RESEARCH ON COORDINATE VOLTAGE CONTROL STRATEGY OF ACTIVE DISTRIBUTION NETWORK

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ABSTRACT

The intermittence and stochastic of renewable energy sources have considerably aggravated the voltage fluctuations which will also increase the difficulty of voltage control. The access and management of distributed generations (DGs) in active distribution network (ADN) provide distribution system operators (DSO) new approaches to control the voltage actively and enable coordinate voltage control (CVC). This paper illustrates the impacts of distributed generations on the existing voltage profile and control strategies of distribution network, thus puts forward a CVC strategy for voltage control. The CVC strategy is to make full use of distribution generations and other voltage adjustment devices in order to realize an efficient closed loop voltage regulation in a relatively short time. Finally, the demonstration application simulation of CVC in ADN in China sponsored by the National High-tech R&D Program is presented which validate the effectiveness of the proposed solutions.

INTRODUCTION

Active distribution network (ADN) is characterized by high penetration of distributed generations (DGs) and advanced control requirements. It can improve asset utilization and DGs' penetration by effective management on distributed energy, controllable loads and DFACTS equipment [1-2]. Voltage control is an important technique for ADN to realize highly reliable energy supply. In recent years, the development of reactive compensation technology and distributed generation control technology has brought more controllable elements to ADN. However, the penetration of DGs has been severely restricted as the voltage fluctuation caused by intermittent energy. IEEE1547 standard specifies the operating time for disconnection of DGs when voltage fluctuation occurs. Thus, an effective control strategy is needed to make better use of all voltage adjustment devices to minimize the voltage regulation time [3].

In this paper, a coordinate voltage control (CVC) strategy is proposed. The strategy will make full use of all voltage adjustment devices to realize voltage regulation. The equivalent voltage drop (EVD) index is used to achieve a more effective regulation. The feasibility and effectiveness of the CVC control strategy described in this paper are verified with simulation results of the demonstration application located in Qingzhen, China.

THE IMPACT OF DG IN DISTRIBUTION NETWORK

The voltage in traditional distribution network will gradually decrease along the feeder. After the interconnection of DGs, the voltage profile in distribution network no longer has the regularity, with which it will affect the existing voltage regulation control strategy. The impact of DGs in distribution network can be analyzed from the following two aspects, the impact on voltage profile and the impact on voltage control strategies.

The impact of DG on voltage profile

The active and reactive power injected by DGs at a certain point of the system will change the voltage profile along the feeder. This change can be either increase or decrease according to the types and control strategies of DGs. The effect of DGs for voltage profile can be simplified as an N-node distribution network, which is shown in fig.1.

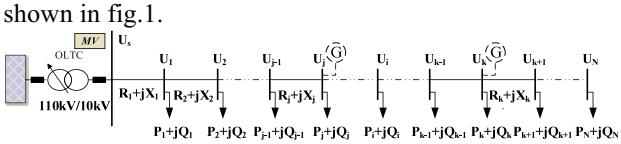


Fig.1 Diagram of an N-node Distribution Network with DG

The voltage change at the i-th node caused by DG injection at j-th and k-th node can be expressed as:

$$\Delta U_i \approx -(P_{G,j}\sum_{t=1}^{j} R_t + Q_{G,j}\sum_{t=1}^{j} X_t)/U_N - (\sum_{s=1}^{i} R_s P_{G,k} + \sum_{s=1}^{i} X_s Q_{G,k})/U_N \quad (1)$$

Here $P_{G,j}$, $Q_{G,j}$, $P_{G,k}$, $Q_{G,k}$ are the active and reactive power for the DG at j-th node and k-th node, U_N is the rated voltage. Obviously, voltage variation mainly depends on the injected power of DGs. Different kinds of DGs will bring different effects to distribution network according to their characteristics. For example, inverter-based distributed generation, such as photovoltaic, generally only generates active power considering the profit. It will cause a voltage rising when the output is large. On the other hand, a DG based on asynchronous motor, such as wind turbine, can generate active power but consume reactive power which will bring uncertain effects on voltage variation. If it maintains at a high power factor the voltage will increase. Conversely, if the power factor is low it is likely to decrease the voltage.

