Research on Voltage Control Method of Distributed Photovoltaic Distribution Network Considering Electric Vehicle Charging

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Abstract. A large number of distributed photovoltaic grid connected to the grid is the main reason for voltage overrun of low-voltage distribution network. Therefore, this paper proposes a voltage control method using electric vehicle (EV) and photovoltaic inverter. Firstly, the distributed control of photovoltaic inverter is adopted. The voltage is regulated by controlling the active power output and reactive power output of the photovoltaic inverter, and the utilization rate of each photovoltaic inverter is the same. If the voltage is not within the safety threshold or the spare capacity of the PV inverter is insufficient, the charging and discharging power control of the electric vehicle will be carried out, and the charging and discharging rate will be controlled according to the consistency target of the electric vehicle power utilization and the SOC local information. The low-voltage distribution system is built in Matlab / Simulink. The simulation results show that the proposed control method is feasible and effective, and the voltage overrun problem in this area is effectively solved.

Keywords: Photovoltaic inverter, Electric vehicle, Voltage overrun, Voltage regulation.

1. Introduction
In recent years, with the rapid economic development, the problems of environmental pollution and energy depletion are becoming more and more serious, and the penetration rate of distributed photovoltaic gradually increases [1-2]. The impact of distributed photovoltaic access on power quality is mainly reflected in voltage overrun, voltage flicker, harmonic and relay protection problems, which will have adverse impact on the operation of distribution network. Voltage stability is the key factor for the safe operation of power grid [3-4]. The environment-friendly characteristics of electric vehicles make electric vehicles have great application prospects in the future. Therefore, the voltage control of electric vehicles connected to distributed photovoltaic distribution network is the focus of this paper.

At present, many domestic and foreign scholars have carried out a lot of research on the power quality problems caused by distributed generation access to distribution network. Relying on energy storage
equipment for short-term high-power input and output can effectively prevent the occurrence of voltage limit problem [6], but energy storage equipment is expensive, which is not conducive to wide use. Reference [7] proposed a continuous reactive power scheduling method using particle swarm optimization (PSO) in the distribution system including photovoltaic system and electric vehicle. In reference [8], a distributed control algorithm is proposed to allocate residual reactive power from EVCS and DG for proper voltage regulation, and an active power reduction strategy is also proposed. When reactive power support is insufficient, DG can correctly integrate on load tap changer into voltage regulation. Reference [9-10] can control the SOC of electric vehicle by DC side descent control, while AC side descent control can help coordinate control of PV and EV. Reference [11-12] proposed the optimal placement of photovoltaic array and electric vehicle in the distribution system at the same time, so as to reduce the actual power loss and improve the voltage curve. Through the meta heuristic optimization algorithm based on artificial bee colony (ABC) population, the optimal allocation of photovoltaic array and electric vehicle in distribution system is determined. Reference [13-14] proposed to establish a voltage regulation model of distribution network in which electric vehicles and photovoltaic power sources are linked. The maximum deviation value of node voltage is used as the penalty function, and the fruit fly optimization algorithm is used for optimization and voltage regulation.

In summary, this paper proposes a voltage control method for electric vehicles connected to a distributed photovoltaic power distribution network. The authors first study the voltage control methods of photovoltaic inverters and electric vehicles, and then propose a voltage control process based on photovoltaic inverters and EV charge and discharge control, and finally build electric vehicles to connect to a distributed photovoltaic power distribution network system in Matlab/Simulink. The simulation results show the effectiveness of the proposed control method, and the voltage limit violation in this area has been reliably resolved.

2. Voltage analysis of distribution network

As shown in Fig. 1, a typical radial distribution feeder consists of multiple buses, each of which contains a household PV, an EV, and a local load. During the peak period of photovoltaic power generation, photovoltaic works in MPPT mode [15-17]. Electric vehicles can store electric energy and then return the stored energy to the grid. In case of voltage overrun, adjust the voltage of the power regulation system of the photovoltaic inverter [18-19]. If the reserve capacity of the photovoltaic system is insufficient, the voltage can be regulated by adjusting the charging or discharging power of the electric vehicle. The imbalance between the power generated by photovoltaic and the load demand makes the power flow along the feeder line, and the direction and size of the power flow make the line voltage rise or fall along the feeder line [20]. Especially at the end of the feeder line, the voltage may exceed the limit during the maximum PV output or line load peak, which is not conducive to the safe operation of the equipment.

