The active control strategy on the output power for photovoltaic-storage systems based on extended PQ-QV-PV Node

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Abstract. In order to solve the problem of voltage exceeding specified limits and improve the penetration of photovoltaic in distribution network, we can make full use of the active power regulation ability of energy storage(ES) and the reactive power regulation ability of grid-connected photovoltaic inverter to provide support of active power and reactive power for distribution network. A strategy of actively controlling the output power for photovoltaic-storage system based on extended PQ-QV-PV node by analyzing the voltage regulating mechanism of point of commom coupling(PCC) of photovoltaic with energy storage(PVES) by controlling photovoltaic inverter and energy storage. The strategy set a small wave range of voltage to every photovoltaic by making the type of PCC convert among PQ, PV and QV. The simulation results indicate that the active control method can provide a better solution to the problem of voltage exceeding specified limits when photovoltaic is connected to electric distribution network.

1. Introduction
Zinc Distributed Photovoltaic Power Generation (DPPG) is a kind of clean energy, which can convert solar energy into electric energy directly. With DPPG's great development, more and more DPPG is connected to distribution network, which makes it convenient for the application of electricity, however, it brings great challenge to the safe operation of power system at the same time[1,2]. As to the problem that voltage exceeds specified limits when DPPG is connected to distribution network, the main solution is to regulate voltage of PCC by controlling power of photovoltaic[2]. A self-adaption control strategy with the limitation of active power and the compensation of reactive power is proposed to restraint over-voltage in [3], but the economic benefit is low while the strategy does not take active and reactive power loss of the network into consideration. Two conditions based on degree of voltage exceeding specified limits are discussed in [4]. One is normal condition and photovoltaic inverter is used to regulate voltage in this case, the other is emergency condition and reactive power of photovoltaic system in the same feeder is used to regulate voltage in this case. But, once there is communication failure between network nodes, the algorithm is invalid. Reactive power control strategy that based on the voltage of grid-connected node and photovoltaic active power output is put forward in [5]. The premise condition of this strategy is that the loss of active power and reactive power is positive correlation with the reactive power output of inverter when the active power output of photovoltaic system is fixed. But the active power outputs of photovoltaic system change...
over time. In [6], inverter's Automatic adjusting voltage of distributed photovoltaic by controlling its power factor \(\cos \theta (U)\) is introduced. But in this strategy, the loss of network and the cost of inverter's adjustment aren't considered. In [7], a control method of over-voltage prevention based on active-reactive power collaborative optimization is established, which doesn't analyze complementary adjustment between energy storage and photovoltaic inverter.

Now the development and application of energy storage technology can increase the penetration of DPPG. The combination of DPPG and energy storage can effectively make up the randomness, the intermittent and uncertainty of DPPG and limit it, it also plays an important role in improving the quality of DPPG, adjusting peak of power grid and stabilizing voltage fluctuation. In [8], energy storage is configured with goals of reliability and economy. A configured method of energy storage takes voltage constraints and voltage disturbance when photovoltaic is connected to distribution network into consideration in [9]. But the method doesn't allow for the inhibition effect of photovoltaic inverter itself to voltage fluctuation. In [10], grid-connected nodes of PVES are extended to QV node, and a day-ahead schedule of PVES based on voltage control method of PCC is put forward. All these works do research in areas of controlling the PVES, photovoltaic inverter and the voltage of PCC. But they didn't give well-directed research to the connotation of grid-connected node in the system of PVES. The combination of DPPG and ES in electric power distribution network and the active control strategy to voltage of PCC based on the transformation of node type of PCC haven't been found at home and abroad yet.

When we talk about voltage exceeding specified limits in distribution network with photovoltaic, it mainly refers to the voltage that is near PCC which is always caused by higher photovoltaic power output and lower absorb of load. The impedance ratio in the line is a little big, so photovoltaic inverter that is needed to restrain over-voltage maybe big. While the capacity of photovoltaic and the carrying capacity of lines both can lead to the invalidation of above-mentioned control strategy related to inverter’s reactive power. This paper analyses the influence to voltage caused by photovoltaic inverter and energy storage of PCC. Then on the basis of detail study of QV node's power flow calculation, this paper gives a active control strategy on the output power for photovoltaic-storage systems based on extended PQ-QV-PV node, which provides optimal power reference value for every inverter and energy storage. The voltage can be effectively restrained within a certain range without communication between nodes by using this method.

