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Coordinated voltage regulation strategy of OLTC and BESS considering switching delay①

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Abstract

When large-scale distributed renewable energy power generation systems are connected to the power grid, the risk of grid voltage fluctuations and exceeding the limit increases greatly. Fortunately, the on-load tap changer (OLTC) can adjust the transformer winding tap to maintain the secondary side voltage within the normal range. However, the inevitable delay in switching transformer taps makes it difficult to respond quickly to voltage fluctuations. Moreover, switching the transformer taps frequently will decrease the service life of OLTC. In order to solve this critical issue, a cooperative voltage regulation strategy applied between the battery energy storage systems (BESSs) and OLTSs. is proposed By adjusting the charge and discharge power of BESSs, the OLTC can frequently switch the transformer taps to achieve rapid voltage regulation. The effectiveness of the proposed coordinated regulation strategy is verified in the IEEE 33 node distribution systems. The simulation results show that the proposed coordinated regulation strategy can stabilize the voltage of the distribution network within a normal range and reduce the frequency of tap switching, as such elongating the service life of the equipment.

Key words: distributed power generation, voltage regulation, distribution network, on-load tap charger (OLTC), battery energy storage system (BESS)

0 Introduction

In order to develop the industry in a low-carbon energy style, China proposed carbon peaking and carbon neutrality goals in 2020[1]. As the most important energy source, power systems need to be developed in a low-carbon way to achieve the dual-carbon goal[2].

With the renewable energy popularizing gradually, more and more new loads are connected to the distribution network[3]. However, the fluctuation and randomness of renewable energy will greatly decrease the voltage quality when many renewable energy sources are connected to the grid[4]. Therefore, an effective voltage regulation strategy is needed for distributed power generation systems in the distribution network.

By controlling the motor, the on-load tap changer (OLTC) can regulate the tap position and maintain the voltage stability[4-5]. Due to the intrinsic motor-driven mechanism, the time-delay is inevitable during the regulation process and makes it difficult to respond quickly to voltage regulation. To overcome the defects of the OLTC, some researchers utilize other devices to coordinate with OLTC for voltage regulation. Ref. [6] proposed a coordinated approach to combine capacitors and OLTC to regulate voltage. However, compared with conventional storage facilities, the high cost of capacitors and the low energy storage capacity limit their wide application. Ref. [7] presented a scheme integrating power switches with OLTC, which needs multiple sets of power switches, complex control mechanisms, and limited regulation capability of reactive power. Ref. [8] combined OLTC with electronic solutions to solve the problem. However, the leakage inductance and the parasitic capacitance will cause prolonged oscillations and voltage fluctuation during switching.

Compared with the reactive power regulation provided by the OLTC, active power is more efficient than reactive power in voltage regulation due to the higher R/X value[5,9]. With the development of energy storage technology, the comprehensive power generation cost decreases gradually. The energy storage systems have been involved with adjusting grid frequency, improving power quality, and realizing peak shaving and

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valley filling[10]. Ref. [11] proposed a novel voltage regulation method for battery energy storage systems (BESSs) based on the amplitude-phase-locked-loop, where the voltage differential control is applied to improve the dynamic performance of voltage control and behaviors of grid voltage based on the dV/dt signal from the amplitude-phase-locked-loop. Ref. [12] proposed a new voltage regulation strategy utilizing BESSs which can guarantee that the voltage regulation burden is appropriately shared among all involved BESSs in the network. Ref. [13] proposed a coordinated control strategy to regulate the charge/discharge of BESSs using a combination of the local droop-based control method and a distributed control scheme to guarantee the voltages of the feeder within allowed limits. However, the regulation capacity of the BESS is limited, which cannot provide voltage regulation service for a long time.

Although methods through OLTC and BESS were proposed to complete voltage regulation, the defects have not been considered. OLTC cannot switch the tap position and rapid response to voltage regulation. The regulation capacity of the BESS is limited, which cannot provide voltage regulation service for a long time. In order to complement each other, both OLTC and BESS can participate in the voltage regulation service together. The quick response characteristic of the BESS can make up the response delay problem of the OLTC. The problem of BESS's insufficient regulation capacity can be perfectly solved by OLTC. Therefore, this paper proposes a coordinated voltage regulation strategy by combining OLTC and BESS for the distribution networks. As an auxiliary regulation device, BESS has high priority and provides voltage regulation service preferentially, when the voltage fluctuates gently, or the OLTC tap is switching. The OLTC is used to eliminate serious voltage problems. In this way, the voltage regulation potential can be fully utilized. The proposed coordinated voltage regulation strategy can take the full advantage of OLTC and BESS and maintain the voltage of the distribution network within an allowable range.