![Figure 1. Radial distribution feeder for high-permeability photovoltaic system containing EV](image)

3. Voltage control

3.1. Control method using PV inverter

In low voltage network, resistance accounts for a large proportion of impedance. When the angle difference between the head end and the end of the line is very small, the voltage amplitude difference at the end of the line depends on the active power and reactive power flowing through the line. Because the
load is relatively dispersed and the transmission line of distribution network is long, the line parameters of low-voltage network will greatly affect the voltage quality. When the voltage at the end of the line exceeds the upper limit, the active power and reactive power compensation of the PV inverter are as follows:

\[
\begin{align*}
\Delta P' &= \lambda \Delta P \\
\Delta Q' &= \frac{R}{X}(1 - \lambda)\Delta Q
\end{align*}
\]  

(1)

Where \( \Delta P' \) is the reduction of PV output, \( \Delta P \) is the original reduction of PV output, \( \Delta Q' \) is the reactive power reduction of PV output, \( \Delta Q \) is the reactive power absorbed by PV inverter, \( \lambda \) is the proportional coefficient of PV output reduction and PV output original reduction (the value range is 0 to 1), \( R \) is the line resistance and \( X \) is the line reactance.

In order to obtain the value of \( \lambda \) in equation (1), the power factor of PV inverter is considered, and \( C \) is the tangent value. Therefore, the value of \( \lambda \) is:

\[
\lambda = \frac{cP + \frac{R}{X}P}{c\Delta P + \frac{R}{X}P}
\]  

(2)

The dynamic response of the power reference at the upper limit is as follows:

\[
\begin{align*}
P_{\text{ref}}(i+1) &= P_{\text{ref}}(i) - \Delta P' \\
Q_{\text{ref}}(i+1) &= Q_{\text{ref}}(i) - \Delta Q'
\end{align*}
\]  

(3)

In addition, when the voltage at the end of the line does not exceed the limit, the PV inverter will operate at unity power factor. The voltage / power control strategy flow chart of PV inverter is shown in Fig. 2 when the line voltage close to AC side is \( V_1 \) and the line voltage close to PV side is \( V_2 \).

![Figure 2. Flow chart of voltage / Power control strategy for PV Inverter](image)

### 3.2. Control method using EV

(1) EV charging current control

In this paper, the distribution line voltage is controlled by the electric vehicle connected to the distribution system. The charging capacity of the electric vehicle is adjusted according to the state of charge (SOC) by the following equation:
When the state of charge of node $i$ $\text{SOC}_i<60$,  
\[
I_{\text{EV},i} = \frac{P_{\text{sur},i}}{V_{\text{EV}C}} + \alpha_{C,i} \frac{P_{PV,R}}{V_{\text{EV}C}}
\]  
(4)

When $60 \leq \text{SOC}_i<70$,  
\[
I_{\text{EV},i} = \frac{P_{\text{sur},i}}{V_{\text{EV}C}}
\]  
(5)

When $70 \leq \text{SOC}_i \leq 85$,  
\[
I_{\text{EV},i} = \frac{P_{\text{sur},i}}{V_{\text{EV}C}} \times \frac{85 - \text{SOC}_i}{15}
\]  
(6)

Where $I_{\text{EV},i}$ is the electric vehicle current at node $i$, $P_{\text{sur},i}$ is the residual power of node $i$, $P_{DG,i}$ is the load power of node $i$, $V_{\text{EV}C}$ is the charging voltage of the electric vehicle, $P_{PV,R}$ is the rated capacity of photovoltaic system, $\alpha_{C,i}$ is the charging current coefficient of node $i$.

