

# Reactive power and voltage control strategy based on dynamic and adaptive segment for DG inverter

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**Abstract.** The inverter of distributed generation (DG) can support reactive power to help solve the problem of out-of-limit voltage in active distribution network (ADN). Therefore, a reactive voltage control strategy based on dynamic and adaptive segment for DG inverter is put forward to actively control voltage in this paper. The proposed strategy adjusts the segmented voltage threshold of  $Q(U)$  droop curve dynamically and adaptively according to the voltage of grid-connected point and the power direction of adjacent downstream line. And then the reactive power reference of DG inverter can be got through modified  $Q(U)$  control strategy. The reactive power of inverter is controlled to trace the reference value. The proposed control strategy can not only control the local voltage of grid-connected point but also help to maintain voltage within qualified range considering the terminal voltage of distribution feeder and the reactive support for adjacent downstream DG. The scheme using the proposed strategy is compared with the scheme without the reactive support of DG inverter and the scheme using the  $Q(U)$  control strategy with constant segmented voltage threshold. The simulation results suggest that the proposed method has a significant improvement on solving the problem of out-of-limit voltage, restraining voltage variation and improving voltage quality.

## 1. Introduction

With the cost of distributed generation (DG) reducing gradually, the governments of many countries have advocated to strengthen the construction of DG, for DG plays an important role in environmental protection. The access of DG makes single-power and radiant traditional distribution network turn to multi-power and scattered, which may lead to the problem of out-of-limit voltage at DG grid-connected point[1]. And the voltage limit seriously impacts the allowable capacity and permeability of DG.

The coordinated reactive power and voltage control method is the main means to solve the problem of out-of-limit voltage active distribution network (ADN), which can be divided into two categories: centralized cooperative control and decentralized autonomous control. A centralized reactive power control is proposed collaborating capacitors and OLTC with DG, DSTACOM in [2], where capacitors are used to meet the basic reactive demand, DSTATCOM to ensure the voltage of key load within qualified range and OLTC to cooperate with other means to maintain the overall voltage level of the entire feeder. In [3], the sensitivity of node voltage to DG output to is deduced through Newton-Raphson equation and the ADN is centrally controlled considering the regulation ability of DG and demand side management. However, it is difficult to support efficient centralized reactive power control for the limitations of structure and communication capabilities of in the existing data acquisition and monitoring system[4]. And the decentralized reactive power control is proposed as transition. A



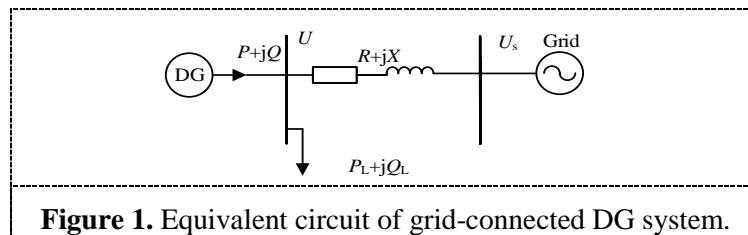
decentralized autonomous method based on the control of DG inverter output current is proposed to adjust the DG inverter reactive power in paper [5]. The method improves voltage profile, reduces the network loss and increases the capacity of system. Aiming at qualified voltage, less active loss and reactive power exchange between DG and distribution system, a distributed optimal control strategy is proposed to achieve decentralized reactive/active control in [6], where the range of voltage at grid-connected point is divided into the allowable interval, the control interval and the operation interval and reactive power is controlled according to voltage.

