

A multistage voltage and power flow control of distribution systems in the presence of DGs

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Abstract –With the rapid increase of distributed generation (DG) in distribution systems, voltage and power flow become more liable to violate. The generation of non dispatchable DG is uncontrolled so traditional controllers such as on load tap changer (OLTC) are unable to keep the distribution system operating all times without violations. As a result voltage and power flow control should be adapted. This paper proposes a multistage method to control voltage and power flow in the system if any bus or line exceeds its voltage or thermal limit respectively. The first stage is the control of (OLTC) and then the reactive power control is applied and if the two last methods are insufficient to keep the system operating within accepted limits, active generated power curtailment is considered. The method proposed here considers the rated reactive power drawn from the transmission system that keeps the voltage of transmission buses within limits. This method is based on the Jacobian sensitivity matrix. This method is tested on IEEE 33 bus radial distribution system using matlab. The simulation is done using matpower5.1 package.

Index Terms – *distributed generation, voltage control, on load tap changer, reactive power control, energy curtailment.*

I. INTRODUCTION

Due to the increase of integrating DG units in distribution systems, those systems are in transition from traditional system with unidirectional power flows to active network with bidirectional power flows. With the presence of DG in distribution systems, if its power exceeds local loads, the power flow direction will be inversed and voltage raise will occur at the DG connected bus. So the voltage and thermal violations depends on the amount of loads and the amount of DG generated power [1-3].

The traditional voltage and reactive power control in distribution networks assumes that load current always flows from substations to ends of feeders, and voltage magnitudes decrease along feeders. The introduction of the DG makes these assumptions not valid any longer as it changes the direction of power flow in some time and alters voltage profiles. The only real time measurement point is the voltage at the secondary of the on load tap changer transformer (OLTC). Unfortunately such a control cannot detect a local voltage rise which occurs due to high penetration of active power from DG [4,5]. As DGs are often connected to weak distribution networks, their impact on voltage is very high [6].

At present many of DG generators are of induction motor type (like wind power), these type of generators can produce real power but they absorb reactive power from the system. It is expected that in the near future more synchronous generators will be used as DG units. Synchronous generators can produce or consume reactive power, when synchronous generators consume reactive power from the system effects on the voltage profile are similar to an induction generator operation when they consume the same amount of reactive power. So DG might always or partly draws reactive power [7-8].

The new addition of reactive power demand due to connecting DG is placing a strain on transmission system voltage resources and resulting in lower voltages at times of high DG output. So it is required to decrease the reactive power drawn from the transmission system according to the transmission network point of view but this means that increasing reactive power compensated by DG or capacitors which cause extra voltage rise on DG bus voltage. So the main problem is to keep voltage and power flow within limits for distribution and transmission system.

Using traditional controllers such as (OLTC) for voltage control may cause voltage and power flow exceeding limits at sum bus bars. To keep the voltage at all network nodes and power flow of all lines within the limits all the time additional measures can be needed. Reinforcement of the network by building new lines, using lines with higher cross sections and transformers with higher ratings is always a solution to solve the voltage and power flow problems. But that solution is expensive and takes a long time.

The authors have developed several methods for solving the overvoltage problem due to integrating DGs into distribution systems. The DGs capacities can be maximized with the minimization of reactive power drawn from the substation keeping both system voltage and thermal limits as presented in [9-10]. A methodology for managing the network voltage based on controlling the reactive power generated from DG is discussed in [11-13]. In [14], a new technique is presented for voltage control in the presence of DG, this technique consists of two control actions on load tap changer (OLTC) and distribution static synchronous compensator (D-STATCOM). In [15], the system network is divided in two areas. The first collects nodes controlled by line drop compensator (LDC) and the second collects nodes controlled by the DG. In [16,17], based on the sensitivity analysis and PSO algorithm to control

the reactive power in the medium voltage distribution system to maintain the voltage in the system within the predefined limits. A new method for voltage and reactive power control in the distribution system is proposed in [18]. The objective is maximizing the generation from DG by controlling reactive power of DG to minimize losses and to minimize the number of switching of OLTC by taking a constraint that OLTC must be changed only three times per day.

This paper proposes a novel voltage control method based on selecting the optimal control action when any bus voltage or line flow violation occurs in the distribution system. Three control actions are considered in this method: on load tap changer, reactive power control and active power curtailment.

II. CONTROL SCHEME

A. Proposed method:

The objective of this method is to keep the distribution system operating within limits all times. Multistage control actions are introduced in this method to counteract any violation in voltage or thermal limits in the presence of DG in the distribution system. In this method three control variables are considered:

- 1) On load tap changer (OLTC) control.
- 2) Reactive power control.
- 3) Active power curtailment.

The reactive power control is performed by changing the power factor of DG in the case of synchronous generators or by changing the output of the reactive power compensation devices such as D-STATCOM connected to induction generators [9]. The reactive power generated from DG or from compensation devices could be controlled. The main goal of integrating DGs to the distribution systems is to generate the maximum allowed level of active power. So the last control action should be active power curtailment. Energy could be curtailed by connecting negative generation or positive loads to the DG.

If any or some of buses exceed the voltage limit, the control actions are arranged as follow:

- 1) The substation tap changer is changed until all buses reach the rated limits or the tap changer reaches its maximum or minimum setting value.
- 2) If the tap changer is arranged and still voltage violation occurs at any bus, the reactive generation is controlled based on Newton_Raphson sensitivity matrix until all buses voltages are within limits or the reactive power drawn from the transmission system reaches a predefined value which not affect the transmission voltage.
- 3) If the last two control actions are applied and still any bus voltage violation, the active generated power by

DGs are curtailed until all buses reach the accepted voltage limits.

