Decision-making of Voltage Control Strategy for Distribution Network after Large-scale PV Participation

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***Abstract*—With the widespread use of distributed PV connected into distribution network, three kinds of voltage control strategies are proposed, namely, centralized, decentralized and multi-time scales voltage control. Centralized voltage control adjusts distributed PV, parallel capacitor group and on-load tap changer to optimize voltage control overall the entire network. Decentralized voltage control using local available information, by monitoring point voltage independent control to improve the operation of the grid. Multi-time scale voltage control is composed of long-time scale and short-time scale control in real time. By case study, this paper obtain the advantages and disadvantages of the three voltage control strategies and their application environments, auxiliary planning staff in distribution network make the best decision.**

***Index Terms*--PV participation network, Voltage control strategy, Application environments, Auxiliary device**

I. Introduction

In order to meet the increasing degree of load, the constraints on the development of distribution network, widespread use of distributed energy resources and so on. Domestic and foreign scholars are actively researching on ADN related technology with certain regulation ability under the background of the smart grid to solve these problems.

With the increase of the permeability of distributed photovoltaic (PV) power supply, the control methods are gradually showing the trend of diversification [1]. In the existing distribution network, there are many researches on reactive power optimization control. In [2], it is necessary to limit equipment operation times the by reducing the cost of distribution network and the minimum operating cost of equipment. To achieve optimal control of OLTC, shunt capacitor banks and PV reactive power. However, due to the fact that the forecast error has not been considered, the practicality of the optimization scheme is greatly affected by the prediction accuracy. In [3], the prediction error of PV active and load is in accordance with the Gaussian distribution. The probability density function of the output reactive power is deduced by using the relationship between active and reactive power, which can eliminate the effect of prediction errors on optimization.

In [4], the formation of the objective function is the operational constraints of OLTC and shunt capacitor banks are transformed into economic cost, as well as the current energy loss cost, which is used for real-time optimization. In [5], the formation of the objective function is the active power loss. The reactive power adjustment capability of distributed power supply is also taken into account in the control, and the multi-agent immune algorithm is used to solve the problem.

In [6], two-stage optimization of pre-scheduling and scheduling real-time optimization is proposed to realize the regulation of OLTC taps and shunt capacitor banks. In [7] proposed to optimize the current through control capacitor group and OLTC and other discrete reactive power equipment to stabilize the larger voltage fluctuations, and real-time optimization through the SVG, DG supply and other continuous adjustment of reactive power equipment control in order to ease small voltage fluctuation.

In this paper, three kinds of voltage control strategies are proposed, namely, centralized, decentralized and multi-time scales. By comparing their control effect with simulation, we consider different application environments and assist distribution network control strategy.

II. Control Method and Strategy of PV Participation Voltage Regulation

A. Control Method and Strategy of Decentralized Voltage

Decentralized voltage regulator using local available information, through monitoring point voltage of the independent control to improve the overall operation of the grid, the voltage and reactive power control equipment all

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belong to local operation [8]. Decentralized control is used widely in China, namely, automatic control of the system are completed by different levels according to their property and complexity. The organizational structure of the system-wide monitoring and control functions, can only completed by the highest level whose control function is global and integrated [9].

a) Power Factor - Voltage Control Mode

Through the local control of the PV operate mode, PV adjust the voltage through power factor - voltage control mode. This voltage regulator does not require a lot of reactive power injection or reactive power absorption, which can provide effective regulation, especially for the rural power grid. It can save a huge investment in centralized control [8]. Specific control measures shown in Fig.1, the power factor control mode is used when the voltage is qualified, or the voltage control mode is used when the voltage is not qualified.