The impact of DGs on voltage control

In China, nine-zone diagram control method is usually applied to voltage control in traditional distribution network as the lack of measurement. When a distributed generation is connected to the network especially inverter-based distributed generation, the increase of its active power will decrease the power factor detected by the VQC device which will lead to a malfunction for capacitors and LTC in the substation.

To solve the problem, decentralized voltage control is usually applied to traditional distribution network [4]. This kind of strategies aims to adjust compensation devices based on local information without communication links. It can reduce the investment in equipment modification and avoid the adjustment for substation automation system. But the pressure on the voltage control devices is relatively large and sometimes the strategy has to sacrifice active power for voltage control, which will reduce the economic benefits.

The development of ADN provides new approaches for voltage control strategy. The control requirement of DGs in ADN makes monitoring device necessary, which inevitably provide more measurement data and controllable devices to voltage control. Some literatures have applied centralized voltage control strategy to high-voltage distribution networks and made considerable achievements [5]. These control strategies based on optimization theory (such as genetic algorithm, tabu search algorithm et.al) can take advantage of different reactive compensation equipment for voltage control when taking the optimal operation of distribution network into account at the same time. But the strategies require communication links to each node, which is not practical. And the strategies will handle large amounts of data, which will lead to a curse of dimensionality when applied to medium-voltage distribution network.

THE STRUCTURE FOR CVC

Considering the limitations of both decentralized and centralized voltage control strategies, a coordinate voltage control strategy is proposed in this paper. The structure of the strategy is shown in fig.2.

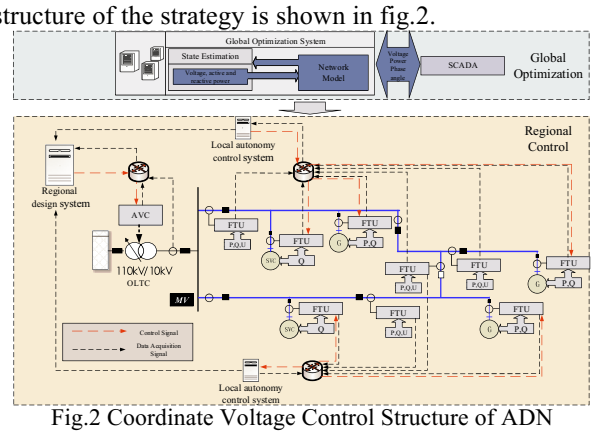


Fig.2 Coordinate Voltage Control Structure of ADN

The coordinate voltage control is combined by two parts: reactive power optimization and regional control. Reactive power optimization will be taken by global optimization system based on global information and state estimation. The optimization can be taken once a day. Regional control will be taken by local autonomy control system and regional decision system to realize voltage regulation by real-time.

Each local autonomy control system manages a separate feeder. Once the voltage violates the limitation, the system will be activated to regulate SVRs、DGs and capacitors connected to the feeder. If local autonomy control system cannot fulfill the regulation requirement, the regional decision system will adjust OLTC with the help of AVC. The management area for both regional design system and local autonomy control system can be reset by global optimization system considering both complex network structure and flexible operation mode in ADN.

THE STRATEGY FOR CVC

Strategy for reactive power optimization

The global optimization system is part of advanced distribution management system (ADMS). The system optimizes the reactive power of capacitors and the statement of tie switches for better economic benefits. The details for solution will not be discussed here, as it is not the focusing of this paper. The global optimization system will send two messages: the initial value for all devices and the management area for all subordinate control systems. The management area for regional design system and local autonomy control system will be sent by list. The list for regional design system includes control numbers for all local autonomy control systems and the AVC controlled by the system. The list for local autonomy control system includes all FTUs and DGs that can get measurement from sequentially arranged and all controllable devices that can be used for voltage regulation.

Strategy for regional control

The strategy for regional control is combined by local autonomy control strategy and regional decision strategy. The equivalent voltage drop index is proposed to achieve a more effective regulation for local autonomy control.