1 Principle of voltage control

1.1 OLTC voltage regulation

As a device for voltage regulation in distribution network, OLTC is an important means of regulation distribution network, which can maintain voltage stability by adjusting the primary stage turns ratio. As shown in Fig. 1, the bus detection technology is used to monitor the condition of the voltage. The amplitude of the bus voltage obtained by the bus detection technology will be compared with the reference voltage to determine the OLTC action. When the voltage exceeds the limit determined and the OLTC is within an adjustable range, the transformer tap of the OLTC will be regulated. However, a mechanical device installed on the power transformer has a certain time delay, during this period the transformer tap is switching. Besides, switching the transformer tap will cause the contact damage, which reduces the service life of the equipment.

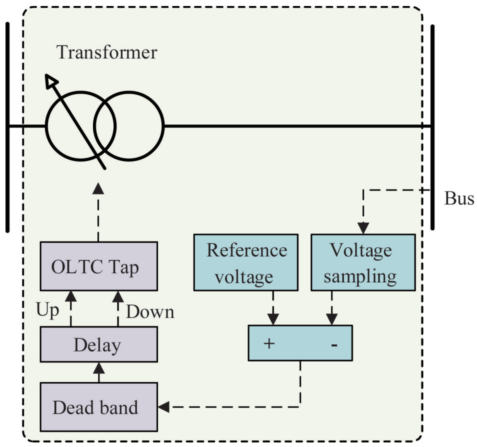

Fig. 1 OLTC busbar detection

1.2 BESS voltage regulation

In a typical distribution network structure, the power flows from the substation to the user. Due to a specific impedance on the transmission line, the voltage drop on the distribution line makes the voltage of the substation higher than the user terminal voltage. Photovoltaics (PV) has changed the power flow direction in the distribution networks whose structure is shown in Fig. 2.

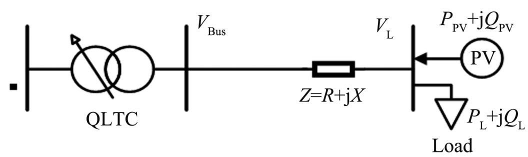

Fig. 2 Distribution network structure of a PV power generation system

As shown in Fig 2, V_{Bus} is the transmission bus, R and X are the resistance and impedance of the transmission line; PV represents photovoltaic; P_{PV} and Q_{PV} are the active power and reactive power of the photovoltaic system; P_{L} and Q_{L} refer to the active power and reactive power of the load respectively. When the PV is connected to the distribution network, the voltage drop can be computed as

$$\Delta V = \frac{R(P_{\text{L}} - P_{\text{PV}}) + X(Q_{\text{L}} - Q_{\text{PV}})}{V_{\text{L}}} \tag{1}$$

According to the IEEE standard, the voltage is considered as exceeding the limit[14] if the duration when the voltage exceeds 1.100 p.u. or less than 0.900 p.u. is more than 1 min. When the PV outputs reverse power flow to the distribution network, the voltage at the user node will increase, which may cause an over-voltage problem. BESS can adjust the voltage bidirectionally by absorbing or releasing energy.

The battery energy storage system consists of a battery management system, a charger, an inverter, and several battery packs. To avoid battery over-charge and over-discharge, state of charge (SOC) of battery is usually kept within a specific range and its requirement is shown in Eq. (2), where $SOC_{\min}$ and $SOC_{\max}$ are the battery discharge and charge threshold respectively.

$$SOC_{\min} \leqslant SOC_i \leqslant SOC_{\max} \tag{2}$$

where SOC_i is dependent on the charge and discharge power (P_c, P_d), initial SOC (SOC_s), battery capacity (B_c), and charging/discharging time (t), and can be estimated as

$$SOC_i = \begin{cases} SOC_s + \dfrac{P_c}{B_c} \cdot t \\ SOC_s - \dfrac{P_d}{B_c} \cdot t \end{cases} \tag{3}$$