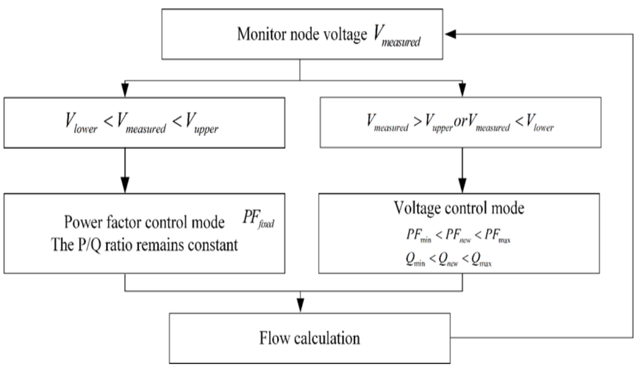

Fig.1. PFC-VC control charts

As shown in Fig.2, the generator operating point (the endpoint of the vector V) changes along the thick dashed line in the figure. When the voltage reaches the limit Vmin or Vmax, the automatic voltage regulator of generator adjust the excitation current under the voltage control mode. Regulating generator's voltage by adjusting the reactive power of the regulator. When the voltage drops to the lower threshold VPFCmin, the P/Q ratio is reduced. However, when the voltage rises to the upper threshold VPFCmax, the P/Q ratio is increased. The power factor also changes, but must be within the allowable range of operation, i.e. PFmin to PFmax. When the voltage is within the qualified range, the power factor control mode is used to maintain the P/Q ratio.

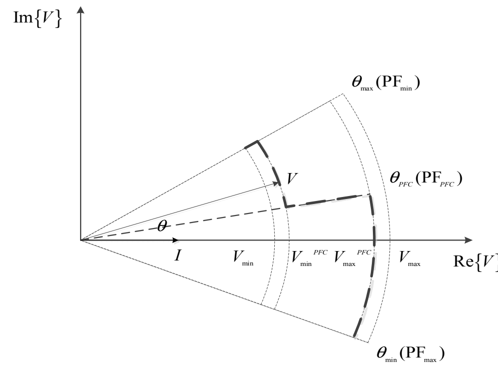

Fig.2. Voltage and current vector under PFC-VC control mode

PFC-VC can better adjust the voltage distribution, and effectively prevent the voltage out of range. In addition, PFC-VC can reduce the number of OLTC action, extend the life of the transformer.

B. *Control Method and Strategy of Centralized voltage*

Centralized coordination voltage control through grasping the overall information of the entire distribution network to optimize the voltage control. With the development of communication technology, it is necessary to make the whole network centralized coordination arrangements by the method which is similar to main network voltage control. By adjusting the DG power, parallel Capacitor group, on-load tap changer and other components in the distribution network, constitute the distribution network voltage centralized coordinated control.

a) Basic Control Structure and Voltage Control Equipment

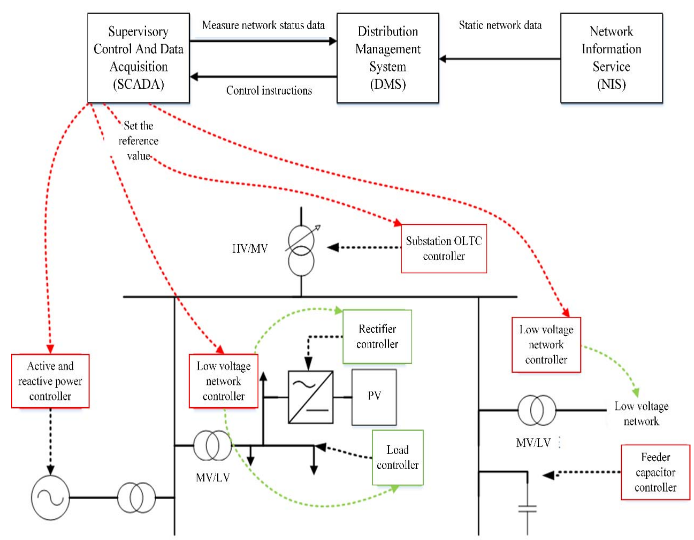

Fig.3. The framework of centralized control

As shown in Fig.3, the Distribution Management System (DMS) can achieve the coordination of controllable components in the distribution network to improve operational efficiency and keep the voltage of each node in the network within the allowable range. The control equipment includes substation OLTC, substation capacitor, DG, feeder capacitance and so on.

b) Control Method and Strategy of PV Participation Centralized Voltage

The centralized coordinated voltage control determines the control action based on the information of the entire distribution network. Thus, information transmission between the nodes are required to coordinate the different voltage regulation devices in the control system.

This paper adopts the centralized voltage control method with variable order of action. It uses OLTC and DG as voltage regulating devices. Because of economic problems, safety problems and other reasons, we do not allow the equipment to regulate too much. We introduce the concept of voltage regulator equipment priority and selectivity, and determine the control area through its sensitivity analysis. In order to achieve the corresponding regional voltage changes, and reduce the number of equipment operations, the devices act in corresponding order to control the operation. In addition, this paper propose the delay action to reduce the interaction between the equipment caused by the oscillation [10].