2. The Mechanism of the restrain of voltage disturbance based on photovoltaic connected energy storage

In order to make full use of electric power generated by photovoltaic, unity power factor is used in DPPG when photovoltaic is connected to power grid. Energy storage can effectively regulate the voltage of photovoltaic PCC while it does well in balancing active power output. The reactive power output of photovoltaic inverter is mainly restrained by self capacity of DPPG. When the active power output of photovoltaic is lower than its rated capacity, the remaining capacity can be used by photovoltaic inverter to provide reactive power for power grid, which can regulate the voltage of PCC. Small DPPG is connected to electric power system by low voltage distribution network, and the impedance ratio of low voltage line is generally big. Fig.1 presents the simplified model of photovoltaic connected to low voltage distribution network. In the Fig.1, PV represents distributed photovoltaic source, \(R\) represents impedance of line, \(X\) represents reactance of line, \(V_{pcc}\) represents the voltage of PCC, \(V_{i}\) represents the equivalent voltage of low voltage distributed network, \(P_{pv}\) represents the active power of photovoltaic, \(Q_{pv}\) represents the reactive power of photovoltaic inverter, \(P_{L}\) represents the local active power of PCC, and \(Q_{L}\) represents the local reactive power of PCC. \(V_{pcc}\) can be calculated by formula 1:

\[
\dot{V}_{pcc} = \frac{(P_{L} - P_{p})R + (Q_{L} - Q_{p})X}{V_{pcc}} - j \frac{(P_{L} - P_{p})X - (Q_{L} - Q_{p})R}{V_{pcc}}
\]  

(1)
Solve formula 1, then we get the value of $V_{pcc}$ as formula 2:

$$V_{pcc} = \frac{V_a - 2a + \sqrt{4a^2 - 4aV_a^2 - 4b^2}}{2}$$

(2)

a and b in formula 2 can be calculated by formula 3 and formula 4:

$$a = (P_{p} - P_{pv})R + (Q_{l} - Q_{pv})X$$

(3)

$$b = (P_{p} - P_{pv})X - (Q_{l} - Q_{pv})R$$

(4)

This paper will discuss the question in two cases.

A) When the active power output of DPPG is less than local need of load (when $P_{pv} < P_{l}$), the power shortage will be met by power network. Obviously, the power which is given by power network flows into the PCC is $P_{l} - P_{pv}$. According to the formula(2), the voltage of PCC is got. If $P_{pv}$ is small but the load is heavy, a is very big so $V_{pcc}$ may be less than the lower limit. In such a situation, if there are energy storage devices in the PCC that provide real power or the photovoltaic inverter provides the system with inductive reactive power, the voltage is easier to be controlled within a qualified range and its quality is improved.

B) When the power output of DPPG is more than local load (When $P_{pv} > P_{l}$), the photovoltaic power output need to transport extra power to distribution network and meet local load. The extra power is $P_{pv} - P_{l}$. In calculating the voltage of PCC, $P_{l} - P_{pv}$ is replaced by $P_{pv} - P_{l}$ and $Q_{l} - Q_{pv}$ is replaced by $Q_{pv} - Q_{l}$. Recalculating a, b and the voltage. In the situation, if $P_{pv}$ is big while the load is small, $V_{pcc}$ may be over the upper limit. If there are energy storage devices which absorb real power or making the photovoltaic inverter absorbs inductive reactive power to reduce voltage of PCC, voltage amplitude will be controlled within a reasonable range and its quality is improved.

