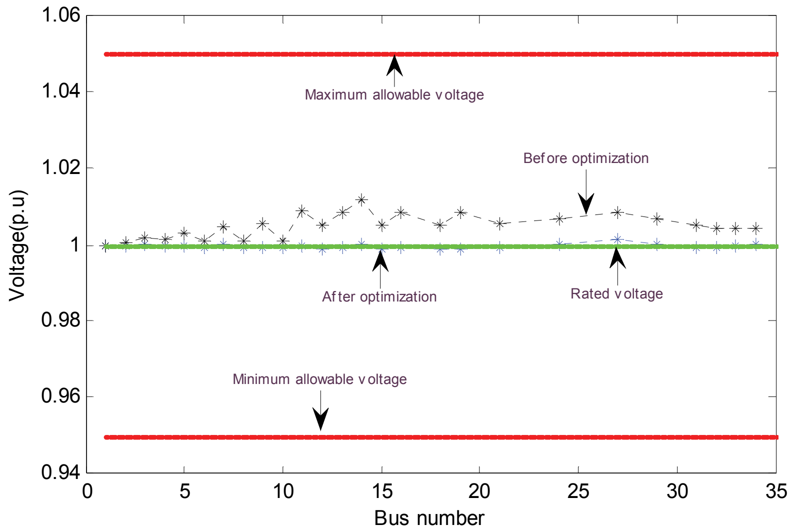

Fig. 10. Voltage profile of 34-buses system before and after optimization

6.1.1.1. Searching over the entire search space of control variables

This method is described in algorithm 1. As shown in Table 1, DG1 and DG2 have 44 and 39 levels of active power respectively, also capacitor 1 and capacitor 2 have 13 and 7 levels of reactive power respectively and OLTC has 32 steps, therefore in order to find an optimum combination, the number of load flows that should be run is as follow:

$$\text{Number of combination} = 44*39*13*7*32 = 4996992.$$

The results of this method are $P_{DG1} = 1400\ \text{kW}$, $P_{DG2} = 650\ \text{kW}$, $Q_{cap1} = 4200\ \text{k var}$, $Q_{cap2} = 3100\ \text{k var}$, $V_{OLTC} = 1\ \text{p.u.}$, SDC = 0.0006 and $f_1(\$) = 565$. Figure 10 shows the voltage profile of system before and after optimization.

In this method, the running time of program that is executed by 32-bit MATLAB and a core 2 duo CPU 2.67 GHz and 4 Gb RAM computer is equal to four hours and fifty minutes. This time is very much for voltage stabilization topic. This method is very exact for finding the optimum values of control variables, which is why the entire searching space of control variables is searched; however, its speed is very low. Therefore this method can be used as a criterion to evaluate the accuracy and speed of the proposed method.

6.1.1.2. Proposed method

The value of control variables and the condition of system after optimization by proposed method are $P_{DG1} = 1150\ \text{kW}$, $P_{DG2} = 800\ \text{kW}$, $Q_{cap1} = 5100\ \text{k var}$, $Q_{cap2} = 1100\ \text{k var}$, $V_{OLTC} = 1\ \text{p.u.}$, SDC = 0.001 and $f_1(\$) = 600$. Figure 11 shows the voltage profile of system before and after optimization.