By proposing the concept of the control space and control order, it achieve the coordination action of OLTC and DG. Taking the radiation feeder with only DG and OLTC as example, the control region is determined according to the sensitivity analysis. The intersection of the sensitivity curve of OLTC and DG is used as the cut-off point of the control area, as shown in Fig.4. The purpose of the demarcation is to give more opportunities of voltage control to the efficient and economical equipment. According to regulator sensitivity of DG and OLTC, there will be divided into two control area. One device is the main voltage regulator equipment, the other device is an auxiliary device. When the main device operation is invalid, then the auxiliary equipment act. The coordination between the main and the auxiliary equipment is coordinated by different delay. When in the control area of DG, DG is used as the main device, while the voltage is overtaken, DG acts to control the voltage and OLTC has a certain delay. However, if DG voltage control is invalid, OLTC acts to control voltage. This method control the voltage between the node and the target controller through the one-way communication, while between the two control devices through the two-way communication. It makes the communication system greatly simplified. When the number of the control devices is more than two, we can also achieve voltage control by using multiple control areas [11].

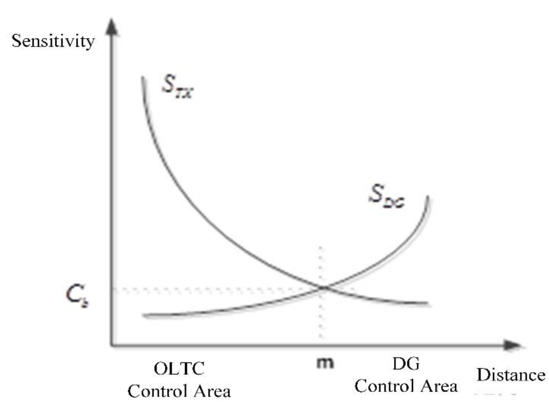

Fig.4. Schematic diagram of control area division

C. Voltage Control Based on Multi-time Scale

When a large number of different types intermittent DG access to the distribution network, simple centralized coordination control may lead network-communication increase significantly. For the solution process is complex, only under long-time scale can achieve optimize control. Because of the uncertainty and randomness of the intermittent energy, only long-time scale optimal control cannot make a timely response to the voltage change. The voltage waveform obtained under this control strategy is not optimal. In view of the above problems, we propose a control strategy for DG voltage control in distribution networks with multi-time scales. It mainly includes two parts, namely, long-time scale and short-time scale control in distribution network. The global optimal control is based on the generator's optimal power flow and the control equipment's optimal operation. The short-time scale control mainly utilizes DG reactive power output, OLTC gear of the substation and control of parallel capacitor bank, in order to adjust the network voltage in order to meet its limit requirements.

Furthermore, multi-time scale voltage control can be optimized controlled in two-stage. They are daily previous-scheduling based on the load demand forecast and daily optimal scheduling based on the short time interval (15min). Real-time control strategy unchanged. The specific control block diagram shown in Fig.5.

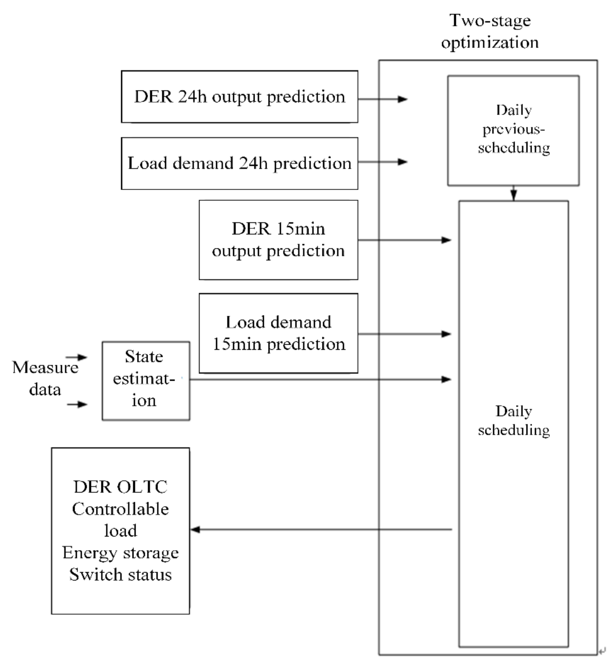

Fig.5. Voltage control based on multi-time scale

The application of multi-time scale voltage control strategy not only satisfies the optimization problem, but also satisfies the rapid response to voltage change. The operation cost of the power grid is effectively decreased, the energy efficiency is improved and the optimization of large-scale resources is nearly achieved.