$\alpha_{C,i}$ is a non negative integer, the default value of $\alpha_{C,i}$ is zero, $\alpha_{C,i}$ is calculated by the following equation:
\[
\alpha_{C,i}(k) = \begin{cases} 
\alpha_{C,i}(k-1) + 0.05 \\
\alpha_{C,i}(k-1) - 0.05 
\end{cases}
\]  
(7)

When the terminal node voltage $V_{\text{end}} \geq V_{UL}$, $P_{\text{sur},i} > 0$, $\alpha_{C,i}$ increase to increase the charging power of electric vehicles. When $P_{\text{sur},i} < 0$, $\alpha_{C,i}$ decrease to reduce the charging power of electric vehicles. When $V_{\text{end}} < V_{UL}$, $\alpha_{C,i} = 0$.

The electric vehicle uses residual power to charge and suppress the voltage rise on the end node voltage. To prevent battery degradation in electric vehicles, the upper limit of SOC is set at 80%. When SOC$<60$, the charging current will increase to charge the EV quickly. When 70$\leq$SOC$\leq$80, the charging current gradually decreases according to SOC. As a result, even if SOC$>80$ and EV stops charging, the node voltage will not increase rapidly.

(2) EV discharge current control

In this paper, the electric vehicle discharge is used to suppress the voltage drop and keep the distribution line voltage within the specified range. When the $V_{\text{end}} < V_{UL}$, the electric vehicle will discharge, where $V_{UL}$ is the lower limit of the reference voltage. The current of electric vehicle is controlled by equation (8).
\[
I_{\text{EV},i} = -0.05 \frac{P_{\text{EV},\text{Max}}}{V_{\text{EV}D}} \alpha_{D,i}(k)
\]  
(8)

Where $P_{\text{EV},\text{Max}}$ is the maximum discharge power of the electric vehicle, $V_{\text{EV}C}$ is the discharge voltage of electric vehicle, $\alpha_{D,i}$ is the control coefficient of discharge current of node $i$. When the electric vehicle is discharged, the current of the electric vehicle is negative.

$\alpha_{D,i}$ is a non negative integer, the default value is 0. $\alpha_{D,i}$ are calculated by the following formula:
\[
\alpha_{D,i}(k) = \begin{cases} 
\alpha_{D,i}(k-1) + 1 \\
\alpha_{D,i}(k-1) - 1 
\end{cases}
\]  
(9)

When $V_{\text{end}} < V_{UL}$, $P_{L,i}+P_{\text{EV},D} > P_{\text{EV},\text{Thr}1}$, $\alpha_{D,i}$ increase to increase the discharge power of electric vehicle. $P_{\text{EV}D}$ is the discharge power of the electric vehicle, $P_{\text{EV},\text{Thr}1}$ is the threshold of discharge power. When $V_{\text{end}} > V_{UL}$, $\alpha_{D,i}$ decrease to reduce the discharge power of electric vehicle.

In addition, the discharge power of electric vehicle is adjusted according to SOC. When $SOC > SOC_{\text{Thr}}$, $P_{L,i}+P_{\text{EV},D} > P_{\text{EV},\text{Thr}2}$, $\alpha_{D,i}$ increase. At this point, $P_{\text{EV},\text{Thr}1} > P_{\text{EV},\text{Thr}2}$, and socthr is the threshold of SOC. On the other hand, when $SOC < SOC_{\text{Thr}}$, $P_{L,i}+P_{\text{EV},D} < P_{\text{EV},\text{Thr}2}$, $\alpha_{D,i}$ decreased. When $SOC \leq SOC_{\text{Thr}}$, the
discharge of electric vehicles stops except at night. This ensures that the electric car can charge the remaining charge the next day.

4. Consistency control

It can be seen from the above that the voltage control can be realized by using the power adjustment of photovoltaic inverter and energy management of electric vehicle. In order to comprehensively utilize the two methods, a consistent voltage control method is proposed in this paper. Firstly, the photovoltaic inverter power is used to adjust the control voltage, and the inverter utilization rate is taken as the consistent goal to make the output of each photovoltaic inverter consistent; if the voltage is not within the safe range, then the energy management strategy of electric vehicle is used to adjust the voltage. The goal of consistency is to coordinate the battery energy of distributed electric vehicles for voltage regulation.