The node voltage determines the charging or discharging power (P_B). Assuming that the charging and discharging threshold voltages are $V_{\max}$ and $V_{\min}$, P_B can be calculated as

$$P_B(t) = \begin{cases} k_c^i(t) \cdot (V_i(t) - V_{\max}) & V_i(t) > V_{\max} \\ 0 & V_{\min} \leqslant V_i(t) \leqslant V_{\max} \\ k_d^i(t) \cdot (V_{\min} - V_i(t)) & V_i(t) < V_{\min} \end{cases} \tag{4}$$

where $k_c^i(t)$ and $k_d^i(t)$ are the charge and discharge coefficients of the battery, $V_{\max}$ and $V_{\min}$ are the threshold voltages of the distribution network. According to the output of the PV and load of the users, the charge and discharge coefficients can be obtained:

$$k_c^i(t) = \frac{P_{PV}^i(t) - P_L^i(t)}{V_{\max} - V_{nom}} \tag{5}$$

$$k_d^i(t) = \frac{P_{PV}^i(t) - P_L^i(t)}{V_{nom} - V_{\min}} \tag{6}$$

where $P_L^i(t)$ and $P_{PV}^i(t)$ are the output of the PV and load, V_{nom} is the nominal voltage of the distribution network.

2 Voltage coordinated regulation strategy

The voltage coordinated regulation strategy can be separated into three steps: power flow calculation, node voltage sequencing regulation strategy, and voltage segment regulation strategy, whose overall flowchart is shown in Fig. 3. Firstly, the power flow of distribution network is analyzed in power flow calculation. Then, the regulation power of BESS is calculated by the node voltage sequencing regulation strategy. Finally, the voltage segment regulation strategy determines the device for voltage regulation.

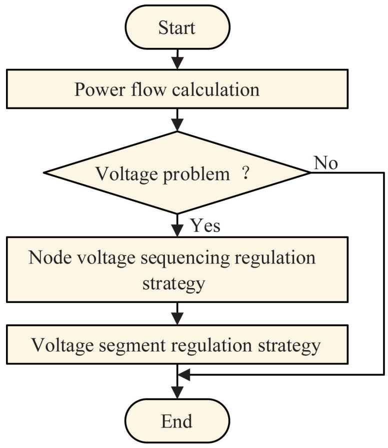

Fig. 3 Voltage coordinated regulation strategy flowchart

2.1 Power flow calculation

The purpose of power flow calculation is to obtain the operation status of the distribution network from network topology, branch parameters, power generation, load, and other conditions. The power system analysis is a foundation to study power system planning and operation problems and several calculation methods have been proposed to solve this problem, including the Newton-Raphson method, P-Q decomposition method, forward iterative method, etc. Compared with other methods, the Newton-Raphson method owns high convergence speed and accuracy, and has been widely used to calculate the power flow of distribution networks [14].

In this work, power flow is calculated to obtain the amplitude and phase of the node voltage. The nodal admittance matrix can be expressed as

$$Y_{ij} = G_{ij} + jB_{ij} \tag{7}$$

where G_{ij} and B_{ij} are the real and imaginary parts of the admittance between node i and node j. According to the node voltage equation, the node active and reactive power equations are

$$\begin{cases} P_i = V_i \sum_{j=1}^{n} V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \\ Q_i = V_i \sum_{j=1}^{n} V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \end{cases} \tag{8}$$

where $\delta_{ij} = \delta_i - \delta_j$, V_i and V_j are the voltage amplitudes of the node i and j, P_i and Q_i are the active and reactive power of node i.

Then, the modified equation for Newton-Raphson power flow calculation can be written as

$$\begin{bmatrix}\frac{\Delta \boldsymbol{P}}{\Delta \boldsymbol{Q}}\end{bmatrix} = \boldsymbol{J}\begin{bmatrix}\frac{\Delta \boldsymbol{\delta}}{\Delta \boldsymbol{V}}\end{bmatrix} \tag{9}$$

$$\boldsymbol{J} = \begin{bmatrix} \frac{\partial \Delta P_i}{\partial \delta_j} & V_j \frac{\partial \Delta P_i}{\partial V_j} \\ \frac{\partial \Delta Q_i}{\partial \delta_j} & V_j \frac{\partial \Delta Q_i}{\partial V_j} \end{bmatrix} \tag{10}$$

where $\boldsymbol{J}$ is the Jacobian matrix; $\Delta \boldsymbol{P} = [\Delta P_1, \Delta P_2 \cdots, \Delta P_m]$, $\Delta \boldsymbol{Q} = [\Delta Q_1, \Delta Q_2 \cdots, \Delta Q_m]$, ΔP_i and ΔQ_i are the active and reactive power, which injects to the node i to regulate the node voltage; δ_i is the phase angle of i.