III. CASE SIMULATION

Taking a prefecture-level city power grid in China as an example, nowadays the grid voltage levels includes 66 kV and 10 kV. The total installed capacity is 4702MW, including 3 thermal power plants whose installed capacity is 1776MW, 22 wind power plants whose installed capacity is 2846.16MW, one biological intelligent power plant whose installed capacity is 30MW, and PV power plant whose installed capacity is 49.914MW. The 66kV grid-connected power plant installed capacity is 486.17MW. The maximum load is 782.7WM, the whole power supply is 3.838 billion kWh. In order to prove the regulation effect of the flow and voltage control analysis system, we select 66kV substation's 10kV line as the test line.

The maximum load of the 10kV line is 2.975+j1.345MVA, and its system structure is shown in Fig.6. The transformation ratio of the on load tap changing transformer is 1±8×1.25%. The low voltage side installs fixed compensation capacitor group, the group number and its capacity is 4*0.1MVar. There are two 0.8MW PV power plants on the line, connect with node 21 and node 29 respectively, as shown in Fig.6.

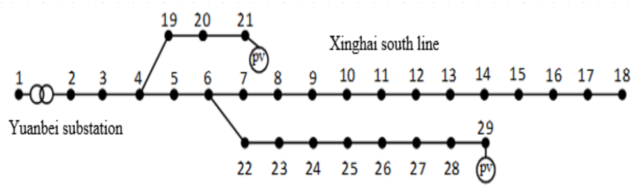

Fig.6. 10kV distribution system of the substation

According to the principle of high light intensity and low load, we select the typical application scene. Simulation results show that each node's maximum voltage, voltage pass rate and RMS of voltage deviation and other statistics during 24h, as shown in Table 1.

TABLE I

Voltage Statistics of Each Node during 24h

N	Vmax (kV)	Pass Rate (%)	V_{RMS} Deviation (%)	N	Vmax (kV)	Pass Rate (%)	V_{RMS} Deviation (%)
1	1.0489	100	0.0387	16	1.0327	100	0.0387
2	1.0459	100	0.0372	17	1.0314	100	0.0368
3	1.0417	100	0.0377	18	1.0291	100	0.0311
4	1.0425	100	0.0389	19	1.0587	100	0.0398
5	1.0471	100	0.0392	20	1.0669	100	0.0401
6	1.0425	100	0.0366	21	1.0707	95.8	0.0439
7	1.0403	100	0.0402	22	1.0441	100	0.0295
8	1.0391	100	0.0400	23	1.0428	100	0.0212
9	1.0382	100	0.0395	24	1.0419	100	0.0205
10	1.0375	100	0.0372	25	1.0432	100	0.0242
11	1.0369	100	0.0379	26	1.0501	100	0.0339
12	1.0353	100	0.0388	27	1.0543	100	0.0367
13	1.0346	100	0.0382	28	1.0640	100	0.0397
14	1.0338	100	0.0353	29	1.0700	96.9	0.0482
15	1.0331	100	0.0390				

The table shows that the voltage of some nodes are over the limit. Although this is temporary, with the widespread use of PV, the problem will be more significantly.

To solve the problem of voltage over-limit, and find a suitable reactive voltage control strategy to meet the minimum loss of the network and the voltage qualified. By the method of time-sharing capacitor switching (conventional method), and PV participate decentralized control, centralized control, and coordinated control. We run the simulation 24 hours a day. It shows that under the regulation of the four control methods, the node voltage is qualified. However, due to the use of PV reactive power in decentralized control, centralized control and coordinated control, network loss has increased. Considering the lack of automation and communication method, as well as the principle of the lowest loss of the network, we choose the time-sharing capacitor switching method as the actual control strategy. Cutting out one capacitor group at 12:00,13:10 respectively, and two capacitor groups at 14:30.Under this strategy, each node's maximum voltage, voltage pass rate and RMS of voltage deviation and other statistics during 24h, as shown in Table 2.