3. The active control strategy on output power for photovoltaic-storage systems based on extended $pq-qv-pv$ node

A Power flow calculation with QV node

In conventional power flow calculation of power system, the nodes has three types that are PQ, PV and balanced nodes[9]. With the increase of the penetration of DPPG, the distribution of power flow of power distribution networks has a profound change. Generally, in order to maximize the use of renewable energy, photovoltaic energy only generates real power with a power factor of 1.0. Suppling DPPG may cause the voltage of PCC rising and even over the limitation. Therefore, under the premise of voltage constraints, it is unavoidable to face the problem that we need to find the real power output of the photovoltaic PCC in order to get the capacity of DPPG and the energy storage[10]. Thus, the calculation of power flow with QV node is derived. It means the reactive power $Q$ and voltage magnitude $V$ is given so the active power $P$ and voltage phase angle $\delta$ are the unknowns. Generally pure active power sources to restrain voltage are QV nodes, such as the photovoltaic power station considering the constraint of voltage with energy storage in distribution power networks. The detailed steps solving power flow calculation including QV nodes based on Newton-Raphson algorithm are elaborated in [10].

The determination of voltage magnitude $V$ is a key problem in treating photovoltaic-storage PCC as QV nodes. At present, the setting of $V$ depends mainly on the historical operation data of photovoltaic system and experiences of experts. Then, the data of power flow of distribution power networks with
QV node based on a fixed value of V is not necessarily the optimal. When the penetration of DPPG in distribution power networks is high, the running cost of energy storage may be high if the PCC are treated as QV node.

A Active control strategy on the output power of photovoltaic-storage system based on PQ-QV-PV node

Configuring the energy storage device at photovoltaic PCC helps effectively to solve the over-limit voltage. Conventional photovoltaic-storage system outputs power in model of limiting the output power of the PVES. Taking into account of the uncertainty of DPPG output and the load fluctuation, the voltage fluctuation of the PCC need to be as small as possible to limit the voltage fluctuation of other nodes and decrease the probability of voltage over its limitation.

Based on this, from the point of voltage control with active transformation among PQ, PV and QV nodes of the node type of PCC, this paper proposes the method that controls the real power of the storage energy and the reactive power of photovoltaic Inverter.

The program block diagram of the active control method on the output power of photovoltaic-storage based on PQ-QV-PV node is shown in Fig.2.

The active control method on output power of photovoltaic-storage based on PQ-QV-PV node is listed:

a) Get data of the distribution network frame.
b) Get the forecasting data of load and photovoltaic power output next day.
c) Treat the PCC as PQ-PV-QV node and configure the upper and lower limit value: $V_{U}, V_{L}$.
d) Each node is treated as PQ node in distribution power system. The real power loss in distribution network is the objective function. Choosing the interior point methods of the optimal power flow to calculate voltage magnitude $V_i$ and real power output $P_{opt}$ of the storage energy and reactive power output $O_{opt}$ of photovoltaic inverter.
f) To determine whether the $V_i$ meets $V_i \in [V_{L}, V_{U}]$. If it is satisfied, active power output of energy storage of each PCC is that $P_{opt}$ and reactive power output of photovoltaic inverter is that $Q_{opt}$. If not, transform the node type whose $V_i$ is over the upper(lower) limit into QV node. Then, reactive power $Q$ is set to be 0, $V$ is set to be $V_{U} (V_{L})$. Then, after calculating the power flow with QV node, real power of storage energy based on the QV node $P_{qvi}$ is got.

4. An example analysis

A simulation model based on 10kV electric power distribution network is established in MATLAB. In order to emphasis the voltage change of key nodes, a complicated electric power distribution network is abstracted to a equivalent electric power distribution network. The structure figure of network flutter is given in Fig. 3. The node 1 is a balance node, and voltage $V_1 = 1.05pu$. Node 6 and Node10 are connected with photovoltaic which capacities are 800kW and 1000 kW. Loads change over 24 hours according to their characteristics, and the outputs of photovoltaic change over a day according to its characteristics.

In order to test the effect of the active control method based on photovoltaic connected energy storage output power, comparisons are made among methods of photovoltaic grid-connected node without ES, a day-ahead schedule of photovoltaic connected energy storage based on the voltage control of grid-connected node. There are three cases.