The matrix $\boldsymbol{S}$ is the inverse of the Jacobian matrix.

$$\boldsymbol{S} = \boldsymbol{J}^{-1} = \begin{bmatrix} \boldsymbol{S}_1 & \boldsymbol{S}_2 \\ \boldsymbol{S}_3 & \boldsymbol{S}_4 \end{bmatrix} \tag{11}$$

where $\boldsymbol{S}_i$ is the inverse element of the $\boldsymbol{J}$ matrix. Using the correction equation, the voltage amplitude correction $\Delta \boldsymbol{V}$ can be computed as

$$\Delta \boldsymbol{V} = \boldsymbol{S}_3 \Delta \boldsymbol{P} + \boldsymbol{S}_4 \Delta \boldsymbol{Q} \tag{12}$$

2.2 Node voltage sequencing regulation strategy by BESS

In the traditional BESS regulation methods, the charging and discharging power of the out-of-limit node is adjusted without considering the mutual influence between the nodes. Therefore, the total voltage regulation power is relatively large. In addition, due to the distribution network structure, the node stability decreases with increasing of its distance from the distribution station, which results in larger voltage fluctuation. In order to solve this issue, this paper proposes a node voltage sequencing adjustment strategy, where the voltage regulation priority of node is determined by sorting the node voltage. The nodes with larger fluctuation have higher priority to be regulated to reduce the regulation times of the BESSs. The detailed BESS node voltage sequencing regulation process is shown in Fig. 4.

When there is an over-voltage problem, the node voltages are sorted to determine the regulation priority, where the node with a larger voltage is preferentially regulated. The active power provided by the BESSs will be calculated. The over-voltage problem is solved by controlling the charging power of batteries. If the over-voltage problem is still not solved after the charging power of the BESSs in this node reaches the maximum, the node with the next larger voltage value will be regulated until the voltage of all the nodes is within [0.900, 1.100] p. u..

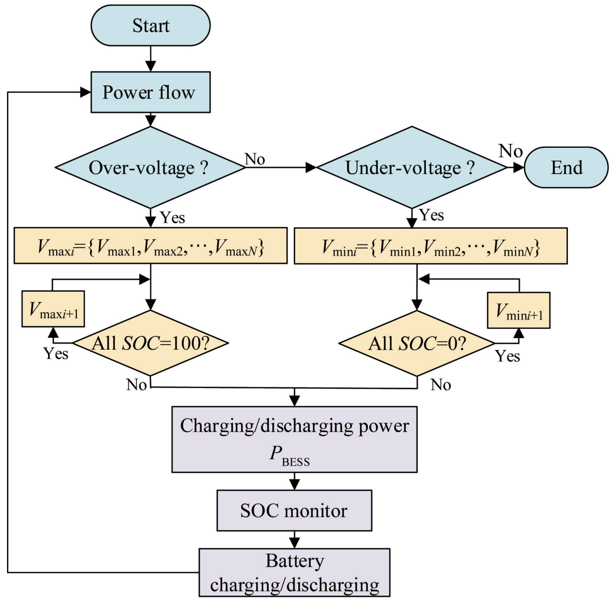

Fig. 4 Node voltage sequencing regulation flowchart

2.3 Voltage segment regulation strategy

To reduce the actions of OLTC taps, an improved voltage segment regulation strategy is proposed, where the adjustment range is separated as shown in Fig. 5. When the outputs of the PVs do not cause serious voltage problems (1.100 p. u. $< V_i <$ 1.105 p. u. or 0.895 p. u. $< V_i <$ 0.900 p. u.), the BESSs are preferentially used to achieve voltage regulation which has advantages in voltage regulation ability, avoiding light abandonment, and improving the utilization efficiency of renewable energy. When the voltage problem is serious ($V_i >$ 1.105 p. u. or $V_i <$ 0.895 p. u.), the voltage is regulated by OLTC and BESS coordinated regulation strategy.

Since there is a delay in OLTC switching, when the tap is switching, the voltage regulation service from BESSs will continue until the action is finished. As such, the voltage can be controlled within the permissible range in the whole regulation process, and the fast response of the voltage regulation can be obtained from Fig. 5, which shows the collaborative adjustment process of OLTC and BESS.

