Dynamic Reactive Power Control Strategy of Generators Based on WAMS

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Abstract. To improve the problem of delayed voltage recovery after fault, a dynamic voltage/var sensitivity model based on integral mapping is set up and a generator excitation control strategy based on WAMS is presented in this paper. It provides voltage supporting after voltage drop through increasing the reactive power output by implementing excitation control to the generator units. According to this control strategy, the problem of delayed voltage recovery of Guangdong grid in 2014 ultimate operation mode is analyzed by using PSD-BPA, and simulation results show that the strategy is effective to shorten the voltage recovery time and improve the dynamic voltage stability of power system.

Introduction

The end-load of AC-DC hybrid power system is highly intensive, and the system is running close to its limit state, voltage stability problems have become increasingly prominent[1,2]. Wherein the delayed voltage recovery is an important cause of transient voltage stability problems. The so-called delayed voltage recovery means the system remains stable during fault transient process, but some bus voltages are at a low level, so that some voltage-sensitive load is not working properly, such as generators, motor, etc., which led to loss of load, and even cause voltage collapse[3]. The means of suppressing voltage delay recovery are fast reactive power compensation of the system side, rapid removal of the motor load of the load side, etc.

In recent years, research has been carried out around the mechanism of delayed voltage recovery. In [4] the excitation droop coefficient is optimized to achieve the improvement of grid voltage and reduce the effect of losses; in [5-7] the impact of the high side voltage control on the improvement of power system voltage stability is analyzed, and points out that the high side voltage control can effectively improve the transmission capacity of transmission lines and system dynamic voltage stability; in [8,9] the response speed of the generator dynamic reactive power is improved through the installation of the power system voltage regulator, in order to improve bus voltage recovery characteristics and the system dynamic voltage stability.

Voltage levels and reactive power is closely related. Properly regulate the reactive power output is an important method to ensure the system voltage stability [10,11]. As the system's most important source of reactive power, if generators can provide more reactive support after a system failure, that will play an important role in voltage recovery [8,9]. This article defines a dynamic voltage/var sensitivity index based on integral mapping, so as to propose a generator excitation control strategy based on WAMS. The generator dynamic reactive power control strategy table is developed by offline simulation of serious faults. When the system voltage reaches a preset criteria, WAMS will send to the relevant generators the excitation voltage step control signal to improve delayed voltage recovery. Simulation results show that the strategy is effective to shorten the voltage recovery time and improve the dynamic voltage stability of power system.

Dynamic Voltage/Var Sensitivity Index based on Integral Mapping

Integral Mapping

Mapping refers to the existence of reciprocal relationship between the two sets of elements. As Fig 1 indicates, the curve l_1 satisfies: f_1: $x \rightarrow y$, curve l_2 satisfies: f_2: $x \rightarrow y$, l_1 and l_2 respectively satisfy the functions:

$$y_1 = f_1(x) \tag{1}$$

$$y_2 = f_2(x) \tag{2}$$

$$S_1 = \int_{x_1}^{x_2} f_1(x)\mathrm{dx} \tag{3}$$

$$S_2 = \int_{x_1}^{x_2} f_2(x)\mathrm{dx} \tag{4}$$

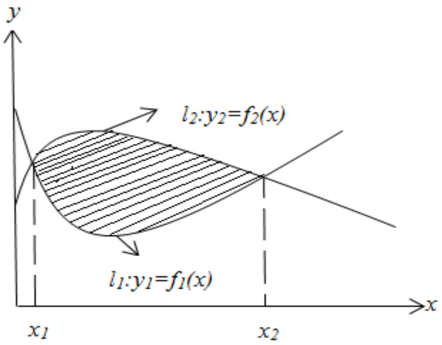

Fig. 1 Integral mapping

Integral mapping means that the mapping between two sets of elements is integral.

The shaded area S in Fig 1 can be obtained by the difference of integral mapping, i.e.

$$S = S_2 - S_1 = \int_{x_1}^{x_2} f_2(x)\mathrm{dx} - \int_{x_1}^{x_2} f_1(x)\mathrm{dx} \tag{5}$$

where x_1 and x_2 are the lower and upper limit of integration respectively.

Dynamic Voltage/Var Sensitivity Index

The difference of variables' integral mapping before and after implementation of excitation control is incremental measure. Assuming failure, the incremental measure of key bus voltage l is $\Delta\overline{V}_{li}$, which means the incremental bus voltage recovery of power plant unit i after excitation control, as (6):

$$\Delta\overline{V}_{li} = \overline{V}_{li}^{(2)} - \overline{V}_{li}^{(1)} = \int_{t_0}^{t_\mathrm{w}} V_{li}^{(2)}(t)\mathrm{dt} - \int_{t_0}^{t_\mathrm{w}} V_{li}^{(1)}(t)\mathrm{dt} \tag{6}$$

where $V_{li}^{(1)}(t)$and $V_{li}^{(2)}(t)$ denote voltages of bus l before and after the implementation of excitation control of generator i at time t. t_0 and t_w represent when failure begins and simulation finishes; and $\overline{V}_{li}^{(1)}(t)$ and $\overline{V}_{li}^{(2)}(t)$ denote integral mapping voltages of bus l before and after the implementation of excitation control of generator i. Discretized $\Delta\overline{V}_{li}$ is calculated by (7) as follows.