When any line exceeds its thermal limit, only the reactive power control and active energy curtailment are applied with the same sequence to return the system to stability mode. If the over voltage and overflow occur at the same time, the three control action are applied with the same sequence. Our problem is constrained by the following equality and inequality constraints:

- 1) Tap changer constraint:

$$V_{oltc \min} \leq V_{oltc} \leq V_{oltc \max} \quad (1)$$

- 2) DG Power Factor constraint:

$$\phi_{DGi \min} \leq \phi_{DGi} \leq \phi_{DGi \max} \quad (2)$$

- 3) Capacity Constraint for DG (MVA):

$$(P_{DGi})^2 + (Q_{DGi})^2 \leq (S_{DGi \max})^2 \quad (3)$$

- 4) Bus Voltage Level Constraint:

$$|V_i|_{\min} \leq |V_i| \leq |V_i|_{\max} \quad (4)$$

- 5) Flow Limit Constraint:

$$(P_{ij})^2 + (Q_{ij})^2 \leq (S_{ij \max})^2 \quad (5)$$

- 6) Sum of generated power equals sum of demand plus losses:

$$P_L + \sum_{i=2}^n P_{Di} = \sum_i P_{DGi} + P_{GSP} \quad (6)$$

$$Q_L + \sum_{i=2}^n Q_{Di} = \sum_i Q_{DGi} + Q_{GSP} \quad (7)$$

Where:

P_{DGi}, Q_{DGi} : active and reactive generated power by DG connected at bus i.

$S_{DGi \max}$: rated apparent generated power by DG connected at bus i.

P_{ij}, Q_{ij} : active and reactive power flow from bus i to bus j.

$S_{ij \max}$: rated power flow from bus i to bus j.

P_L, Q_L : total active and reactive power losses.

P_{Di}, Q_{Di} : active and reactive power demand at bus i.

P_{GSP}, Q_{GSP} : active and reactive generated power by slack bus.

B. Mathematical formulation:

The relations between active and reactive injected power to each bus and the voltage and node angle are represented by the Newton Raphson sensitivity matrix given by:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \quad (8)$$

The values of the Jacobian elements are obtained from the derivative of the following equations:

$$P_i = V_i \sum_{j=1}^n V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad (9)$$

$$Q_i = V_i \sum_{j=1}^n V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \quad (10)$$

Where:

P_i, Q_i : the active and reactive injected power to bus i.

V_i : is the voltage at bus i.

θ_{ij} : is the phase angle between buses i& j.

G_{ij} : is the conductance of line between buses i& j.

B_{ij} : is the susceptance of line between buses i& j.

So both amount of change in bus voltage and line angle can be controlled by changing both the active and reactive generated power as given by:

$$\Delta \theta = A \Delta P + B \Delta Q \quad (11)$$

$$\Delta V = C \Delta P + D \Delta Q \quad (12)$$

Matrices A, B, C, and D are the elements of the inverse Jacobian matrix. The maximum change in the line angle $\Delta \theta_{i \max}$ or bus voltage $\Delta V_{i \max}$ is given by:

$$\Delta V_{i \max} = V_{i \max} - V_i \quad (13)$$

$$\Delta S_{ij \max} = S_{ij \max} - S_{ij} \quad (14)$$

$$\Delta \theta_{i \max} = \frac{\Delta S_{ij \max}}{\frac{\partial S_{ij}}{\partial \theta_i}} \quad (15)$$

Where $S_{ij}, S_{ij \max}$ are the power flow and the rated power flow of line between buses i& j.

C. Implementation :

The above mentioned method is based on linearization of the problem based on the Jacobian matrix [19]. Three control stages are introduced: tap changer setting then reactive power control and active power control at the last. The first step is solving the power flow problem to calculate the Jacobian and inverse Jacobian matrix. Then the values of $\Delta \theta_{i \max}$ and $\Delta V_{i \max}$ are calculated to check if any line flow or voltage violation occurs. The control actions are applied with the same sequence. The reactive power constrained is constrained by the critical amount of reactive power drawn from the transmission system. The values of $\Delta \theta_{i \max}$ and $\Delta V_{i \max}$ are updated after each control action to make sure that voltage and line flow become within limits or not. A flow chart describing the multistage control method is shown in Fig.1. The control method was coded by matlab language and the simulation was done using matpower5.1 package [20] to solve the power flow problem.

III. RESULTS AND DISCUSSION

A. IEEE 33 bus results:

The proposed control method is tested on IEEE 33 bus radial distribution system shown in fig.2. This system has a base voltage of 12.66 kV with 100 MVA base. The results obtained from the proposed method are compared with results obtained from literature review [16]; at which the same studied system was tested. All the study system conditions that were in [16] are taken in consideration. The voltage limits are ranging from 0.97 pu to 1.03 pu.