The actions of OLTC depend on the maximum node voltage $V_{\max}$ and minimum node voltage $V_{\min}$. If 1.100 p. u. $< V_{\max} <$ 1.105 p. u. or 0.895 p. u. $< V_{\min} <$ 0.900 p. u., only BESS is involved in the voltage regulation. If $V_{\max} >$ 1.105 p. u. or $V_{\min} <$ 0.895 p. u., the OLTC switches the tap position to regulate the node voltage to [0.900, 1.100] p. u.. When the tap of the OLTC is switching, the BESSs will charge and discharge to balance supply and demand temporarily. Fig. 6 is OLTC co-regulation flowchart.

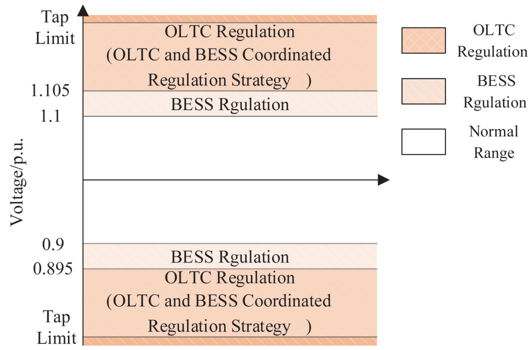

Fig. 5 Voltage segment regulation range

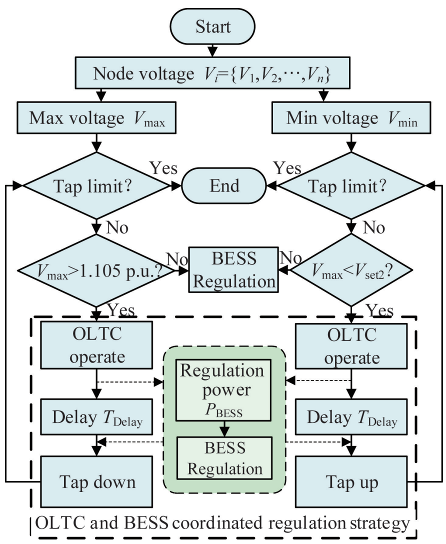

Fig. 6 OLTC co-regulation flowchart

3 Simulation condition and result

3.1 Simulation condition

The IEEE 33 node distribution network model[15] is applied to verify the node voltage regulation strategy whose structure is shown in Fig. 7. The node 1 is a reference node. The voltage value of node 1 is 1 p. u. The rest of the nodes are 'PQ' nodes. The value of node voltage should be controlled within [0.900, 1.100] p. u. to keep the power supply quality of the distribution network.

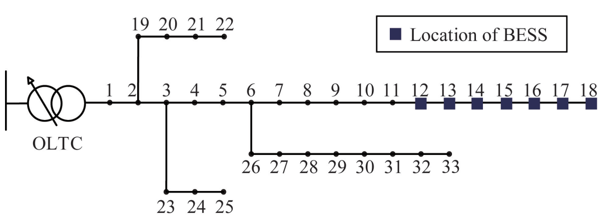

Fig. 7 IEEE 33 distribution network model[15]

There are six taps in the substation installed with an OLTC and each tap is 0.012 5 p. u., the maximum tap position of OLTC is Tap_{max}, minimum tap position of OLTC is Tap_{min}. The tap switching delay time is set to 1 min. The PV generation system is configured on the user node. The BESS is installed from nodes 12 to 18. The scale of the BESS is 58 kWh/135 kWh. Fig. 8 shows the PV generation and user load power data within 24 h. The data is collected from Ref. [16]. The peak generating power is 9.3 mW, and the peak load power is 3.8 mW.

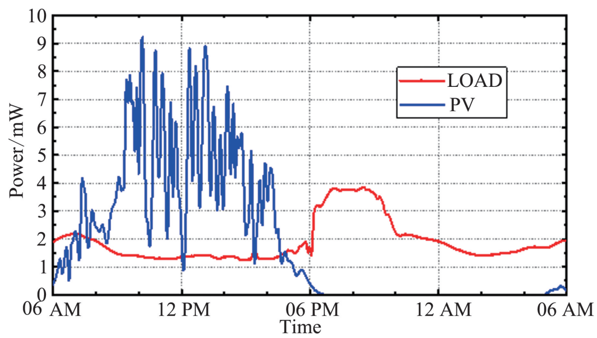

Fig. 8 Photovoltaic generation and load data

The simulation sets the sampling time to 1 min and sets four cases.

Case 1 The voltage regulation service is not provided for the distribution network. The over-voltage and unde-voltage problems occur. This case is used to be compared with the voltage regulation effect of other cases.