The decentralized autonomous control is unsuitable for the independent reactive power control of DG[7], for the current researches focus on the joint control of DG system and reactive power compensation devices. For the reactive power control of DG inverter, the German Electrical Engineering Association has proposed several control strategies including constant  $Q$ , constant  $\cos\phi$ ,  $\cos\phi(P)$  and  $Q(U)$ . In the  $\cos\phi(P)$  strategy, DG inverter adjusts power factor once active power exceeds the predetermined limit[8]. In the  $Q(U)$  strategy, DG inverter adjusts reactive power according to the voltage of grid-connected point[9]. Several modified  $Q(U)$  strategies have been proposed in [10-13]. A autonomous  $Q(P)$  control strategy tracking the active output of PV for low-voltage distribution network is proposed in paper [10], where the  $Q(P)$  droop curve was modified with three inclined segments. In [11], the voltage-rise mitigation strategy by reactive power injection and absorption is comprised with active power curtailment strategy. With constant segmented voltage threshold, those strategies can't realize reactive power support between DG inverters and fully restrain out-of-limit voltage in the other zones of ADN, for the strategies only autonomously control DG inverter to curb the local voltage.

Based on the deep analysis of the mechanism of out-of-limit voltage and reactive power and voltage control, a reactive power and voltage control strategy based on dynamic and adaptive segment is proposed to provide the optimal reference value of reactive power for each inverter. With this method, each inverter adaptively participates in the reactive voltage regulation of ADN, which can solve the problem of out-of-limit voltage.

## 2. Mechanism analysis

The equivalent circuit model of distribution network with grid-connected DG is shown in Fig. 1.  $P$  and  $Q$  represent the active and reactive power of DG respectively;  $P_L$  and  $Q_L$  represent the active and reactive power of load respectively;  $R$  and  $X$  represent the resistance and reactance of line respectively;  $U$  and  $U_s$  represent the voltage of DG grid-connected point and grid respectively.



**Figure 1.** Equivalent circuit of grid-connected DG system.

Choosing the grid voltage  $U_s$  as reference vector, (1) is available:

$$U = U_s + \frac{[(P - P_L)R + (Q - Q_L)X]}{U} + j \frac{[(P - P_L)X - (Q - Q_L)R]}{U} \quad (1)$$

Assuming the grid voltage as a constant, the direction of power flow is from the grid side to the end of feeder and the voltage gradually decreases along the feeder without grid-connected DG. While the power flow from the DG grid-connected point to the grid and the voltage of grid-connected point may exceed the voltage ceiling with grid-connected DG, if  $P$  outstrips  $P_L$  or  $Q$  outstrips  $Q_L$ . Neglecting the transverse component of voltage variation, the voltage difference between the DG grid-connected point and the grid can be expressed as (2).

$$\Delta U = \frac{(P - P_L)R + (Q - Q_L)X}{U} \quad (2)$$

DG inverter has been operating in unit power factor until the voltage DG grid-connected point reaches the upper and lower bounds of the allowable voltage range in the distribution network. And then the DG inverter starts to output reactive power to prevent the out-of-limit voltage. Assuming that the voltage of grid-connected point reaches the voltage ceiling when the active output of DG is  $P_1$ , the voltage difference can be expressed as (3).

$$\Delta U_1 = \frac{(P_1 - P_{L1})R - Q_{L1}X}{U_{\max}} \quad (3)$$

When the active power of DG turned to  $P_2$ , the DG inverter should output reactive power of  $Q_2$ , in order to maintain the voltage of grid-connected point within allowable range (that is  $\Delta U_1 = \Delta U_2$ ). At this moment, (4) is satisfied.

$$\frac{(P_1 - P_{L1})R - Q_{L1}X}{U_{\max}} = \frac{(P_2 - P_{L2})R + (Q_2 - Q_{L2})X}{U_{\max}} \quad (4)$$

By (4), the reactive power of DG inverter  $Q_2$  can be expressed as (5).

$$\Delta P = (P_2 - P_1) - (P_{L2} - P_{L1}); Q_2 = -\Delta P \frac{R}{X} + (Q_{L2} - Q_{L1}) \quad (5)$$

By (5), it is shown that DG inverter should output reactive power to maintain the voltage of grid-connected point with the variation of load and the active power of DG. And the demanded reactive power of DG is related to the variation of load and the active power of DG and the impedance ratio of distribution line.