4.1. Consistency control of photovoltaic inverter

For all PV inverters in the distribution network, it is very important to control them in a fair way to participate in the voltage regulation process. In order to use limited communication links between inverters to control the fair absorption / emission of reactive power, a distributed control algorithm based on consistency algorithm is proposed. In order to ensure the full utilization of inverters with different capacities, the utilization ratio \( u_{PV,i} \) of the inverter is selected as the consistency target, which is expressed as follows:

\[
\frac{Q_{PV,i}}{Q_{PV,max}} = u_{PV,i} \tag{10}
\]

During the period of peak photovoltaic generation and peak load, the proposed consensus algorithm will satisfy the conditions given in equation (11) for any bus voltage \( V_i \) in distribution feeders:

\[
V_{\text{min}} \leq V_i \leq V_{\text{max}} \tag{11}
\]

The purpose of the consistency algorithm is to modify its own state variables through the information exchange between adjacent nodes, so that the state quantity of all nodes tends to the same stable state. The purpose of the consistency algorithm is to modify its own state variables through the information exchange between adjacent nodes, so that the state quantity of all nodes tends to the same stable state. In the system shown in Fig. 1, the communication topology can be expressed as \( G=(V, E) \), \( V=\{1, 2, \ldots N\} \). If \((j, i) \in E\), then node \( i \) is adjacent to node \( j \) and can receive information from node \( j \). Assuming that the state of the \( i \)-th bus at time \( t \) is expressed as \( x_i(t) \) and the sampling interval is \( T_s \), a discrete consistency algorithm can be expressed as follows:

\[
x_i(t+T_s) = \sum_{j\in E} d_{ij} x_j(t) \tag{12}
\]

\( d_{ij} \) is the coefficient of state transition matrix, and its size is:

\[
d_{ij} = \begin{cases} 
1 / (1 + D) & (j,i) \in E \\
0 & (j,i) \notin E
\end{cases} \tag{13}
\]

Where \( D \) is the number of nodes that can send information to node \( i \).

As shown in Fig. 1, for radial distribution feeders with multiple buses, the last bus is the critical bus with the highest / lowest voltage in the system. Therefore, the last bus is selected as the leading node to start voltage control. By measuring the voltage of the last bus, the utilization ratio \( u_{PV,ref} \) of the leading node is determined. Then, through the communication link, the \( u_{PV,ref} \) is shared with available inverters to achieve the desired voltage regulation objectives, and \( u_{PV} \) is updated according to equation (13).
Where $a_1$ and $a_2$ are control gains, which affect the convergence speed and control accuracy of distributed control.

In this paper, it is assumed that the photovoltaic system can only communicate with adjacent cells. The inverter utilization of the $i$-th photovoltaic system is updated as follows:

$$u_{PV,i}^{ef}(t) = \sum_{j=1}^{N-1} d_{ij}(t) u_j(t - T_j) + d_{i,j}(t) u_{PV}^{ref}(t - T_s)$$ (15)

Then the reactive power to be output by the $i$-th inverter is as follows:

$$Q_{PV,i}(t) = u_{PV,i}(t) Q_{pv,i}^{max}$$ (16)

$$-1 \leq u_{PV,i}(t) \leq 1$$ (17)

The constraint of distributed control of inverters is the reactive power capacity of each inverter:

$$-Q_{pv,i}^{max} \leq Q_{PV,i}(t) \leq Q_{pv,i}^{max}$$ (18)

### 4.2. Consistency and coordination control of EV

When the capacity of PV inverter is insufficient and the voltage is still beyond the limit, the EV control of phase II is entered. The first goal is to coordinate the battery energy of distributed electric vehicles for voltage regulation. Similar to the distributed control of inverter, the last node is selected as the leading node, and the battery utilization ratio $u_{EV,i}$ of the electric vehicle is taken as the consistent target. The utilization rate of the leading node is calculated by equation (23):

$$u_{EV}^{ef}(t) = u_{EV,i}^{ef}(t) = \begin{cases} u_{EV}^{ref}(t-T_s) + b_1(V_n(t)-V_{min}) & V_n(t) > V_{max} \\ u_{EV}^{ref}(t-1) & V_{min} \leq V_n(t) \leq V_{max} \\ u_{EV}^{ref}(t-T_s) + b_2(V_n(t)-V_{max}) & V_n(t) < V_{min} \end{cases}$$ (19)

Where $b_1$ and $b_2$ are control gains.