Case 2 The voltage regulation service is only provided by the OLTC. In this case, the time-delay is caused by the characteristics of the OLTC. This case is used to be compared with the Case 3 to show that the proposed voltage regulation strategy can respond to voltage regulation quickly.

Case 3 The voltage regulation service is only provided by the OLTC and BESS. In this case, the voltage regulation service is provided by the BESS during the transformer tap of the OLTC is switching. Therefore, the proposed voltage regulation strategy can provide more timely and better regulation services for the distribution network.

Case 4 In this case, the voltage regulation powers are calculated by the sensitivity coefficient method and the node voltage sequencing regulation method. The advantages and disadvantages of the two methods show that the node voltage sequencing regulation method is more suitable for the distribution network with limited BESS.

The constant parameters are shown as Table 1.

Table 1 Constant parameter initialization

Symbol	Definition or description	Value	Unit
V_{max}	The maximum threshold voltage for the distribution network	1.1	p. u.
V_{min}	Minimum threshold voltage for the distribution network	0.9	p. u.
V_{nom}	Voltage value under normal circumstances	1.0	p. u.
SOC_{max}	Maximum SOC value	90	%
SOC_{min}	Minimum SOC value	10	%
B_c	Maximum BESS capacity	58/135	kWh
Tap_{max}	Maximum tap position of OLTC	1.037 5	p. u.
Tap_{min}	Minimum tap position of OLTC	0.962 5	p. u.

3.2 Results and analysis

Figs 9 – 11 show the simulation results of node voltage without regulation measured within 24 h. From 9:00 AM to 11:00 AM and 12:00 PM to 2:00 PM, the sunlight intensity is very large. As such, the power generation of the PV is higher than the load power of the users, resulting in the voltage of some nodes exceeding the limit. After 6:00 PM, the PV generation gradually decreases with the sun gone. The current flowing into the nodes increases with the increment of user load power which results that the voltage of some nodes is lower than the normal voltage range.

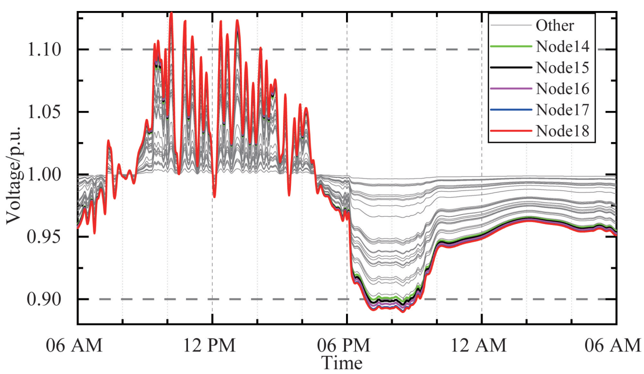

Fig. 9 Case without voltage regulation

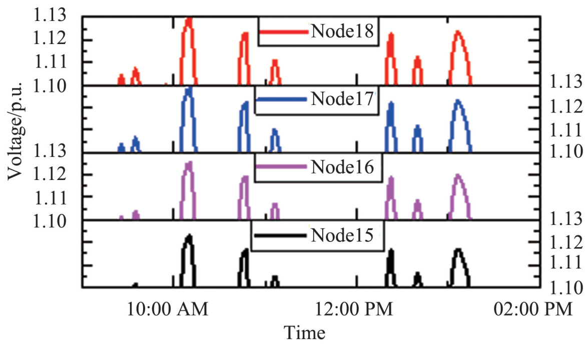

Fig. 10 Case without voltage regulation at 10 AM – 2 PM

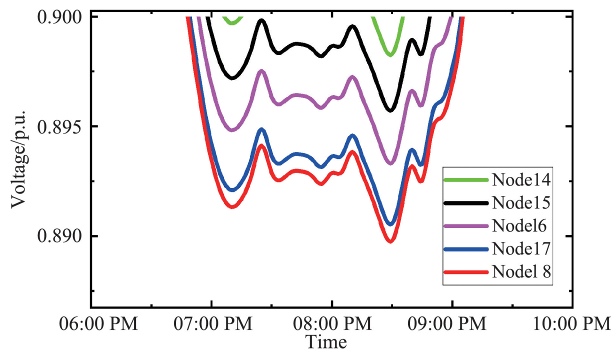

Fig. 11 Case without voltage regulation at 6 AM – 10 PM

Fig. 12 shows the 24 h simulation results for node voltage regulation with OLTC. The over-voltage problem occurs at 9:25 AM at which time the switching of the OLTC taps is not completed. The voltage values at nodes 17, and 18 are 1.102 p. u. and 1.103 p. u., which are still larger than 1.100 p. u. Similarly, the voltage value at node 18 around 6:49 PM being 0.899 p. u. is still less than 0.900 p. u. The OLTC cannot solve the problem of voltage over-limit perfectly. In addition, it can be seen from Fig. 13 that the OLTC is required to participate in the adjustment once the PV causes a slight voltage violation.