### 3. The reactive power and voltage control

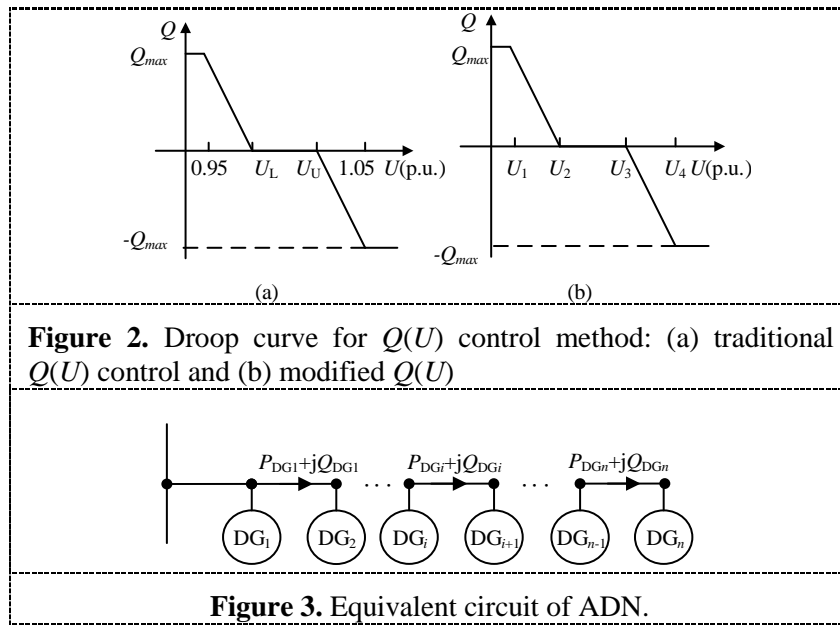
#### 3.1. The $Q(U)$ control

The  $Q(U)$  control strategy determines the reactive power of DG inverter according to the voltage at the grid-connected point, as shown in Fig. 2(a). The DG inverter absorbs reactive power when the voltage of grid-connected point is lower than  $U_L$ . While the DG inverter injects reactive power when the voltage of grid-connected point is higher than the  $U_U$ .  $U_L$  and  $U_U$  represent the lower and upper segmented voltage threshold, respectively. As well as, the reactive power of DG inverter is limited by the maximum reactive capacity of DG inverter.

#### 3.2. The proposed modified control strategy

The  $Q(U)$  control strategy only works on eliminating the out-of-limit voltage at grid-connected point, with constant segmented voltage threshold. Aiming to restrain out-of-limit voltage in the whole ADN, a modified control strategy is proposed as shown in Fig. 2(b). The reactive power and voltage control strategy based on dynamic and adaptive segment for ADN can adjust the voltage thresholds dynamically and adaptively according to the voltage at grid-connected point and the power direction of adjacent downstream distribution line with the variation of load and the active power of DG. The proposed control strategy can not only set the control parameter with independence of the DG location, but also effectively restrain the problem of out-of-limit voltage in ADN.

As shown in Fig. 3, the ADN is be equivalent to a radiant distribution network with  $n$  nodes.  $DG_i$  represents the DG connected at the  $i^{\text{th}}$  node;  $P_{DG_i}$  and  $Q_{DG_i}$  represent the active and reactive power delivered for  $i^{\text{th}}$  node to  $(i+1)^{\text{th}}$  node (if  $P_{DG_i} < 0$ , the direction of power flow is the opposite).



**Figure 2.** Droop curve for  $Q(U)$  control method: (a) traditional  $Q(U)$  control and (b) modified  $Q(U)$

**Figure 3.** Equivalent circuit of ADN.

The steps of the proposed reactive power and voltage control scheme are as follows:

- collect the structure information of the distribution network and measure the voltage at the grid-connected point of  $DG_i$  and the current of the adjacent downstream line;
- judge the power direction of the adjacent downstream line;
- calculate the segmented voltage thresholds by (7) to (8) according to the power direction of adjacent downstream line and the voltage at grid-connected point;
- adjust the value of four voltage thresholds and calculate the reference reactive power of  $DG_i$ ;
- adjust the reference reactive power of the inverter controller.