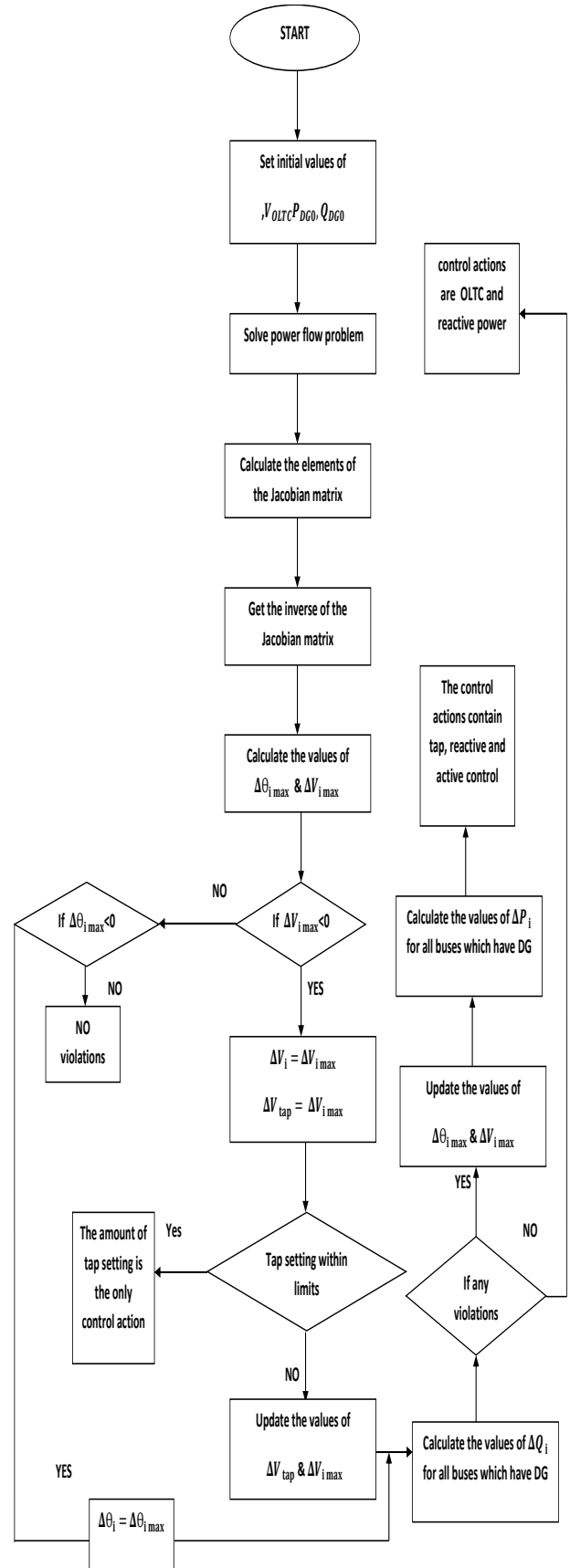


Fig.1 Flow chart of the multistage control method

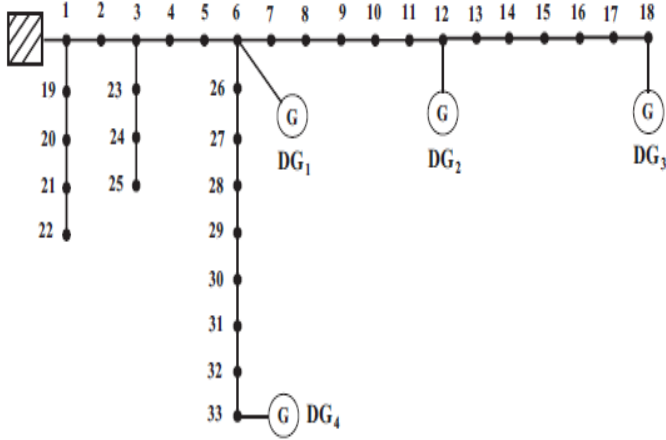


Fig.2 IEEE 33 bus radial distribution system

Four DGs are assumed to be connected to buses 6, 12, 18, 33 as shown in fig.2. The four DGs are doubly fed induction generators and have a maximum active power output of 1 MW. Modern doubly fed induction generators by the virtue of the modern electronic that are connected to them are able to control both the active and reactive power like the synchronous generators. At the base case, these DGs are operating at the unity power factor. The maximum and minimum reactive power to generated or absorbed by DG is given in table 1. There are two worst cases that must be considered when DGs are integrated to the distribution system: the first is the point of zero DG generation and maximum load while the second critical point is the point of maximum DG generation & minimum load. If the proposed control system is able to solve the voltage and power flow problems at those two critical points, it can manage the system at all other operating points. The detailed results for the two critical points are described as follow:

Table 1
Power capability of DGs (% from rated power) [10]

Point	DG active power output (%)	$Q_{max} \cdot Q_{min}$
1	0	$\pm 95\%$
2	$\pm 25\%$	$\pm 95\%$
3	$\pm 50\%$	$\pm 90\%$
4	$\pm 100\%$	$\pm 60\%$

Case 1: (minimum DG generation & maximum load)

For this case, buses loads are at its maximum values (100% of the rated load), while the generated power by DG is 15% of the maximum rated generated active power by DG, so each one generates 0.15 MW. According to table 1, the maximum accepted controlled reactive power is ± 0.95 MVar for each generator. The voltage profile of the IEEE 33 bus

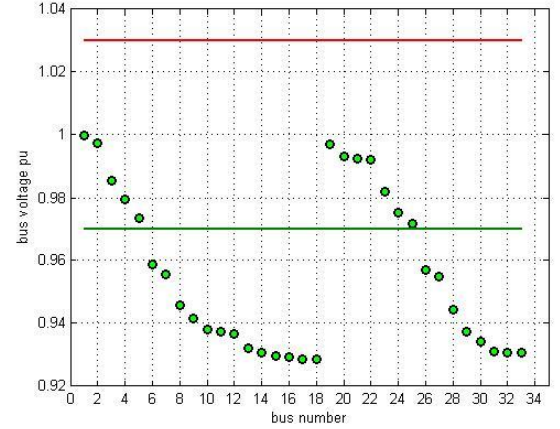


Fig.3 IEEE 33 bus voltage profile without control action

system before any control action in this case is shown in fig.3. It is clear that most of buses have voltage lower than the lower limit. All system lines are within power flow limits. A control action must be taken to return all buses voltages within the permitted range. The literature approaches proposed in [16] to solve the problem is presented here. Also the tap changer only, reactive power only and our proposed methods are applied to keep all buses within voltage limits. A comparison between all methods is introduced at the end of this section.