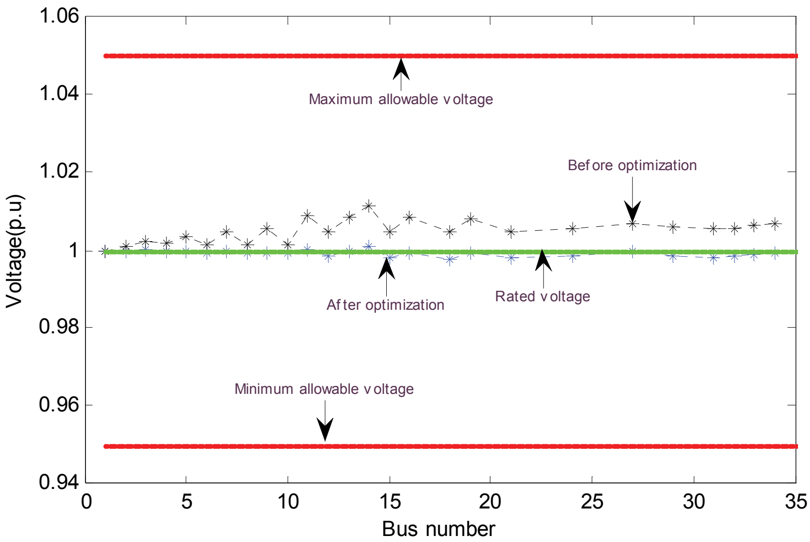

Fig. 11. Voltage profile of 34-buses system before and after optimization

In this method, the running time of program is equal to 3 seconds that it is executed by the same computer in the previous method. The comparison of voltage profile of the system after optimization by searching the entire search space of control variables and the proposed method is shown in Figure 12.

By comparison the obtained results from the proposed method and the previous method, it is cleared that the voltage stabilization in the previous method is a little better than the voltage stabilization in the proposed method but the speed of program in the proposed method is so much better than the previous method. Therefore can be claimed the proposed method is efficient to improve voltage profile in the microgrid.

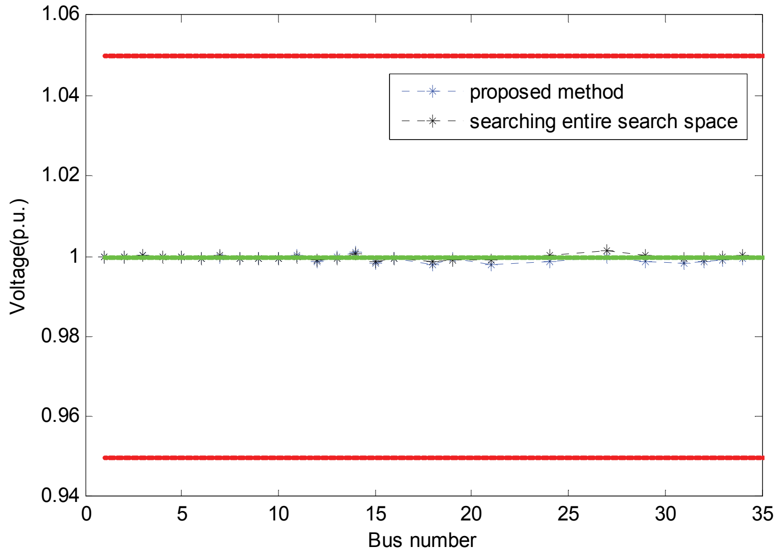

Fig. 12. Comparison of voltage profile of system after optimization by searching the entire search space of control variables method and proposed method

As described above, this algorithm used of fuzzy logic to determinate the sensitive bus. References [1, 11] used the line stability indicator (*SI* index) for determination sensitive bus. If *SI* index is used instead of the proposed index in the proposed algorithm, then the standard deviation criteria and the cost of input active power to the network are 0.011 and 687 $ respectively.

With comparing the above results it is clear that if sensitive bus is determined by the proposed index, the standard deviation criteria of voltage buses is less than when it is determined by *SI* index.

6.1.2. Scenario 2

The forecasted and practical load levels data are given in Tables 2 and 3. The optimum values of weighting factors are given in Table 4 that have previously been founded for each forecasted load level by genetic algorithm. These are used for practical load levels as online.
In this paper, we consider 3-hour time intervals for practical load level, we could consider 15-minute time intervals or even less (for example 30 second time intervals), but by considering less time interval, the size of Table 3 becomes very large.

Table 5 shows the standard deviation criteria and the cost of input power and Figure 13 shows changing of control variables during a day for practical load levels.

6.2. Voltage stabilization with attention to sharing the input active power of system between available system resources

In this section the objective function is as Equation (7). The lambda value that is obtained by trial and error process is equal to 100.