The principles for segmented voltage threshold selection are as follows:

- when  $i < n$ : if  $P_{DG_i} > 0$ , the segmented voltage threshold of  $DG_i$  is selected according to (6); if  $P_{DG_i} < 0$ , the segmented voltage threshold of  $DG_i$  is selected according to (7)
- when  $i = n$ , the segmented voltage threshold of  $DG_i$  is the same as the  $Q(U)$  control strategy with constant segmented voltage threshold.

$$\begin{cases} U_{i1} = \min[0.93 + \frac{P_{DG_i} R_{DG_{iend}} + Q_{DG_i} X_{DG_{iend}}}{U_{DG_i}}, 1.07]; U_{i2} = \frac{(1.07 - U_{i1}) * 3}{10} + U_{i1} \\ U_{i3} = \frac{(1.07 - U_{i1}) * 7}{10} + U_{i1}; U_{i4} = 1.07 \end{cases} \quad (6)$$

Where  $U_{i1}$ ,  $U_{i2}$ ,  $U_{i3}$  and  $U_{i4}$  represent the segmented voltage thresholds;  $R_{DG_{iend}}$  and  $X_{DG_{iend}}$  represent the resistance and reactance between the grid-connected point of  $DG_i$  and the terminal node of feeder, respectively;  $U_{DG_i}$  represents the voltage amplitude at the grid-connected point of  $DG_i$ .

In (6), when  $P_{DG_i} > 0$ , the terminal voltage of the distribution feeder may be the lowest, and  $U_{i1}$  is selected to guarantee that the terminal voltage of distribution feeder is higher than the voltage floor. The value of  $U_{i1}$  is equal to the possible maximum voltage difference plus 0.93 p.u., preventing the low-voltage problem at the terminal of distribution feeder. The value of  $U_{i4}$  is selected as 1.07 p.u., with the aim of preventing the over-voltage problem at the grid-connected point.

$$\begin{cases} U_{i4} = \max[1.07 - \frac{P_{DG_i} R_{ij} + Q_{DG_i} X_{ij}}{U_{DG_i}}, 0.93]; U_{i3} = U_{i4} - \frac{(U_{i4} - 0.93) * 3}{10} \\ U_{i2} = U_{i4} - \frac{(U_{i4} - 0.93) * 7}{10}; U_{i1} = 0.93 \end{cases} \quad (7)$$

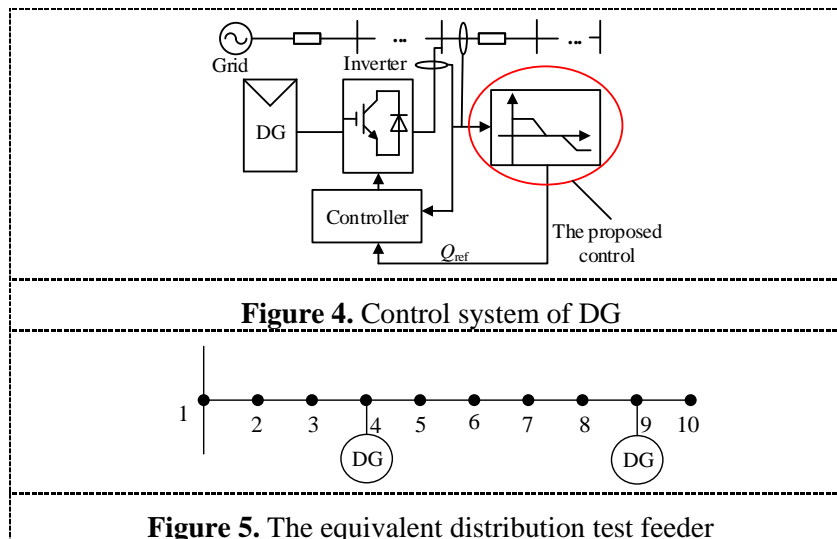
Where  $R_{ij}$  and  $X_{ij}$  represent the resistance and reactance between the grid-connected point of  $DG_i$  and  $DG_j$ , respectively.