1. Literature:

The goal of the proposed method in [16] is to return all buses within voltage limits with the minimum amount of controlled reactive power in the system. The only control action in this method is the reactive power generated or absorbed by DGs. As shown in fig.4 this method succeeds to return all buses within voltage limits. The lowest bus voltage occurs at bus 30 with a value slightly close to 0.97 p.u (the lower voltage limit). The generated reactive power by DGs to return all buses to be within voltage limits is given in table 2. The total amount of controlled reactive power is 2.3537 MVar.

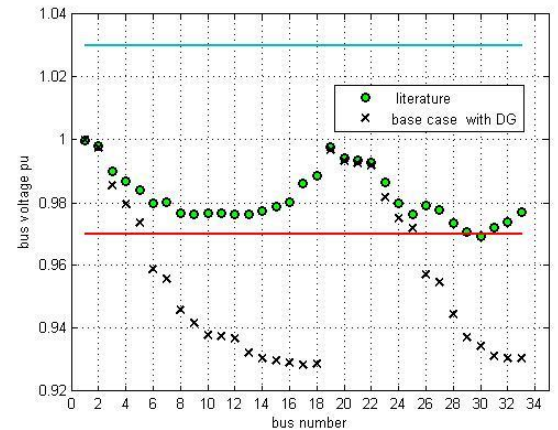


Figure 4 Voltage profile before and after literature control

Table 2*Active and reactive generated power by DGs (case literature)*

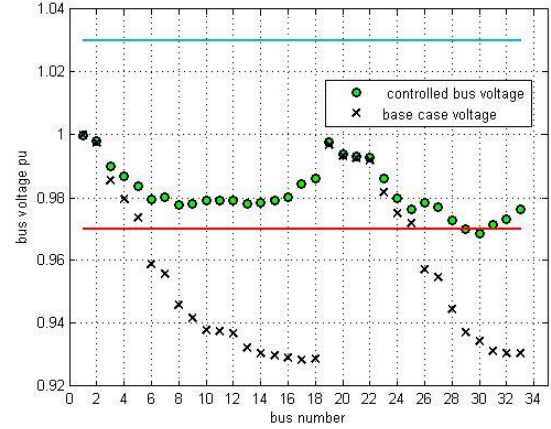
DG	Bus	Active power output (MW)	reactive power output (MVar)
1	6	0.15	0.5944
2	12	0.15	0.20562
3	18	0.15	0.6037
4	33	0.15	0.95
sum	-----	0.6	2.3537

2. Tap changer only:

Each control action in our proposed method is applied individually to control voltage to check which is able to keep all voltages within limits. The tap changer is the only control action in this method. The tap changer secondary voltage is accepted to vary between 0.97 pu and 1.03 pu with a step of 0.01 pu. The voltage profile before and after applying the tap changer control action is shown in fig.5. The tap changer secondary voltage is raised to its upper limit 1.03 pu. Number of buses still has voltages lower than the lower voltage limit. So this control action is insufficient to return all buses within accepted voltage limits.

3. Reactive power control only:

The reactive generated or absorbed power by DGs is the control action in this section. The voltage profile of the IEEE 33 bus system before and after applying this control action is shown in fig.6. It is observed that the reactive power control action succeeds to return all buses to be within the lower and upper voltage limits. The lowest bus voltage occurs at bus 30 with a value nearly equal to (0.97 pu) the lower voltage limit. The amount of controlled reactive power by each DG is given

**Figure 6** Voltage profile before and after reactive power control

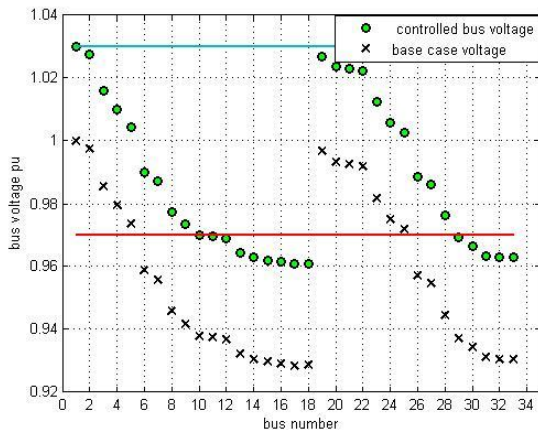
in table 3. The total amount of controlled reactive power is 2.2944 pu which is lower than the literature case by 60 kVAr, so the proposed method is more accurate than the literature approach presented in [16].

Table 3*Active and reactive generated power by DGs (reactive power control only)*

DG	Bus	Active power output (MW)	reactive power output (MVar)
1	6	0.15	0.4
2	12	0.15	0.5
3	18	0.15	0.4444
4	33	0.15	0.95
sum	-----	0.6	2.2944

4. Proposed control approach:

The proposed control method depends on the tap changer, then the reactive power control and at least active power curtailment. In this case the tap changer and reactive power controllers are sufficient to return all buses voltages within limits as shown in fig.7. The substation secondary voltage is raised to be 1.03 pu by the aid of the tap changer as shown in fig.7. The reactive generated power by DG is shown in table 4. The total amount of controlled reactive power is 0.3629 MVar as given in table 4 which considered a small amount compared with the last two methods. A comparison between all control methods has been done and given in table 5. All methods succeed to return all voltages within limits except "the tap changer only". All methods introduce better voltage deviation and losses than the case before any control action.