Case 1: photovoltaic grid-connected node is not connected energy storage, node 6 and 10 are free outputs of photovoltaic power. For the convenience of observation, voltages of node 2,3,5,6,9,10 are focused on. The voltage curve of each node is calculated by power flow calculation, which is presented in Fig. 4.

The safe operation constrain of 10kV electric power distribution network is 0.93pu~1.07pu. The symbol "A" represents that the voltage is over the upper limit.

Voltage fluctuation of each node is displayed in Fig. 4. Voltage fluctuation of node 6 and 10 is more violent because they are photovoltaic grid-connected nodes and their voltage fluctuation change along with the randomness and intermittency of photovoltaic outputs. Specially, voltage values of node 6 are
The power output of energy storage is controlled by the voltage of grid-connected nodes. The voltage of grid-connected node maintain constant which achieve by combining the active power output of energy storage with the active power output of photovoltaic. The voltage value of node 6 and 10 is supposed to be 1.050, that is to say, node 6 \((Q=0, U=1.050)\) and node 10 \((Q=0, U=1.050)\) are QV nodes, and the method including power flow calculation of QV node is used to analyze the control effect of the voltage of every node for case 2.

The maximum power of energy storage is confined in case 2, which is 0.7 times of the maximum output power of photovoltaic. The maximum output power of energy storage that is equipped to node 6 is 560kW, and node 10 that is 700kW. So when the value of output power of energy storage is over the limit, the node related should be transformed from QV node to PQ node, and the output of energy storage is the maximum output power of it. Under this circumstance, the voltage curve and the output power curve of photovoltaic connected energy storage are given in Fig. 5, Fig. 6 and Fig. 7.

Compared to Case 1, the voltage fluctuation of each node in case 2 is obviously gentler according to Fig. 5. Because of using the joint power output of photovoltaic connected energy storage, the voltage of photovoltaic grid-connected node is directly controlled. It seems like there are some nodes whose voltage is almost constant. So, this method could effectively solve the voltage fluctuation problem. But, the power output of energy storage in photovoltaic connection point is maximum as QV node is transformed into PQ node, the voltage is not constant. It will cause large voltage fluctuation and influence the capacity of energy storage to some extent.
Case 3: Active control strategy on the output power of photovoltaic-storage system based on PQ-QV-PV node
This case transforms the type of grid-connected node among PQ,QV and PV node in turn according to the voltage of the PCC. Based on this operation, voltage of connection point is stabilized with the real power output of energy storage and reactive power output of photovoltaic inverter. After configuring voltage limitation [1.047, 1.053](p.u) of connection points of node 6 and node 10, the output power curve and voltage curve of each node is shown in Fig. 8, Fig. 9 and Fig. 10. The biggest power output of ES in case 3 is same as what in case 2. But voltage fluctuation is not only obvious gentler than what in case 2 but not beyond upper and lower limit. Case2 and case 3 all need enough ES to regulate voltage of photovoltaic connection point. In order to avoid excessive charging and discharging in ES, the state of charge of the energy storage battery is limited to 10%-90%. In the situation, the capacity of ES and real power loss of distribution network for case 2 and case 3 are compared in table 1. The real power loss of case 3 is less than 104.929KW and storage capacity is less than 10.061MW.h compared to case 2.
Based on the above analysis, the active control method on the output power of photovoltaic-storage systems based on PQ-QV-PV node makes a better performance in solving the problem that the node voltage is out of limit, improving the power flow of the distribution network and filling and shifting the peak load. Therefore, the capacity of ES could be reduced and voltage fluctuation could be controlled with the appropriate operation mode. Furthermore, the appropriate operation mode is helpful to reduce the investment of storage cell and voltage regulating device and the costs of the device need in its regulating action.
Conclusion

A) The active control method of output power for photovoltaic-storage systems based on PQ-QV-PV node is able to more directly reflect the fluctuation of photovoltaic power output and load of distribution network, owning better performance in reducing voltage fluctuation and improving the reasonability of allocating the output of ES. This method can reduce the real power loss of network.

B) The future research work will consider the rejusting cost of the ES and inverter together. In the same time, the future research will deduce the accurate mathematical model of this method.

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