In (7), the value of  $U_{i4}$  is equal to 1.07 p.u. minus the voltage difference between  $i^{\text{th}}$  node and  $j^{\text{th}}$  node. When the  $j^{\text{th}}$  node was exposed to the risk of overvoltage and the inverter of  $DG_j$  has no enough capacity to solve the over-voltage problem, the inverter of  $DG_j$  can act to help solve the overvoltage at the grid-connected point of  $DG_j$ .  $U_{i1}$  is chosen as 0.93 p.u., aiming to prevent the DG low-voltage problem at grid-connected point.

The control system of each DGs the proposed active power and voltage control strategy is shown in Fig. 4, where the proposed active power and voltage control strategy provides the reference reactive power of DG to the control of inverter.

#### 4. Simulation results

An actual 10 kV distribution network is developed to investigate the performance of the proposed reactive power and voltage control strategy for DG inverter in ADN. In order to highlight the voltage variation at the key nodes, the distribution network is equivalent to a single, radiant and 10-node distribution test feeder, as shown in Fig. 5. There are two DGs located at nodes 4 and 9 respectively. The installed capacity of PV connected at nodes 4 and 9 are 2.1 MW and 5.1 MW respectively. And the capacity of PV inverter are the same to the installed capacity. There are 3 test schemes are set to verify the validity of the proposed reactive power and voltage control strategy, as shown in Table 1.



**Table 1** Three Test Schemes

Scheme	Control Strategy
Scheme I	Without reactive power support of DG inverter
Scheme II	$Q(U)$ control with constant voltage thresholds
Scheme II	The proposed control strategy

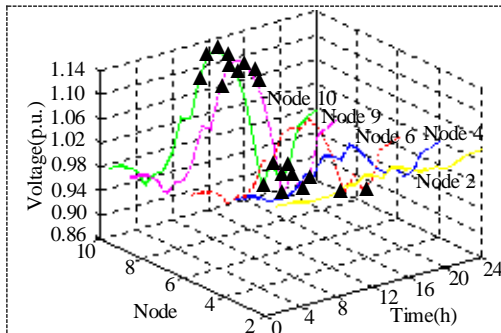
##### 4.1. The result of scheme I

The voltage variation curves of the key nodes in scheme I are shown in Fig. 6. It's known that the voltage of some nodes sometimes varies below the lower voltage bound without any voltage control method.

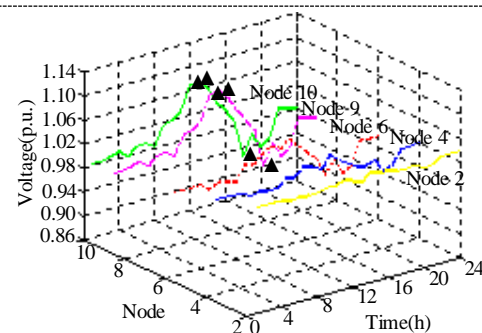
##### 4.2. The result of scheme II

The voltage variation curves of the key nodes in scheme II are shown in Fig. 7. Compared with scheme I, the voltage at the key nodes varies slowly and the problem of out-of-limit voltage is restrained.

However, the problem of out-of-limit voltage still exists at nodes 9 and 10. The voltage is over the upper voltage bound at 12 and 13 o'clock, while the voltage is below the lower voltage bound at 18 o'clock. This is mainly due to that the  $Q(U)$  control strategy with constant voltage threshold only targets at controlling the local voltage of grid-connected point. The reactive power of PV inverter at node 9 reach the lower or upper bound and still can't solve the problem of out-of-limit local voltage. While the reactive power of PV inverter may be lower than the maximum reactive capacity at node 4. The  $Q(U)$  control with constant voltage threshold does not fully consider the ability of mutual reactive power support between several PVs.



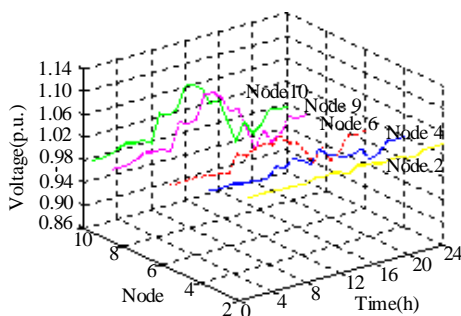
**Figure 6.** Voltage curves in Scheme I.