**Figure 5** Voltage profile before and after tap changer control

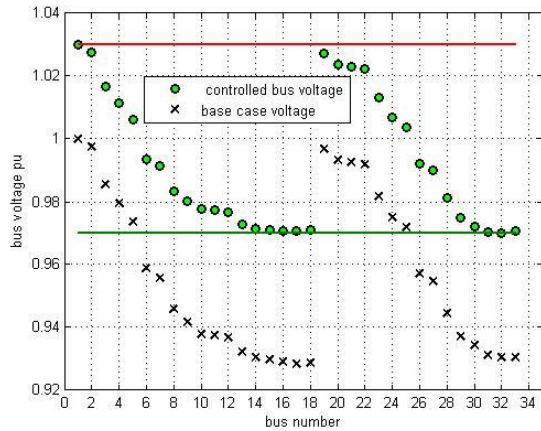


Figure 7 Voltage profile before and after proposed control approach

Table 4

Active and reactive generated power by DGs (proposed approach)

DG	Bus	Active power output (MW)	reactive power output (MVar)
1	6	0.15	0.0171
2	12	0.15	0.1264
3	18	0.15	0.0624
4	33	0.15	0.1571
sum	-----	0.6	0.3629

It is clear that our proposed control method gives the lowest amount of controlled reactive power lower than the others by nearly 2 MVar which is a very big difference. The proposed method gives close losses ratio and voltage deviation to the case when applying the reactive power control only that is the lowest in losses and voltage deviation.

Case2: (maximum DG generation & minimum load)

The load in this case is 25% of the rated load for all buses while the DG output is 90% which means that each DG have an output of 0.9 MW. The maximum amount of reactive power to be generated or absorbed by DG is ± 0.66 MVar. The voltage profile of all system buses before applying any control action is shown in figure 5.8. At the point of maximum DG generation and minimum load, the voltage reaches its highest values so if the control approach is able to return all buses within voltage limits, this approach must be able to return voltage within limits when any over voltage occurs at any either operating point. As shown in fig.8, most of buses have voltages higher than the upper voltage limit. The highest over voltage occurs at the remotest bus from the substation (18) as one of the DGs is connected to that bus. One or more control action must be taken to return all buses within voltage limits. Like in case1, the tap changer only, literature, reactive power only and the proposed approach are different methods applied here to solve the overvoltage problem. The comparison between these different method will show which is the best to solve the over voltage problem presented here.

Table 5

Comparison between control methods

method	Controlled reactive power (MVar)	Voltage limit satisfied	Active losses (MW)	Reactive losses (MVar)	Losses ratio %	Mean voltage deviation %
Without control	-----	No	0.1473	0.0989	3.9%	4.52%
Literature [16]	2.3537	yes	0.1085	0.0791	2.98%	1.87%
Tap changer only	-----	No	0.1378	0.0925	3.66%	2.47%
Reactive power only	2.2944	yes	0.1072	0.0771	2.93%	1.86%
Proposed method	0.3629	yes	0.1128	0.0753	3.01%	2.04%

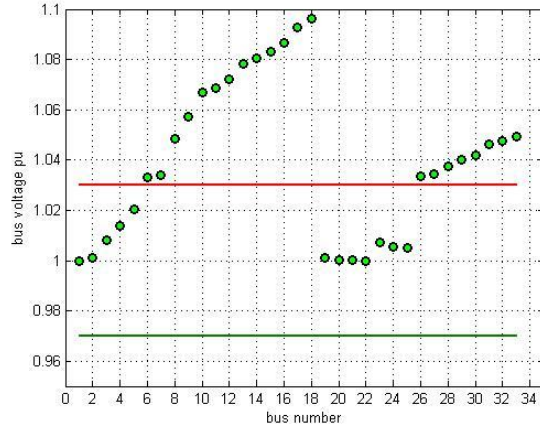


Fig. 8 IEEE 33 bus voltage profile without control action(case2)

1. Literature:

The literature proposed method in [16] succeeded to solve the overvoltage problem as shown in fig.8. The literature method in [16] is based on absorbing reactive power by DGs from the grid. The total amount of reactive power to be absorbed by DGs is 1.8684 MVar. This reactive power represents a strain on the transmission network as the absorbed power by DGs is supplied from the transmission network affecting the voltage profile at the transmission buses.

2. Tap changer only:

In this case, the on load tap changer is the only control action. The substation secondary voltage is set at its lower limit 0.97 pu to overcome the over voltage problem. the tap changer control action alone is insufficient control action to return all buses voltages within limits. As buses from 10 to 18 have very high voltages than the upper voltage limit (1.03 pu). An additional control action is required to return all buses voltages within limits besides the tap changer control action.

3. Reactive power control only:

The control action that considered here is the reactive power generated or absorbed. As the problem here is over voltage, so amount of reactive power should be absorbed by DGs to return the voltage within accepted range. The voltage profile of system buses before and after applying the reactive power control action is shown in fig.9. It is clear that after applying the control action all buses voltages become equal or lower that the upper voltage limit. The total amount of absorbed reactive power is 1.6430 MVar, which is lower than the literature amount of absorbed reactive power by more than 200 kVar. So the accuracy of the proposed method here is better than the literature proposed method.

4. Proposed control approach:

When the proposed method applied to the studied system to overcome the presented over voltage problem , the tap changer secondary voltage is set at 0.97 p.u and 0.6927 MVAR are absorbed by DGs to return all buses to be within

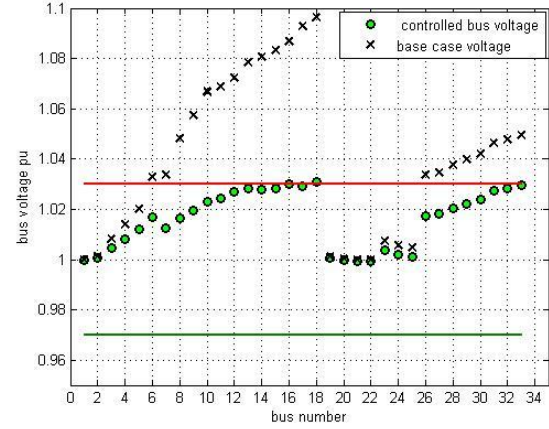


Fig.9 Voltage profile before and after reactive power control (case2)

accepted voltage limits as shown in fig.10. The amount of controlled reactive power here is very small compared with the last two methods. A comparison between different applied control methods is given in table 6. All methods succeed to return all voltages within limits except "the tap changer only". Also all methods give better voltage deviation than the case without control but the losses ratio for all control methods is higher than the case without control. This is because the aim of all control methods in this case is to decrease voltage which means increase in the flowing current in lines resulting higher losses.