The battery utilization of the $i$-th EV is updated to:

$$u_{EV,i}(t) = \sum_{j=1}^{N-1} d_{ij}(t) u_j(t - T_j) + d_{i,j}(t) u_{EV}^{ref}(t - T_s)$$ (20)

The above distributed control will regulate the feeder voltage and determine the battery utilization of each EV. However, because EVs have different SoC and are unpredictable, EVs may be fully charged / discharged when required. The second goal is to effectively utilize the available EV battery capacity in the network for voltage regulation. Therefore, for each EV, localized control will be implemented based on the local SoC information to adjust the charging / discharging speed.

The localized SoC control proposed in this paper adjusts the SoC of each EV within the expected range of its predefined reference SoC. The availability $\varepsilon$ is determined by comparing the estimated SoC (t) with the reference $SoC(t)$. $SoC_{ref}(t)$ represents the expected SoC of EV in daily operation, and $\varepsilon$ is defined by equation (21):

$$\varepsilon(t) = \begin{cases} 0 & (SoC(t) - SoC_{ref}(t)) \geq k_2 \\ 1 - b_1 (SoC(t) - SoC_{ref}(t)) & k_1 < (SoC(t) - SoC_{ref}(t)) < k_2 \\ 1 & (SoC(t) - SoC_{ref}(t)) \leq k_1 \end{cases}$$ (21)

Where $k_1$ and $k_2$ are the threshold values for SoC control and are used to define the allowable deviation range between the SoC and the reference SoC, and $b_1 = 1/(k_2-k_1)$. 


Taking charging as an example, the discharge process is similar. When \( \text{SoC}(t) \geq \text{SoC}_\text{ref}(t) + k_2 \), EV does not charge; when \( \text{SoC}(t) \geq \text{SoC}_\text{ref}(t) + k_1 \), EV is fully charged; when \( \text{SoC}(t) \) is within \([\text{SoC}_\text{ref}(t) + k_1, \text{SoC}_\text{ref}(t) + k_2]\), EV charging is slowed down.

Combined with the proposed distributed and local control, the output of EV can be expressed as:

\[
P_{\text{EV},j}(t) = u_{\text{EV},j}(t) \times e_i(t) \times P_{\text{EV},j}^{\text{rated}}
\]

(22)

\[-1 \leq u_{\text{EV},j}(t) \leq 1, \quad 0 \leq e_i(t) \leq 1
\]

(23)

The constraints of EV distributed local coordinated control are power and energy constraints of each EV:

\[-P_{\text{EV},j}^{\text{rated}} \leq P_{\text{EV},j}(t) \leq P_{\text{EV},j}^{\text{rated}}
\]

(24)

\[\text{SoC}_{\text{min}} \leq \text{SoC}(t) \leq \text{SoC}_{\text{max}}
\]

(25)

5. Example analysis

As shown in Fig. 3, the simulation is built in Matlab / Simulink to analyze the voltage control of electric vehicle connected to photovoltaic power generation system. As shown in Fig. 3, the simulation is built in Matlab / Simulink to analyze the voltage control of electric vehicle connected to photovoltaic power generation system. The distribution system is a part of IEEE 33 node power distribution system. The reference voltage is 6.6kV, which is composed of 13 buses. There are 520 households in total. The families on bus 1, 3, 5, 7, 10, 12 and 13 are connected to electric vehicles, and a total of 300 electric vehicles are connected. The simulation parameters are shown in Table 1.