TABLE □

Voltage Statistics of Each Node during 24h in Voltage Simulation

N	Vmax (kV)	Pass Rate (%)	V_{RMS} Deviation (%)	N	Vmax (kV)	Pass Rate (%)	V_{RMS} Deviation (%)
1	1.0459	100	0.0282	16	1.0314	100	0.0275
2	1.0432	100	0.0269	17	1.0309	100	0.0259
3	1.0417	100	0.0275	18	1.0291	100	0.0304
4	1.0428	100	0.0283	19	1.0554	100	0.0293
5	1.0414	100	0.0287	20	1.0629	100	0.0382
6	1.0409	100	0.0262	21	1.0689	100	0.0395
7	1.0381	100	0.0289	22	1.0393	100	0.0282
8	1.0360	100	0.0291	23	1.0427	100	0.0260
9	1.0349	100	0.0288	24	1.0430	100	0.0239
10	1.0332	100	0.0266	25	1.0489	100	0.0272
11	1.0328	100	0.0272	26	1.0494	100	0.0284
12	1.0326	100	0.0285	27	1.0562	100	0.0335
13	1.0323	100	0.0278	28	1.0606	100	0.0351
14	1.0320	100	0.0250	29	1.0642	100	0.0379
15	1.0317	100	0.0287				

TABLE □
Average Network Loss Rate in Different Control Strategies

Voltage Control Strategy	Decentralized Control	Centralized Control	Coordinated Control	Time-sharing Capacitor Switching
Network Loss(MW)	1.78	1.65	1.69	1.53

In actual operation, the strategy can obtain each node's maximum voltage, voltage pass rate and RMS of voltage deviation and other statistics during 24h on the second day, as shown in Table 4.

TABLE □
Voltage Statistics of Each Node during 24h in Actual Operation

N	Vmax (kV)	Pass Rate (%)	V_{RMS} Deviation (%)	N	Vmax (kV)	Pass Rate (%)	V_{RMS} Deviation (%)
1	1.0490	100	0.0387	16	1.0429	100	0.0392
2	1.0467	100	0.0382	17	1.0517	100	0.0372
3	1.0422	100	0.0381	18	1.0661	100	0.0412
4	1.0443	100	0.0392	19	1.0577	100	0.0408
5	1.0438	100	0.0395	20	1.0706	97.9	0.0395
6	1.0420	100	0.0373	21	1.0719	95.8	0.0389
7	1.0417	100	0.0408	22	1.0397	100	0.0399
8	1.0403	100	0.0408	23	1.0429	100	0.0412
9	1.0378	100	0.0397	24	1.0442	100	0.0406
10	1.0361	100	0.0383	25	1.0463	100	0.0405
11	1.0356	100	0.0381	26	1.0517	100	0.0401
12	1.0347	100	0.0392	27	1.0591	100	0.0387
13	1.0335	100	0.0391	28	1.0676	100	0.0392
14	1.0331	100	0.0368	29	1.0702	96.9	0.0428
15	1.0329	100	0.0393				

It is shown that the problem of voltage over-limit has been solved, and each node's RMS of voltage deviation is reduced, from 0.0388% to 0.0267%. The voltage fluctuation range reduce from 6% to 4.9%, and minimize network loss. This software can assist the grid operators to make scientific decisions timely and control voltage effectively to ensure the safety of the grid.

IV. Analysis of Regulating Effect under Large-Scale PV Grid Connection

According to the distribution network planning, between 2016 to 2020, this city will put more PV power plants into operation. With the increase of PV penetration, the voltage control strategies need to improve to ensure the voltage qualified, and reduce the line loss. Therefore, the analysis of simulation in different control strategies obtain the best voltage control strategy and its operation boundaries.

On the basis of the existing lines and PV power plants in this city, add other two 0.8MW PV power plants in node 13 and 18 to the distribution network. Line topology shown in Fig.7. Simulation according to the typical daily load data in this city, the maximum line load is 3.064 + j1.474MVA.

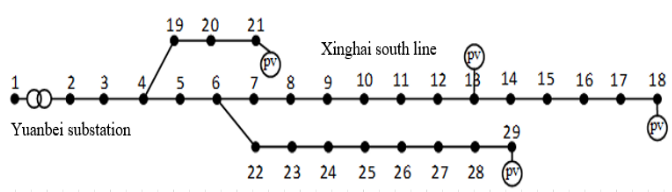

Fig.7. System topology after large-scale PV connected

In the strategy of time-sharing capacitor switching, simulating after PV connection, each node's maximum voltage, voltage pass rate and RMS of voltage deviation during 24h are shown in Table 5.