The proposed method is the best control method as it requires the least amount of controlled reactive power lower than the nearest method by nearly 1 MVar. This method gives an acceptable losses and deviation values very close to lowest values at the literature and reactive power only methods. At the end of this study case, we can conclude that the tap changer is not sufficient control action. The reactive power control action is sufficient when the installed capacity of each DG is lower than 1.35MW. The tap changer & reactive power control action could be only applied when the installed capacity of each DG is lower than 1.75MW. The full proposed control action is sufficient for any installed capacity of DGs.

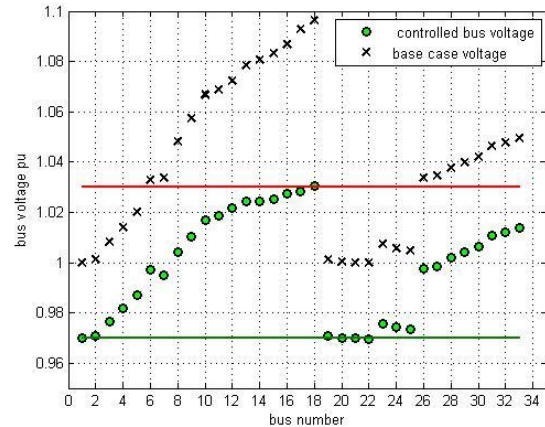


Figure 10 Voltage profile before and after proposed control approach (case2)

Table 6
Comparison between control methods (case2)

method	Controlled reactive power (MVar)	Voltage limit satisfied	Active losses (MW)	Reactive losses (MVar)	Losses ratio %	Mean voltage deviation %
Without control	-----	No	0.2069	0.1523	7%	4.04%
Literature [16]	-1.8684	yes	0.3586	0.2642	9.89%	1.56%
Tap changer only	-----	No	0.2183	0.1607	7.38%	2.8%
Reactive power only	-1.6430	yes	0.345	0.2555	9.83%	1.67%
Proposed method	-0.6927	yes	0.2654	0.1974	8.51%	1.79%

B. IEEE 33 bus (sever case):

For this sever case, both the DG generation and loads are assumed to be doubled. Four doubly fed induction generators are connected to buses [6, 12, 18, 33] as shown in fig.2, each of these DGs has a rated output of 2 MW. The rated buses loads are 200% of the rated loads. As in the last case, the most two critical points are studied here, the point of (minimum DG generation& maximum load) and the point of (maximum DG generation& minimum load). All limits that previously mentioned are applied here. For these sever case an additional constraint is considered; the maximum reactive power drawn from the transmission system shouldn't exceed certain value defined by transmission network operators (TNOs). For the IEEE 33 bus system, this value is assumed to be 5MVar and the power flow limit is not considered.

Case 1: (minimum DG generation& maximum load)

The generated power by each DG is at its minimum value (0.3 MW) while system loads are at their maximum values 200% of the loads. The maximum amount of reactive power to be generated or absorbed by each DG is 1.9 MVar. The voltage profile of the IEEE system buses in this case is shown in fig.11. It is noted that most of the buses have very low voltages below the lower voltage limit. The lowest voltage value occurs at bus 17 with a value of 0.84 p.u nearly.

The results obtained from different presented control method to solve the problem of under voltage are given in table 7. With the very decrease in system voltage shown in fig.11, the tap changer and reactive power control methods failed to solve the problem. The only control method that succeeded to satisfy voltage limit is the proposed control method. The results obtained from the proposed control method will be presented here in details.

The first control step is adjusting the tap changer setting to raise the substation secondary voltage to its highest accepted value (1.03 p.u). The second control action is supplying reactive power to the study system from DGs. The total generated reactive power by DGs is 5.0442 MVar. The

proposed control method introduces very low losses ratio and mean average voltage deviation compared to the case before applying any control action. In this sever case the power flow limit is not considered and the only method that succeeds to solve the problem is the proposed method. When the power flow limit is considered the problem will be doubled, that will be mentioned later in the next section.

Case2: (maximum DG generation& minimum load)

At the point of maximum DG generation& minimum load, the generated power by each DG is 90% of the rated DG output

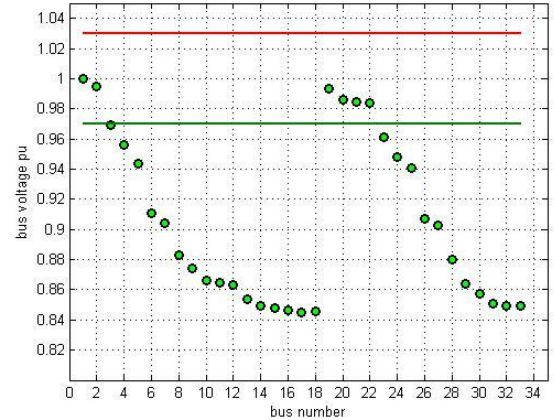


Fig.11 Voltage profile of sever case (minimum generation and maximum load)

(1.8 MW for each DG). System loads are 25% of the rated load. The maximum amount of reactive power to be generated or absorbed by each DG is 1.32 MVar. The voltage profile of all system buses is shown in fig.12. It is observed that most of buses exceed the upper voltage limit by high values. The highest voltage value occurs at the furthest bus 18 with a value of 1.2 p.u. Different control methods are applied to return all buses voltages within limits and the obtained results are inserted in table 5.8.