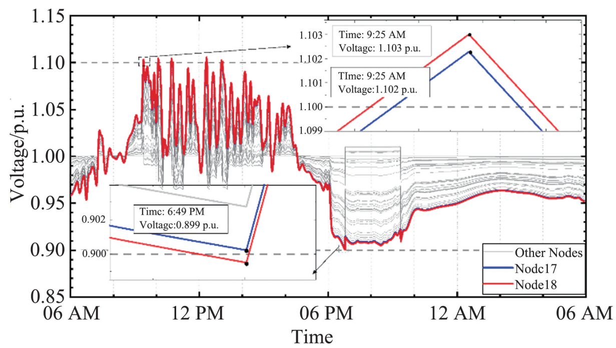

Fig. 12 Regulation by OLTC

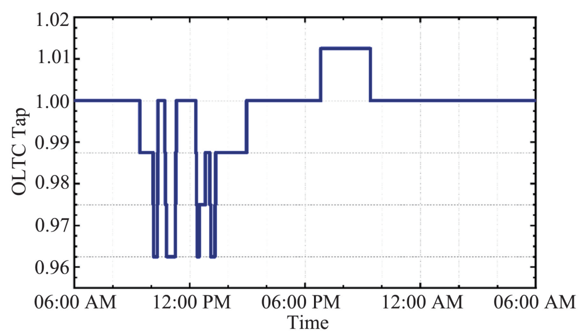

Fig. 13 OLTC regulation tap position

Fig 14 shows the simulation results of the proposed voltage regulation strategy of the OLTC and BESS strategy. At 9:25 AM and 6:49 PM, nodes 17 and 18 are regulated to [0.900, 1.100] p. u. by controlling the charging and discharging power. The problem of out-of-limit voltage during the OLTC tap switching is solved. At the same time, it can be seen from the comparison of Fig. 15 and Fig. 13 that the switching times of the OLTC taps are reduced to 6 times.

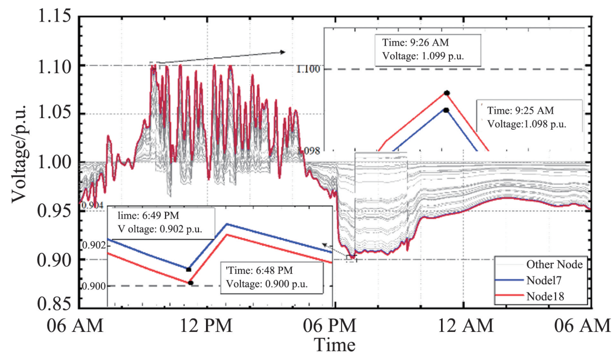

Fig. 14 OLTC and BESS co-regulation

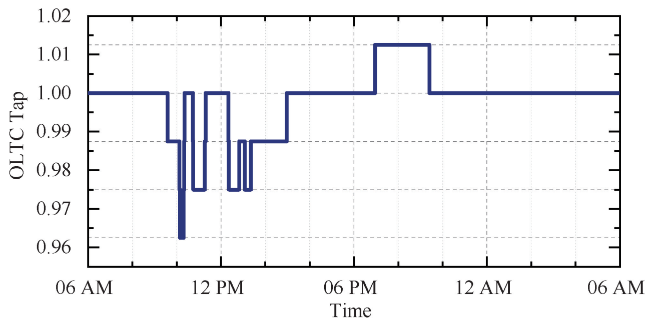

Fig. 15 OLTC and BESS co-regulation tap position

Comparing Fig. 16 (SOC curves of the proposed strategy) and Fig. 17 (the traditional strategy), the proposed strategy can effectively reduce the voltage regulation power and reduce the frequency of BESSs' charging and discharging in voltage regulation, which can effectively extend the lifespan of the BESSs.