Table 2. Data of daily load curve of each load for forecasted load levels

Bus	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8
1	0.7	0.3	0.4	0.6	0.6	0.75	0.85	0.8
2	0.4	0.4	0.4	0.7	0.7	0.8	1	1
3	0.5	0.55	0.55	0.7	0.7	0.85	0.9	0.95
4	0.7	0.5	0.6	0.85	0.75	0.8	0.9	0.8
5	0.4	0.3	0.7	0.7	0.75	0.8	0.9	0.85
6	0.35	0.55	0.7	0.75	0.7	0.75	0.9	0.95
7	0.5	0.4	0.75	0.65	0.7	0.8	1	0.9
8	0.7	0.45	0.5	0.7	0.7	0.8	0.85	0.9
9	0.65	0.45	0.75	0.65	0.7	0.85	0.85	0.8
10	0.5	0.4	0.45	0.75	0.7	0.8	1	0.95
11	0.35	0.35	0.8	0.85	0.8	0.8	0.9	0.8
12	0.7	0.3	0.45	0.6	0.7	0.85	0.9	1
13	0.65	0.4	0.5	0.7	0.65	0.8	0.85	0.8
14	0.5	0.4	0.65	0.7	0.7	0.7	0.9	1
15	0.45	0.5	0.75	0.75	0.6	0.7	1	0.9
16	0.8	0.45	0.7	0.75	0.7	0.8	0.95	0.8
17	0.85	0.55	0.65	0.8	0.75	0.8	0.9	1
18	0.5	0.45	0.5	0.8	0.7	0.8	0.9	0.95
19	0.7	0.35	0.4	0.65	0.7	0.8	0.9	0.85
20	0.7	0.5	0.6	0.7	0.7	0.8	0.9	0.95
21	0.5	0.3	0.65	0.8	0.65	0.8	1	0.95
22	0.6	0.45	0.75	0.75	0.65	0.85	1	0.9
23	0.7	0.3	0.7	0.7	0.75	0.8	1	0.85
24	0.35	0.5	0.8	0.6	0.65	0.8	0.9	1
25	0.45	0.3	0.7	0.75	0.7	0.8	1	0.85
26	0.55	0.35	0.65	0.8	0.75	0.7	0.95	0.95
27	0.6	0.65	0.55	0.8	0.7	0.8	0.95	0.8
28	0.6	0.35	0.45	0.7	0.7	0.75	0.9	0.9
29	0.75	0.4	0.55	0.6	0.7	0.75	0.8	0.95
30	0.5	0.6	0.5	0.75	0.75	0.7	0.8	1
31	0.4	0.4	0.45	0.65	0.7	0.8	0.9	0.85
32	0.45	0.4	0.45	0.75	0.75	0.85	0.9	0.9
33	0.4	0.6	0.45	0.7	0.7	0.8	0.85	0.9
34	0.5	0.45	0.55	0.65	0.65	0.75	0.85	0.8

6.2.1. Scenario 1

The optimum values of weighting factors and control variables when the nominal loads are connected to the network are $W_v = 1$, $W_p = 1.8$, $W_q = 1$, $P_{DG1} = 2250$ kW, $P_{DG2} = 2000$ kW, $Q_{cap1} = 600$ k var, $Q_{cap2} = 2300$ k var and $V_{OLTC} = 1$ p.u. respectively.

The standard deviation criteria and the cost of input active power to the network for these control variables are 0.0015 and 455.86 \$ respectively.