Strategy for local autonomy control

An important prerequisite for local autonomy control is an accurately estimation on the voltage level, to be simplified, the maximum and minimum voltage. But it is impossible to install measurement unit on every node along the feeder considering the complexity of distribution network. As shown in above section, the injection of DGs may increase the voltage at the access point. So the maximum voltage along the feeder can be got by comparing the voltage where a distributed generation or a capacitor is connected and the beginning of the feeder, which can be expressed as:

$$U_{f,i}^{\max} = \max\left(U_{DG_j}, U_{C_k}, U_0\right)$$
$$where \quad DG_j \in Ctrl\_list(LACS_i) \qquad (2)$$
$$C_k \in Ctrl\_list(LACS_i)$$

Here, U_{DG_j}, U_{C_k} are the voltage where DG_j or C_k is connected. All equipment belongs to i-th local autonomy control system $LACS_i$. U_0 is the voltage at the beginning of the feeder.

The minimum voltage along the feeder is hard to be estimated as DGs change the voltage profile. In recent years, distribution automation devices such as FTUs or DTUs have been configured along the feeder for status monitoring. The measurement supplied by these devices and by DGs provides us an efficient way for voltage estimation. In this paper, we call those nodes that can get measurement from as 'monitorable nodes'. The types of measurement data include voltage, active power and reactive power. The estimation of $U_{f,i}^{\min}$ mainly based on these measurement data. Taking into account that the devices for local autonomy control are microcontrollers, the logic for the estimation need to be simple.

Voltage sensitivity is usually used to guide the equipment action sequence for an effective voltage regulation. But the sensitivity is hard to be estimated as it will change with power variations and rather complex when there is too many equipment involved in voltage control. The estimation for voltage sensitivity will also delay the control process. To avoid this problem, the equivalent voltage drop index (EVD) is proposed to represent the maximum $U_{f,i}^{\min}$ can be with the help of reactive power compensation equipment. The index is used to make a quick and economical decision for voltage regulation using the reactive power compensation equipment in respective regions in order to avoid economic decline caused by long-distance transfer of reactive power.

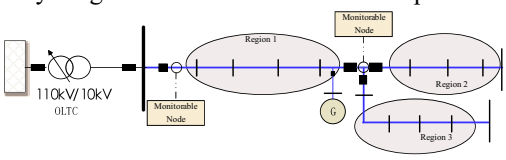


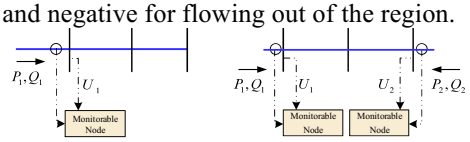
Fig.3 Distribution Automation Terminal Configuration for ADN

The process for $U_{f,i}^{\min}$ and EVD's estimation can be described based on an example shown in fig.3. Assume the feeder in fig.3 is the control area of a local autonomy control system. In this paper, the control area will be divided into several regions in accordance with the following principles:

--The bay between two 'monitorable nodes' can be regarded as a region;

--The area from a 'monitorable nodes' to the end of the feeder is also a region.

As shown in fig.3, there is two 'monitorable nodes' configured along the feeder, which divide the feeder into three regions. $U_{f,i}^{\min}$ can be estimated by comparing the minimum voltage in each region. The regions separated by 'monitorable nodes' can be divided into two categories: single-port region shown as fig.4(a) and dual-port region shown as fig.4(b). For both categories the active and reactive power are positive for flowing into the region and negative for flowing out of the region.



(a) Single-port Region (b) Dual-port Region

Fig.4 Categories for Regions

As shown in Fig.4(a), a single-port region normally locates at the end of the feeder. The minimum voltage in the region $U_{sp}^{\min}$ can be estimated as:

$$U_{sp}^{\min} = \begin{cases} U_1 - \dfrac{P_1R + Q_1X}{U_1} & when\ P_1R + Q_1X > 0 \\ U_1 & when\ P_1R + Q_1X < 0 \end{cases} \qquad (3)$$

Here, P_1, Q_1, U_1 are the active power, reactive power and voltage at 'monitorable nodes'.

The corresponding EVD for single-port region can be calculated by:

$$\underset{sp_j \in LACS_i}{EVD_j} = \begin{cases} U_1 - \dfrac{P_1R + Q_{mr}X}{U_1} & when\ P_1R + Q_{mr}X > 0 \\ U_1 & when\ P_1R + Q_{mr}X < 0 \end{cases} \qquad (4)$$

Here Q_{mr} is the minimum reactive power consumed by the region, which can be calculated by:

$$Q_{mr} = Q_1 - Q_{remain} \qquad (5)$$

Q_{remain} is the maximum reactive power can be increased by all reactive power resources in region j.