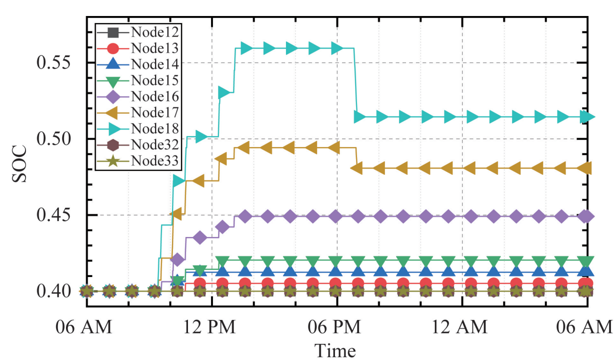

Fig. 16 Proposed strategy SOC curves

In addition, the proposed node voltage sequencing regulation strategy can use less regulation power to optimize the voltage in distribution networks. The node voltage curves with regulation by sensitivity coefficient method and node voltage sequencing regulation strategy are shown in Figs 18 and 19. Both methods can keep the voltage within [0.900, 1.100] p.u., but the sensitivity coefficient method consumes more regulation power (Fig. 20). The voltage quality of the distribution network will be better. However, the regulation capacity of the BESSs on the user side is limited. The node voltage sequencing regulation strategy is more suitable to improve the voltage quality of the distribution network.

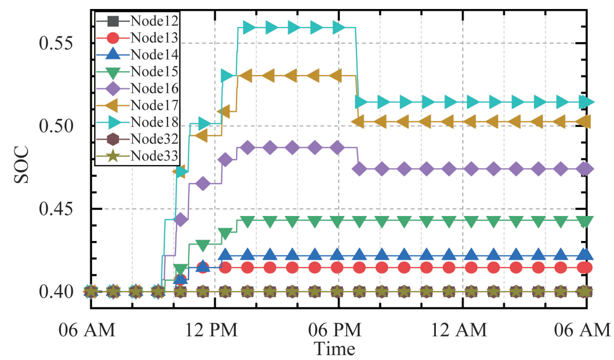

Fig. 17 Traditional regulation strategy SOC curves

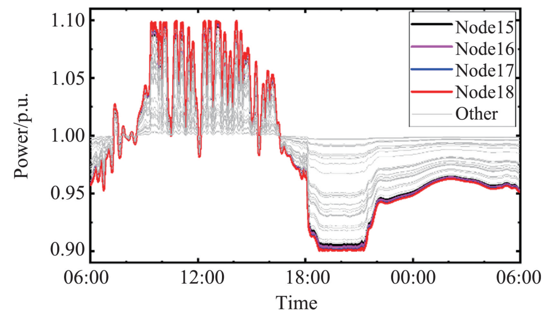

Fig. 18 The voltage curve regulated by the node voltage sequencing regulation method

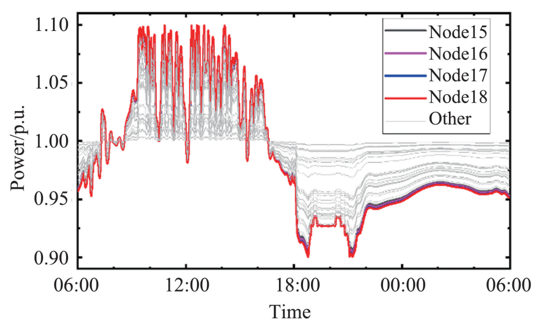

Fig. 19 The voltage curve regulated by the sensitivity coefficient method

4 Conclusion

This paper proposes a coordinated strategy based on OLTC and BESS for voltage regulation. The simulation results based on IEEE 33 distribution network model show that the co-regulation strategy can reduce the switching frequency of the OLTC taps. By using the BESS, the voltage over-limit can be avoided when the tap of the OLTC is switching. At the same time, the node voltage sequencing regulation strategy can reduce the regulation power and regulation frequencies of the BESS in voltage regulation, as such prolonging the life span of the BESS.

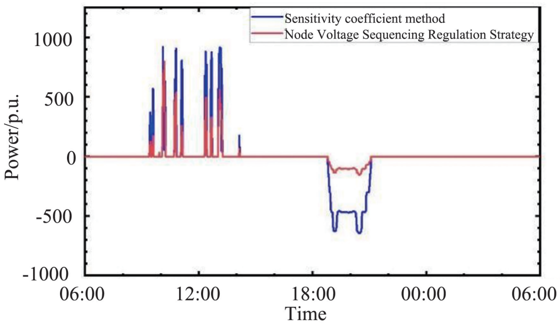

Fig. 20 The voltage regulation power

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