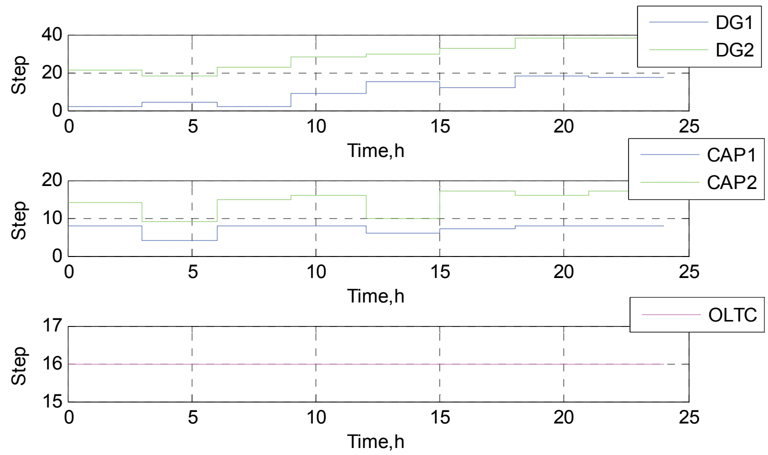

Fig. 13. Change of control variables during a day

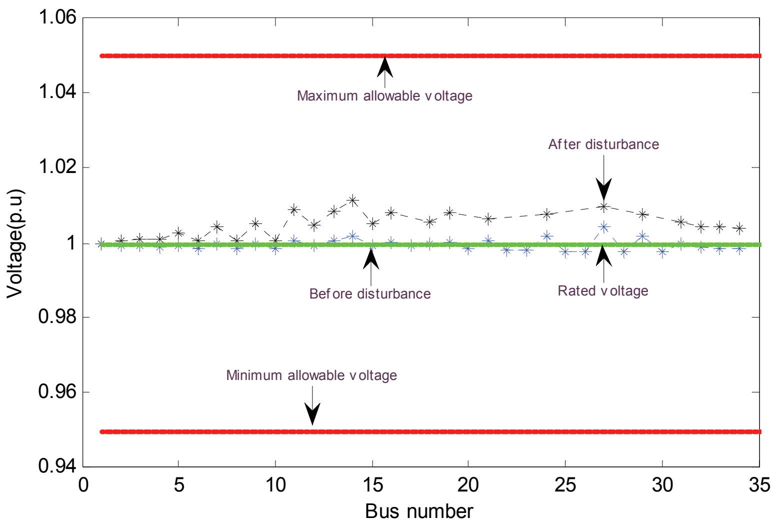

Fig. 14. Voltage profile of 34-buses system before and after disturbance

Now it is assumed that the line between bus 14 and bus 17 is removed from the network. In this case the above control variables are not optimum for new network. The standard deviation criteria and the cost of input active power to the network for above control variables are 0.0076 and 313.5 $ respectively. Figure 14 shows the voltage of buses before and after disturbance.

For finding the optimum values of control variables to minimization the Equation 7 for new network we use one of the below methods.

Table 3. Data of daily load curve of each load for practical load levels

Bus	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8
1	0.79	0.32	0.42	0.65	0.65	0.75	0.85	0.83
2	0.45	0.38	0.44	0.7	0.68	0.8	1	1
3	0.55	0.53	0.55	0.75	0.7	0.85	0.91	0.92
4	0.75	0.47	0.61	0.8	0.72	0.83	0.95	0.81
5	0.42	0.31	0.63	0.7	0.75	0.8	0.88	0.85
6	0.33	0.56	0.7	0.7	0.73	0.76	0.9	0.96
7	0.5	0.38	0.75	0.65	0.75	0.77	0.99	0.89
8	0.71	0.46	0.52	0.75	0.7	0.83	0.85	0.91
9	0.63	0.45	0.75	0.7	0.7	0.85	0.86	0.8
10	0.5	0.39	0.45	0.75	0.7	0.8	1	0.95
11	0.35	0.34	0.8	0.8	0.75	0.79	0.89	0.83
12	0.7	0.3	0.43	0.65	0.72	0.84	0.92	1
13	0.65	0.4	0.51	0.68	0.68	0.77	0.86	0.85
14	0.51	0.42	0.62	0.68	0.69	0.75	0.87	0.95
15	0.43	0.5	0.75	0.7	0.65	0.75	1	0.9
16	0.81	0.46	0.7	0.75	0.73	0.8	0.95	0.82
17	0.83	0.55	0.6	0.8	0.75	0.84	0.91	0.99
18	0.52	0.45	0.5	0.78	0.72	0.76	0.87	0.96
19	0.67	0.35	0.45	0.65	0.71	0.78	0.9	0.88
20	0.73	0.54	0.68	0.7	0.72	0.8	0.87	0.95
21	0.52	0.32	0.64	0.75	0.65	0.83	1	0.95
22	0.63	0.45	0.75	0.75	0.66	0.85	0.98	0.91
23	0.71	0.32	0.73	0.65	0.74	0.8	0.97	0.8
24	0.33	0.5	0.78	0.65	0.7	0.79	0.88	1
25	0.45	0.32	0.72	0.75	0.7	0.79	1	0.85
26	0.55	0.34	0.65	0.78	0.75	0.78	0.94	0.95
27	0.6	0.67	0.55	0.8	0.65	0.82	0.93	0.82
28	0.63	0.36	0.45	0.65	0.7	0.8	0.9	0.9
29	0.74	0.41	0.55	0.65	0.7	0.78	0.83	0.95
30	0.52	0.63	0.5	0.7	0.73	0.76	0.89	1
31	0.4	0.37	0.45	0.7	0.75	0.79	0.94	0.83
32	0.45	0.39	0.41	0.75	0.74	0.82	0.9	0.88
33	0.41	0.61	0.43	0.75	0.68	0.79	0.85	0.86
34	0.5	0.44	0.6	0.7	0.6	0.7	0.8	0.82