![Figure 3. Topology of electric vehicle connected to photovoltaic distribution network](image)

| Symbol | Value |
|--------|-------|
| Safe voltage range \([V_{\text{min}}, V_{\text{max}}]\) | [0.95 p.u., 1.05 p.u.] |
| SoC allowable variation range of EV | [20 %, 80 %] |
| Sample interval time \(T_i\) (min) | 5 |
| Distance between adjacent buses \(L\) (m) | 500 |
| Line impedance \(/(\Omega/\text{km})\) | 0.647+j0.463 |
| PV rated power \(/(kW)\) | 9 |
| EV battery capacity \(/(kW)\) | 30 |
| EV maximum charging and discharging power \(/(kW)\) | 6 |

Because of the close geographical location, and the focus of this paper is the voltage control analysis of photovoltaic system, so the output curve of photovoltaic system is the same as that of residential load. The simulation time is set as 24h, the photovoltaic power generation capacity of each building within 24h is shown in Fig. 4, and the load of each residential building is shown in Fig. 5.
Assume that the initial SoC of EV on bus 1, 3, 5 and 7 is 20%, that of EV on bus 10 and 12 is 50%, and that of EV on bus 13 is 80%. Since the distance between bus 13 and transformer is the longest, the voltage offset on bus 13 is the largest. Therefore, the node where bus 13 is located is selected as the leading node. The voltage curve of bus 13 without any control is shown in Fig.6.

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**Figure 4.** Photovoltaic power generation per building

**Figure 5.** Residential load of each building

**Figure 6.** Bus 13 voltage curve
As can be seen from Fig. 6, due to the absence of any voltage control, the lower limit of the voltage safety threshold occurs from 6:00 to 7:00 and from 18:00 to 24:00, which reaches to 0.93 p.u., which is less than the specified 0.95 p.u. From 10:00 to 15:00, it is higher than the upper limit of voltage safety threshold, and the maximum value is 1.08 p.u., which is greater than the specified 1.05 p.u. The above conditions seriously affect the power quality of the line, and are not conducive to the safe operation of the electrical equipment.

When only the photovoltaic inverter is used to adjust the voltage, the voltage curve of bus 13 and the output power of the inverter are shown in Fig. 7. It can be seen that when the photovoltaic inverter is used to control, the situation that the voltage exceeds the upper limit can be effectively improved, but the situation that the voltage exceeds the lower limit is not improved. Because the photovoltaic storage capacity is insufficient at night, it is impossible to adjust the voltage, so it is necessary to use EVs to adjust voltage.

In view of the deficiency of control effect in Fig.7, the voltage control method proposed in this paper is adopted. The consistency control parameters of PV inverter $a_1=0.001, a_2=0.001$; EV consistency control parameters $b_1=0.001, b_2=0.001$, EV charging parameters $b_3=20, k_1=0, k_2=0.05$; EV discharge parameters $b_3=-20, k_1=0, k_2=-0.05$. The voltage curve of bus 13 is shown in Fig.8, and the output current of electric vehicle is shown in Fig.9.

![Figure 7. Bus 13 voltage control effect with inverter only](image)

![Figure 8. Voltage control effect using the proposed control strategy](image)
As can be seen from Fig.8 and Fig.9, the voltage of all nodes is kept within the specified voltage range through the proposed control mode. In the early morning, the electric vehicle is discharged to suppress the voltage drop. In the morning, the remaining photovoltaic power is used for charging. During the day, the voltage is regulated by the photovoltaic inverter. At night, the electric vehicle is discharged to make the voltage not lower than the lower limit of the range.

6. Conclusion
In this paper, the problem of voltage overrun is solved by controlling photovoltaic and electric vehicles. Considering the operation cost of the equipment, the distributed control of photovoltaic inverter is firstly adopted. The voltage is regulated by controlling the active power output and reactive power output of the photovoltaic inverter, and the utilization rate of the inverter is taken as the consistent goal to make the utilization rate of each photovoltaic inverter the same. If the voltage is not within the safety threshold or the spare capacity of the PV inverter is insufficient, the charging and discharging power control of the electric vehicle will be carried out, and the charging and discharging rate will be controlled according to the consistency target of the electric vehicle power utilization and the SoC local information. The low-voltage distribution system is built in Matlab/Simulink. The simulation results show that the proposed control method is feasible and effective, and the voltage overrun problem in this area is effectively solved. In the future work, the load type of distribution network system will be increased, and the proposed control strategy can be applied to a variety of application scenarios.

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