Dual-port region is shown in fig.4(b). As we cannot get any details apart from the measurement at both ends, the minimum voltage in the region $U_{dp}^{\min}$ will be estimated under the worst case thus it could be considered as a good lower bound for the minimum voltage point.

We will assume that the load in the region concentrated at one point between two 'monitorable nodes', which will cause the largest voltage drop. The position of the point can be described as:

$$U_1 - \frac{xP_1R + xQ_1X}{U_1} = U_2 - \frac{(1-x)P_2R + (1-x)Q_2X}{U_2} \qquad (6)$$

Here x is the location proportion assuming a uniform cable in the region.

The minimum voltage $U_{dp}^{\min}$ in the section can be estimated as:

$$\underset{dp_j \in LACS}{U_{dp}^{\min}} = \begin{cases} U_1 & when\ Jg_1 < 0\ \&\&\ Jg_2 > 0 \\ U_2 & when\ Jg_1 > 0\ \&\&\ Jg_2 < 0 \\ \min(U_1, U_2) & when\ Jg_1 < 0\ \&\&\ Jg_2 < 0 \\ \dfrac{Par_1R + Par_2X - Par_3}{Par_4R + Par_5X} & when\ \text{else} \end{cases} \qquad (7)$$

Here:

$$Jg_1 = P_1R + Q_1X \quad Jg_2 = P_2R + Q_2X$$
$$Par_1 = U_1^2P_2 + U_2^2P_1 \quad Par_2 = U_1^2Q_2 + U_2^2Q_1 \tag{8}$$
$$Par_3 = (P_1R + Q_1X)(P_2R + Q_2X)$$
$$Par_4 = U_1P_2 + U_2P_1 \quad Par_5 = U_1Q_2 + U_2Q_1$$

The corresponding EVD can be calculated by replace Q_1, Q_2 by Q_{mr1}, Q_{mr2} in formula (7).

Here:

$$Q_{mr1} = Q_1 - \frac{Q_1Q_{remain}}{Q_1 + Q_2} \quad Q_{mr2} = Q_2 - \frac{Q_2Q_{remain}}{Q_1 + Q_2} \tag{9}$$

The minimum voltage for the feeder can be expressed by:

$$U_{f,i}^{\min} = \min_{\substack{dp_j \in LACS_i \\ sp_k \in LACS_i}} (U_{dp_j}^{\min}, U_{sp_k}^{\min}) \tag{10}$$

It should be noticed that the estimation for both situation is not suitable when DGs and loads are concentrated and separated relatively far apart from each other. The control strategy for local autonomy control system is shown in fig.5 based on foregoing calculated parameters.

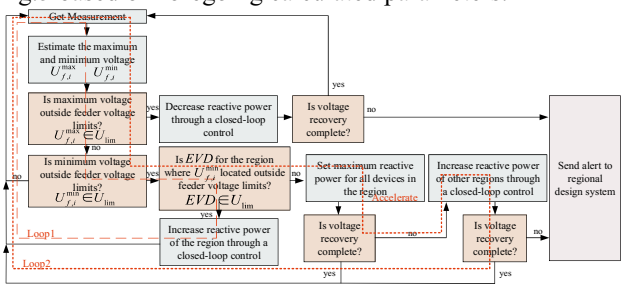


Fig.5 Control Strategy for Local Autonomy Control System

The strategy in fig.5 is mainly based on EVD. When the voltage violation is caused by slight fluctuations of intermittent energy or loads ($EVD \in U_{\lim}$), the strategy can realize an effective voltage regulation with devices in the region as shown in fig.5 loop1. On the other hand, when there is a relatively large voltage fluctuation ($EVD \notin U_{\lim}$), EVD can also accelerate the voltage regulation as shown in fig.5 loop2.