6.2.1.1. Searching the over entire search space of control variables

The results of this method are $P_{DG1} = 2250$ kW, $P_{DG2} = 2000$ kW, $Q_{cap1} = 600k$ var, $Q_{cap2} = 1900$ k var, $V_{OLTC} = 0.9938$ p.u., SDC = 0.0039 and $f_1(\$) = 313$. Figure 15 shows the voltage profile of system before and after optimization.

In this method, the running time of program is equal to four hours and fifty minutes that it is executed by the same computer in the previous method. This time is very much for voltage stabilization topic.

Table 4. Optimum values of weighting factor for each forecasted load level

	First load level	**Second load level**	**Third load level**	**Forth load level**	**Fifth load level**	**Sixth load level**	**Seventh load level**	**Eighth load level**
W_v	18.4	18.023	16.67	6.23	17.83	14.28	7.4	7.08
W_p	14.2	5.6	12.54	7.65	15.37	12.12	3	3.64
W_q	10.47	7.31	11.37	5.67	18.9	16.1	10.84	10.57

6.2.1.2. Proposed method

The optimum values of control variables, standard deviation criteria and the cost of input active power to the network that are obtained by proposed method, are $P_{DG1} = 2250$ kW, $P_{DG2} = 2000$ kW, $Q_{cap1} = 600$ k var, $Q_{cap2} = 1900$ k var, $V_{OLTC} = 0.9938$ p.u., SDC = 0.0039 and $f_1(\$) = 313$.

In this method, the running time of program is equal to 2 seconds. The results of this method are equal to the obtained results with pervious method. This equality verifies the high accuracy of the proposed algorithm. The voltage profile of the system is as Figure 15.