Table 7*Different control methods(sever case)*

<i>Case1</i>	<i>Controlled reactive power (MVar)</i>	<i>Voltage limit satisfied</i>	<i>Active losses (MW)</i>	<i>Reactive losses (MVar)</i>	<i>Losses ratio %</i>	<i>Mean voltage deviation %</i>
<i>Without control</i>	-----	<i>No</i>	<i>0.6805</i>	<i>0.4578</i>	<i>8.58%</i>	<i>9.76%</i>
<i>Tap changer only</i>	-----	<i>No</i>	<i>0.6296</i>	<i>0.4234</i>	<i>7.99%</i>	<i>6.97%</i>
<i>Reactive power only</i>	<i>6.5269</i>	<i>No</i>	<i>0.7216</i>	<i>0.5331</i>	<i>8.59%</i>	<i>2.61%</i>
<i>Proposed method</i>	<i>5.0442</i>	<i>yes</i>	<i>0.3958</i>	<i>0.2796</i>	<i>5.2%</i>	<i>1.88%</i>

Taking a look on the results in table 8, both the tap changer and reactive power control variables fail individually to the great over voltage problem here due to excess DG generation. When the tap changer and reactive power control variable are combined together, they succeed to return all buses within

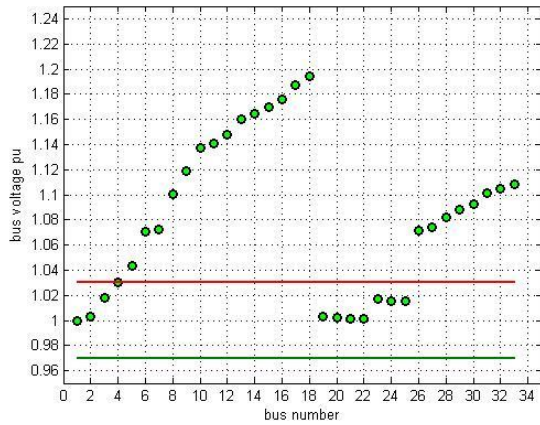


Fig.12 Voltage profile of sever case (maximum generation and minimum load)

limits but with a large absorbed mount of reactive power from the transmission system which will affect voltage levels of the transmission system. TNOs should define the maximum amount of reactive power to be drawn from their transmission network. The maximum amount of reactive power drawn from transmission network here is assumed to be 5 MVar. The proposed full control method considers this constraint in its calculations and also succeeds to return all buses voltages within accepted limits. The results obtained from the successful methods in table 8 are presented here in details.

Although the tap changer& reactive power control method succeed to satisfy system voltage limits, the amount of reactive power drawn from the substation is nearly 6.09 MVar which considered a high amount that may affect the transmission system voltages. The maximum amount of reactive power to be drawn from the transmission system should be equal or lower that 5MVar, so an additional control action is required to be considered besides the tap changer& reactive power control actions. So the full control method is the best method to return all system voltages within limits considering both transmission and distribution constraints.

Table 8*Different control methods (sever case at the maximum DG generation& minimum load)*

<i>Case1</i>	<i>Controlled reactive power (MVar)</i>	<i>Controlled Active power (MW)</i>	<i>Voltage limit satisfied</i>	<i>Active losses (MW)</i>	<i>Reactive losses (MVar)</i>	<i>Losses ratio %</i>	<i>Mean voltage deviation %</i>
<i>Without control</i>	-----	-----	<i>No</i>	<i>0.8342</i>	<i>0.6093</i>	<i>14.16%</i>	<i>8.48%</i>
<i>Tap changer only</i>	-----	-----	<i>No</i>	<i>0.8749</i>	<i>0.639</i>	<i>14.84%</i>	<i>6.85%</i>
<i>Reactive power only</i>	<i>-5.0413</i>	----	<i>No</i>	<i>1.6899</i>	<i>1.232</i>	<i>21.05%</i>	<i>1.91%</i>
<i>Tap changer & reactive power</i>	<i>-4.362</i>	-----	<i>yes</i>	<i>1.5767</i>	<i>1.1509</i>	<i>20.7%</i>	<i>1.79%</i>
<i>Full control</i>	<i>-3.6505</i>	<i>-1.0454</i>	<i>yes</i>	<i>1.0671</i>	<i>0.7754</i>	<i>16.63%</i>	<i>1.77%</i>

C. sever case considering power flow limit:

The problem here is more complicated than the last two cases as the power flow limit is an additional constraint that must be satisfied. For this case the third control action may be used: active energy curtailment in the case of overvoltage or load shedding in the case of under voltage. The maximum accepted power flow limit here is taken as 5 MVA for all system lines. The most critical points are studied here: (the point of maximum DG generation& minimum load) and the point of minimum DG generation& maximum load).

Case 1: (minimum DG generation& maximum load)

At the point of minimum generation and maximum load, all buses loads are 200% of the rated loads. The active power generated by each DG is 0.3 MW. Both the voltage power flow limits are considered here. The power flow before applying any control action is shown in fig.13 in the trace marked with "x". It is observed that branches 1& 2 which are the line from bus 1 to bus 2 and the line from bus 2 to bus 3 exceed the rated power flow limits, as most of the loads in this case are supplied from the substation through these two branches. When the proposed control method is applied to this sever case, the power flow for all system lines become equal or lower than the rated power flow limit as shown in fig.13. The voltage profile after applying the proposed control action is shown in fig.14.