Strategy for regional design

If there is a failure for local autonomy control system, it will send an alert to regional design system. Regional design system will adjust OLTC with the help of AVC. The maximum and minimum voltage for all feeders influenced by the OLTC can be calculated by:

$$U_b^{\max} = \underset{i}{Max}(U_{f,i}^{\max}) \tag{11}$$

$$U_b^{\min} = \underset{i}{Min}(U_{f,i}^{\min}) \tag{12}$$

If $U_b^{\max} \le U_{\max} \,\&\&\, U_b^{\min} \ge U_{\min}$, where $U_{\min}$ and $U_{\max}$ are the limitation for voltage, There is no need for adjustment.

If $U_b^{\max} > U_{\max} \,\&\&\, U_b^{\min} < U_{\min}$, there is no way to recover all voltage by AVC, so it will send the alert to global optimization system

If $U_b^{\max} > U_{\max} \,\&\&\, U_b^{\min} > U_{\min}$, the tap change for OLTC can be calculated by:

$$\Delta T = ceil\left(\frac{U_b^{\max} - U_{\max}}{\Delta U_T}\right) \tag{13}$$
$$S.T.\ U_b^{\min} - \Delta T \times \Delta U_T \ge U_{\min}$$

ΔU_T is the amount of voltage change corresponding to each tap position. The constraint is to ensure the voltage limitation while tap changing.

Similarly, if $U_b^{\max} < U_{\max} \,\&\&\, U_b^{\min} < U_{\min}$, the tap change for OLTC is:

$$\Delta T = ceil\left(\frac{U_{\min} - U_b^{\min}}{\Delta U_T}\right) \tag{14}$$
$$S.T.\ U_b^{\max} + \Delta T \times \Delta U_T \le U_{\max}$$

DEMONSTRATION

The demonstration application of coordinate voltage control located in Qingzhen, Guiyang is involved with 300kW photovoltaic, 250kW wind turbines, and two 400kW/800 kWh energy storage systems, which can be presented as fig.6. The configuration of regional control systems and FTUs is also marked in the figure.

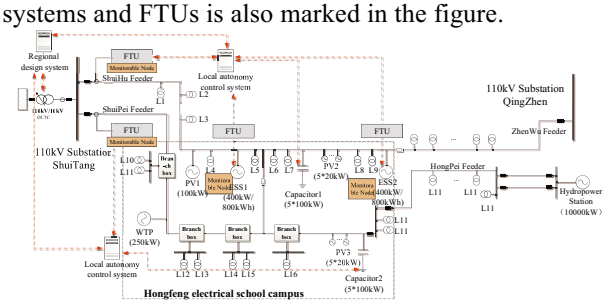
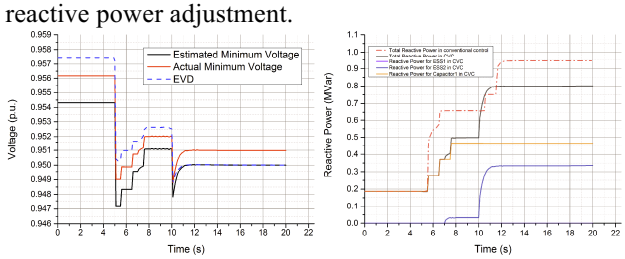


Fig.6 Demonstration Project of Coordinate Voltage Control

Several simulation results are reported to validate the proposed voltage control strategy in this section. To verify the effectiveness of the voltage estimation algorithm, the number of FTUs is reduced to only four in the simulation. For all of the following cases we assume that the maximum allowable voltage is 1.05p.u. and the minimum allowable voltage is 0.95p.u. The CVC strategy in this paper is compared with conventional voltage control strategy with DGs when all devices are activated by close loop control in fixed order.

1) Case 1: In this case we aimed to test the effectiveness of voltage control strategy when voltage was less than minimum allowable voltage and $EVD \in U_{\lim}$. Fig.7 shows the process for both voltage regulation and reactive power adjustment.