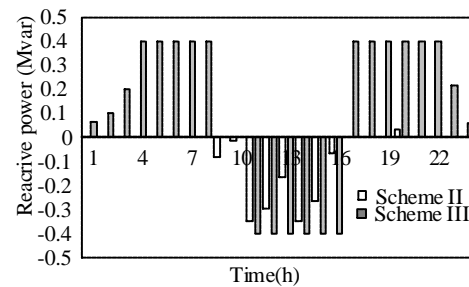
**Figure 7.** Voltage curves in Scheme II.

#### 4.3. The result of scheme III

The voltage variation curves of the key nodes in scheme III are shown in Fig. 8. Among three schemes, the voltage curve in scheme III is significantly flatter without out-of-limit voltage. The Fig. 9 shows the reactive power of PV inverter at node 4 in scheme II and scheme III. The Fig. 10 shows the reactive power of PV inverter at node 9 in scheme II and scheme III. Fig.11 shows the curves of segmented voltage thresholds in scheme III. It's known that the reactive power of PV inverter in scheme III are larger than scheme II. The proposed control strategy considers the problem of undervoltage at the terminal node of the distribution feeder and overvoltage at the adjacent downstream PV grid-connected point, restraining out-of-limit voltage in the whole ADN. Therefore, the PV inverter not only maintains voltage with qualified range by adjusting reactive power but also supplies reactive support for other downstream PV inverters.

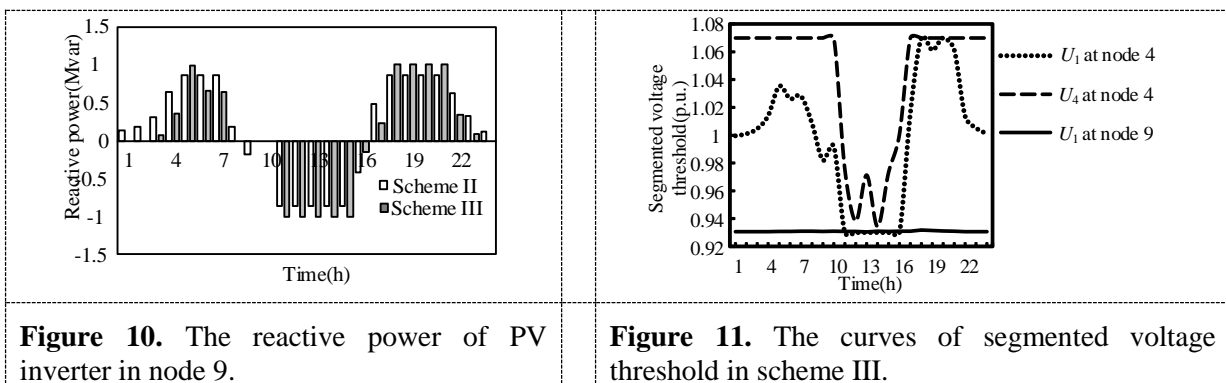


**Figure 8.** Voltage curves in Scheme III.



**Figure 9.** The reactive power of PV inverter in node 4.





## 5. Conclusion

The mechanism of reactive power and voltage control is analyzed and then a reactive power and voltage control strategy based on dynamic and adaptive segment for DG inverter is proposed to solve the out-of-limit voltage in ADN. The main conclusions are as follows:

- The proposed control strategy collects the voltage and current information and adjust the segmented voltage threshold of  $Q(U)$  droop curve dynamically and adaptively considering the voltage of terminal node and the downstream grid-connected point;
- the proposed control strategy adjusts the reactive power according to the modified  $Q(U)$  curve to maintain reasonable voltage;
- the result of simulation suggests that the proposed control strategy can effectively solve the problem of out-of-limit voltage.

## 6. References

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