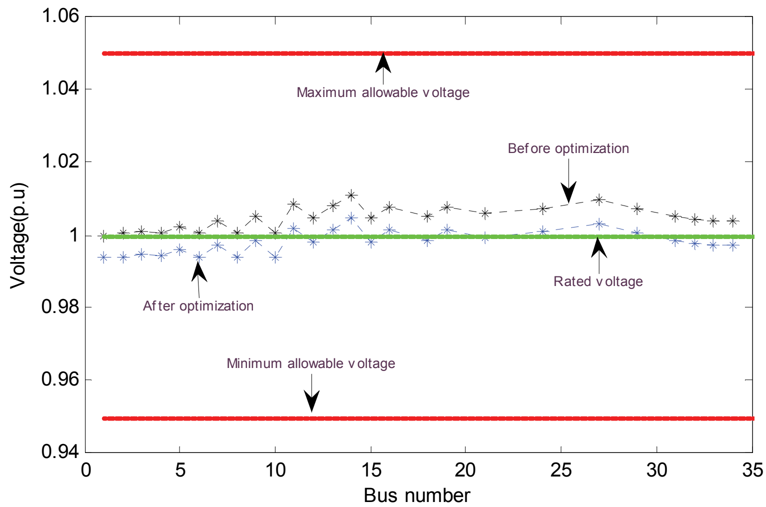

Fig. 15. Voltage profile of 34-buses system before and after optimization

If *SI* index is used instead of the proposed index in the proposed algorithm, then the standard deviation criteria and the cost of input active power to the network are SDC = 0.03 and $f_1(\$) = 315$.

With comparing the above results it is clear that if sensitive bus is determined by the proposed index, the standard deviation criteria of voltage buses and the cost of input active power is less than when it is determined by *SI* index.

6.2.2. Scenario 2

The optimum values of weighting factors are given in Table 6 that have previously been founded for each forecasted load level by GA, and these are used for practical load levels as online.

Table 5. The standard deviation criteria and cost of input active power for each practical load level

	First load level	**Second load level**	**Third load level**	**Forth load level**	**Fifth load level**	**Sixth load level**	**Seventh load level**	**Eighth load level**
SDC	0.00094	0.00083	0.0009	0.0008	0.0007	0.00086	0.00092	0.00089
f_1($)	396	263	426	487	393	522	566	573

Table 7 shows the standard deviation criteria and the cost of input power and Figure 16 shows changing of control variables in a day for practical load levels.

Table 6. Optimum values of weighting factor for each forecasted load level

	First load level	**Second load level**	**Third load level**	**Forth load level**	**Fifth load level**	**Sixth load level**	**Seventh load level**	**Eighth load level**
W_v	1.12	12.11	1.1	1	1.26	7.8	8.8	10.76
W_p	1	18.25	10.1	1.68	15.03	19.7	1	17
W_q	1	6	1	1	17.4	2.26	4.9	5.2

Table 7. The standard deviation criteria and cost of input active power for each practical load level

	First load level	**Second load level**	**Third load level**	**Forth load level**	**Fifth load level**	**Sixth load level**	**Seventh load level**	**Eighth load level**
SDC	0.0065	0.008	0.0062	0.0044	0.0048	0.0034	0.0026	0.0028
f_1($)	94.54	5.2	125	227	221	290	390	382.64

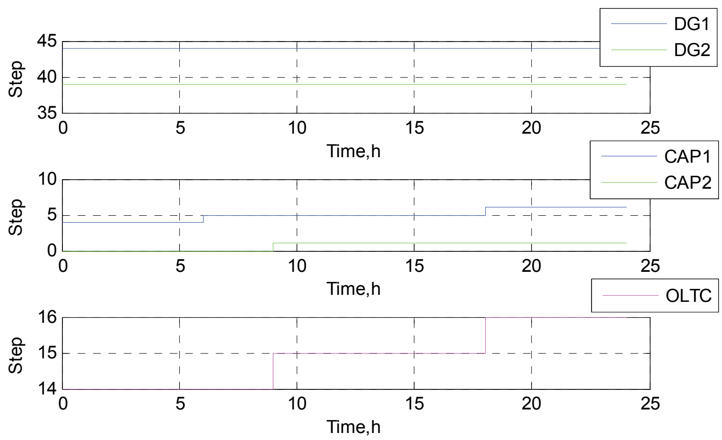

Fig. 16. Change of control variables during a day

7. Conclusion

This article presents a new method for coordinating control variables such as OLTC, DGs and feeder switched capacitors in order to establish voltage stabilization in a microgrid. These variables are controlled in a MGC by communication link. The considered DGs can produce several active power output and considered OLTC has 32 steps. The proposed method has been tested on 34-buses system and then the results are compared by an accurate method. The comparison shows that the proposed method effectively minimizes objective function by very high speed. Also it was shown that determining sensitive bus by proposed index has better performance for minimization of objective function than determining it by SI index.

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