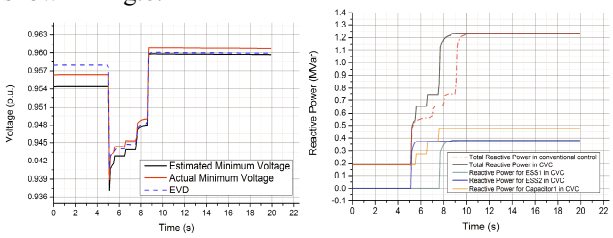
(a)Minimum Voltage & EVD (b) Reactive Power Adjustment

Fig.7 Process for Voltage Regulation of ShuiHu Feeder

The red line in fig.7(a) represents the actual minimum voltage along ShuiHu feeder measured by real FTUs and the black one represents the estimated minimum voltage. By comparison, the difference between estimated voltage and actual voltage is about 0.002p.u. Although the estimation is lower than actual value, it is still reliable enough to be the criterion for coordinated voltage control. With more FTUs configure along the feeder, a more accuracy estimation can be obtained.

When the simulation started, the voltage kept at 0.954p.u. At 5s, the load at L6 increased from 0.606MW to 1.15MW, which caused a voltage violation(0.947p.u.). As EVD index was still an allowable voltage(0.951p.u.), the devices inside the dual-port region were activated for voltage regulation. The yellow line represents the reactive power supported by capasitor1, and the blue line represents the reactive power supported by ESS2. At 10s L6 increased to 1.45MW, by this time the EVD index was less than minimum allowable voltage(0.949p.u.). So the reactive power for all devices in the region was set to maximum as shown in fig.7(b). The recovery was complete after the adjustment. The total reactive power needed for voltage regulation is shown as the black line in fig.7(b). Compared with the voltage regulation for conventional voltage control strategy shown as the red dashed line in fig.7(b), the CVC strategy uses less reactive power and realizes a faster regulation.

2) Case 2: In this case we aimed to test the effectiveness of voltage control strategy when voltage was less than minimum allowable voltage and $EVD \notin U_{\lim}$. The process for voltage regulation and reactive power adjustment is shown in fig.8.

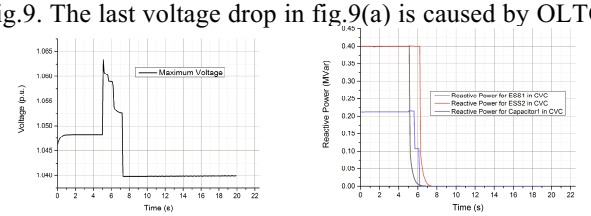


(a)Minimum Voltage & EVD (b) Reactive Power Adjustment

Fig.8 Process for Voltage Regulation of ShuiHu Feeder

The simulation in case 2 started with the same situation as case 1. At 5s, the load at L6 increased from 0.606MW to 1.93MW. The voltage violation was quite large(0.937 p.u.) which made EVD index out of the allowable voltage limit(0.942p.u.), the reactive power for all devices in the region was set to maximum at same time as shown in fig.8(b). After the adjustment the voltage was still outside the limitation(0.943p.u.). ESS1 was then used for further adjustment, which raised the voltage to 0.948p.u. As the failure for local autonomy control system happened, the regional design system set a new tap change for OLTC to complete the regulation. Compared with the voltage regulation for conventional voltage control strategy shown as the red dashed line in fig.8(b),the CVC strategy realizes a faster regulation because the strategy activates all devices in the dual-port region at the same time.

3) Case 3: In this case we aimed to test the effectiveness of voltage control strategy when the voltage was larger than maximum allowable voltage. As the maximum voltage can be measured by FTUs directly, the control strategy is relatively simple. The process for voltage regulation and reactive power adjustment is shown in fig.9. The last voltage drop in fig.9(a) is caused by OLTC.



(a)Maximum Voltage (b) Reactive Power Adjustment

Fig.9 Process for Voltage Regulation

CONCLUSION AND FUTURE WORK

A multi-layer control strategy of coordinate voltage control is proposed in this paper to achieve efficient voltage regulation for ADN. The CVC strategy can judge voltage violation based on limited measurements got by FTUs. Moreover, equivalent voltage drop index is used in the strategy to make quick and economical decisions for voltage regulation. Simulation analysis of different scenarios verified the effectiveness of the proposed strategy in regulating the voltage of multiple feeders in real-time. However, a better control effect can be obtained by replace the PI control with a more efficient control strategy, which will worth a further research.

Acknowledgments

This paper was supported by the National High-tech R&D Program of China (863 Program): 2014AA051902.

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