Fig.14 shows that the proposed control method also succeed to return all system voltage within accepted voltage limits besides controlling the power flow though system lines. The control actions applied in this case are described in the following lines. The first control action is adjusting the tap changer secondary voltage to be 1.03 p.u. Then DGs should generate reactive power to return all buses within accepted limits. These control actions still insufficient to solve the power flow problem in branches 1&2. The last control action is the active power management. In this case some of loads should be shed to decrease the power flow from the substation at this critical point (minimum DG generation& maximum load). Several studies are made on the priority of load shed. Here for simplicity and as this research is not focused on the load shedding, a simple technique for load shedding is

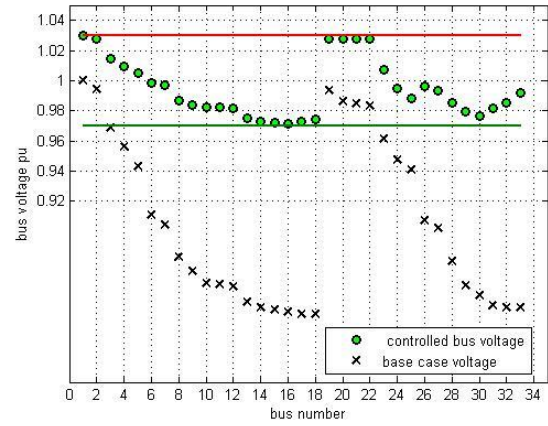


Fig.14 Voltage profile before and after the proposed control method

presented. The load adjacent bus to the line which complains from over flow problem is firstly shedded and if still insufficient the second neighbor bus load will be shedded and so on. In this sever case, the total shedded loads are 1.6414 MW& 0.8171 MVar

Case2: (maximum DG generation& minimum load)

This case is similar to case presented in the sever case; the only difference is that the power flow limits are considered here. System loads are 25% of the loads while the active generated power by each DG is 1.8 MW and the maximum reactive power generated or absorbed by each DG is 1.32 MVar. The power flow for all system buses before and after applying the proposed control action is shown in fig.15. It is noticeable that branches from 1 to 5 exceed from over flow problem. The power flow problem is at its highest value at branch 5 connecting from bus 5 to bus 6 (DG is connected to it). The problem in this case is that the power flow direction is reversed due to the excessive generation from DG and low system loads. So a large amount of the active generated power is supplied to the transmission system resulting over voltage and over flow problems. Returning to fig.15, it is clear that the over flow problem is solved after applying our proposed control method. The voltage profile before and after applying the proposed control actions is shown in fig.16. The proposed

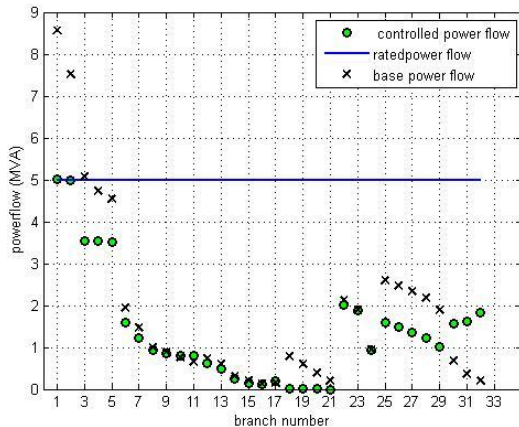


Fig.13 power flow before and after the control action

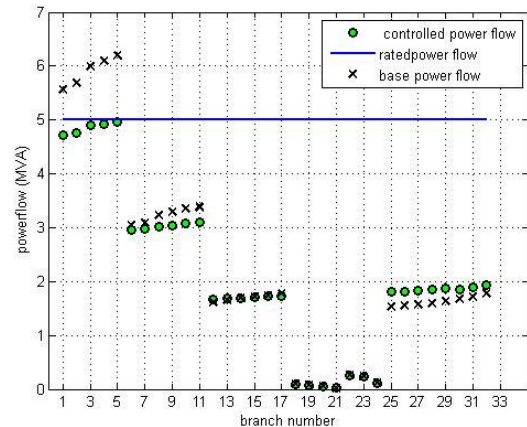


Fig.15 power flow before and after the control action

control method succeeds to solve this worst over voltage problem returning all system voltages within limits. Firstly the tap changer secondary voltage is set at its lowest value 0.97 p.u. Then the reactive power is absorbed by DGs and at least the active power curtailment is applied as a last solution to solve both the over voltage and over flow problems. The total amount of reactive absorbed power by DGs is 2.1908 MVAR while the amount of curtailed active power is 2.2 MW.

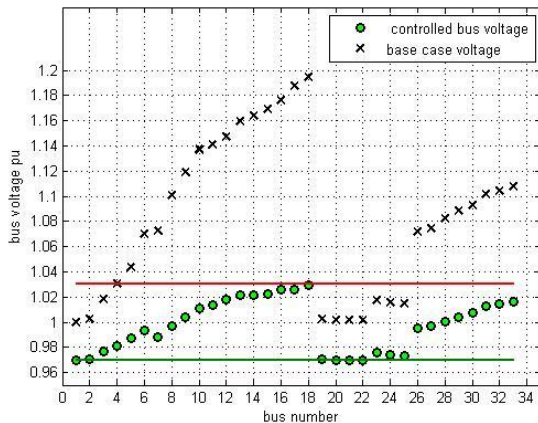


Fig.16 Voltage profile before and after the proposed control method

V. CONCLUSION:

The objective of this paper is to introduce a multistage approach for voltage and power flow control of distribution systems in the presence of DGs. Three control actions are considered here: OLTC then reactive power control and at last the active power curtailment. The proposed method is tested on the IEEE 33 bus system and the results are compared with more than one literature. The proposed method is tested also on IEEE 33 bus sever case and succeeds to return all buses voltages and system lines within rated limits.

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