TABLE □

Voltage Statistics of Each Node during 24h before Voltage Control

N	Vmax (kV)	Pass Rate (%)	V_{RMS} Deviation (%)	N	Vmax (kV)	Pass Rate (%)	V_{RMS} Deviation (%)
1	1.0456	100	0.0279	16	1.0319	100	0.0278
2	1.0438	100	0.0272	17	1.0317	100	0.0258
3	1.0413	100	0.0272	18	1.0311	100	0.0205
4	1.0440	100	0.0285	19	1.0483	100	0.0319
5	1.0428	100	0.0287	20	1.0572	100	0.0375
6	1.0411	100	0.0259	21	1.0695	100	0.0394
7	1.0395	100	0.0291	22	1.0403	100	0.0288
8	1.0360	100	0.0289	23	1.0390	100	0.0261
9	1.0346	100	0.0287	24	1.0394	100	0.0290
10	1.0342	100	0.0266	25	1.0438	100	0.0270
11	1.0339	100	0.0274	26	1.0465	100	0.0303
12	1.0332	100	0.0283	27	1.0518	100	0.0355
13	1.0326	100	0.0268	28	1.0596	100	0.0356
14	1.0324	100	0.0247	29	1.0653	100	0.0381
15	1.0324	100	0.0292				

As it can be seen from the above table, the time-sharing capacitor switching cannot make the voltage fully qualified. PV participation or other control strategies become necessary. The effect of other voltage control strategies is shown in Table 6.

TABLE

Effect of Different Voltage Control Statistics

Voltage Control Strategy	Time-sharing Capacitor Switching	Decentralized Control	Centralized Control	Coordinated Control
Maximum Voltage(kV)	1.0719	1.0681	1.0674	1.0679
Voltage Pass Rate (%)	99.89	100	100	100
RMS of Voltage Deviation (%)	0.0338	0.0219	0.0224	0.0221
Network Loss(MW)	1.65	1.93	1.72	1.78

It can be seen from the simulation that except time-sharing capacitor switching, the other three control methods can ensure the voltage qualified. However, because of the different control strategies, the network loss is also different.

By increasing the capacity of the power station, it is found that when the capacity of the four PV plants reached 1.0MW, the decentralized control do not work, only the centralized control and coordinated control can ensure the voltage qualified. Due to the voltage quality and the network loss are not only related to the voltage control strategies, but also has an effect on the location of the distributed PV. We simulate the distribution network planning scenes, the result shows that different line flows can be calculated in the same way.

Large number of simulations obtain the principle of PV connected distribution network planning. When the total access capacity of PV is less than 1.6MW, time-sharing switching capacitor strategy is adopted. When range from 1.6MW to 4MW, decentralized control strategy is adopted. In these two case, electric communication and automation system need not to be established. However, when the capacity of PV is more than 4MW, centralized control and coordination control strategy must be adopted and the corresponding automation system must be established. Depending on the load level and the location of PV, the principle may be different.

Through the simulation of the PV connected distribution network planning, we obtain the voltage regulation strategy of different penetration. It ensures the quality of the voltage and the optimal network loss, also provides the principle of power network construction to ensure its economy.

V. CONCLUSION

This paper mainly research on PV voltage control strategy. Taking this city 10kV power distribution system as an example, it provides three voltage control strategies, namely, distributed voltage control, centralized voltage control based on component coordination, and multi-time scale coordinated voltage control. Get the following conclusions.

1) When the PV is not involved in voltage control, the voltage control system provides the traditional nine-zone voltage control strategy. The output of PV, load level and weather conditions are important factors that affect the system voltage and network loss.

2) The voltage control strategy of PV participating in distribution system can effectively reduce the maximum voltage and improve the system voltage level. With the increase of PV connection capacity, the influence of load level on the maximum voltage is gradually reduced, because the distribution network inject active power to the main network at this time.

3) As for the maximum voltage during 24h, the participation of PV control system can reducing the maximum voltage, so as to improve the PV connected grid capacity. Centralized control and coordinated control which are based on the global control play more important role than decentralized control. As for the network loss, we need to consider the limit of PV grid capacity as well as the control strategy after its connection. Make a comparison between the decentralized control based on local information, and a centralized coordinated voltage control based on global optimal consideration. The centralized voltage control does better in suppressing voltage and reducing the network loss. While the decentralized voltage control strategy cost lower, which is suitable for small PV power capacity in distribution system.

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