$$\Delta\overline{V}_{li} = [\sum_{k=1}^{N} V_{li}^{(2)}(t_k) - \sum_{k=1}^{N} V_{li}^{(1)}(t_k)]\Delta t \tag{7}$$

In order to establish the model of sensitivity of voltage to reactive power during dynamic process, not only the incremental measure of key bus voltage after fault is necessary, but also the reactive power incremental measure of power plant units after excitation control, which is calculated as (8).

$$\Delta\overline{Q}_i = \overline{Q}_i^{(2)} - \overline{Q}_i^{(1)} = \int_{t_0}^{t_\mathrm{w}} Q_i^{(2)}(t)\mathrm{dt} - \int_{t_0}^{t_\mathrm{w}} Q_i^{(1)}(t)\mathrm{dt} \tag{8}$$

where $Q_i^{(1)}(t)$ and $Q_i^{(2)}(t)$ denote reactive power of power unit i before and after the implementation of excitation control at time t. $\overline{Q}_i^{(1)}(t)$ and $\overline{Q}_i^{(2)}(t)$ denote integral mapping reactive power of power unit i before and after the implementation of excitation control. Discretized $\Delta\overline{Q}_i$ is calculated by (9) as follows.

$$\Delta\overline{Q_i} = [\sum_{k=1}^{N} Q_i^{(2)}(t_k) - \sum_{k=1}^{N} Q_i^{(1)}(t_k)]\Delta t \tag{9}$$

With voltage incremental measure $\Delta\overline{V_{li}}$ of key bus *l* and reactive power incremental measure $\Delta\overline{Q_i}$ of power unit *i*, the dynamic sensitivity index of key bus voltage to power unit reactive power after fault is defined as follows:

$$\mu_{li} = S_i \frac{\Delta\overline{V_{li}}}{\Delta\overline{Q_i}} \tag{10}$$

where S_i indicates the capacity of power plant *i*.

Dynamic voltage/var sensitivity index based on integral mapping reflects the contribution of power plants reactive power control to critical bus voltage recovery when the system voltage drops. The higher the value μ_{li} is, the more contribution the same proportion of incremental reactive power output to key bus voltage recovery.

Voltage Control Strategy based on WAMS

WAMS

Wide Area Measurement System (WAMS) consists of synchronized phase measurement technology and modern communication technology to provide complete monitoring, protection, and control of the power system. The measured quantities include both magnitudes and phase angles, and are time-synchronized via Global Positioning System (GPS) receivers. WAMS has many applications in power systems, such as data processing, power plant parameter measuring, operation status monitoring [12-16]. As a complementary system, WAMS is designed to enhance the safe and reliable grid operation [17-20].

Considering the problem of voltage recovery, this paper proposes a multi-machine voltage control strategy based WAMS, which requires real-time monitoring of key bus and generator terminal voltage, and WAMS can provide an effective means of monitoring.

Dynamic Reactive Power Control Strategy

In order to improve delayed voltage recovery, reactive power output during the dynamic process can be increased through generator excitation voltage step control. Taking into consideration the dynamic sensitivity index of key bus voltage to power unit reactive power after fault, the control problem is equal sorting the sensitivity index, which can quickly and effectively choose the power plants that participate in excitation control, and form the dynamic generator reactive power control strategy table under serious failure.

In practice, the maximum of reactive output of generator has been considered:

$$\Delta\overline{Q_{li}} \le (\Delta\overline{Q_i})_{\max} \tag{11}$$

Meanwhile, the safety range of generator terminal voltage has also been taken into account:

$$V_i \le (V_i)_{\max} \tag{12}$$

The flowchart of multi-machine excitation voltage control based on WAMS is shown as Fig. 2:

In Fig 2, power plants involved in excitation control are selected according to dynamic voltage/var sensitivity index. Excitation voltage steps are chosen within the generator terminal voltage safety range.

In order to decide to what extent to start excitation control, the key-bus-voltage-drop-after-fault index K_{D} and the key-bus-voltage-recovery index after fault clearing are defined, making the start criteria of multi-machine excitation voltage control after fault.

K_{D} represents the voltage drop rate after bus voltage fault in unit time, reflecting the post-fault bus voltage drop of speed, which is calculated as (13):

$$K_{\mathrm{D}} = \frac{\Delta V}{\Delta t} = \frac{V_{t_{\mathrm{G}}} - V_{t_{\mathrm{D}}}}{t_{\mathrm{D}} - t_{\mathrm{G}}} \tag{13}$$

where t_{G} is the time when fault happens, t_{D} is the time when the bus voltage falls to the minimum; $V_{t\mathrm{G}}$ and $V_{t\mathrm{D}}$ are the bus voltage p.u. when fault happens and ends respectively; The unit of voltage drop is p.u./s. When PMUs monitor the key bus voltage drop index K_D is beyond the threshold K_0 and the key bus voltage recovery index after fault clearing is under the threshold u_0, orders are sent to certain power plants to start the excitation voltage step control.

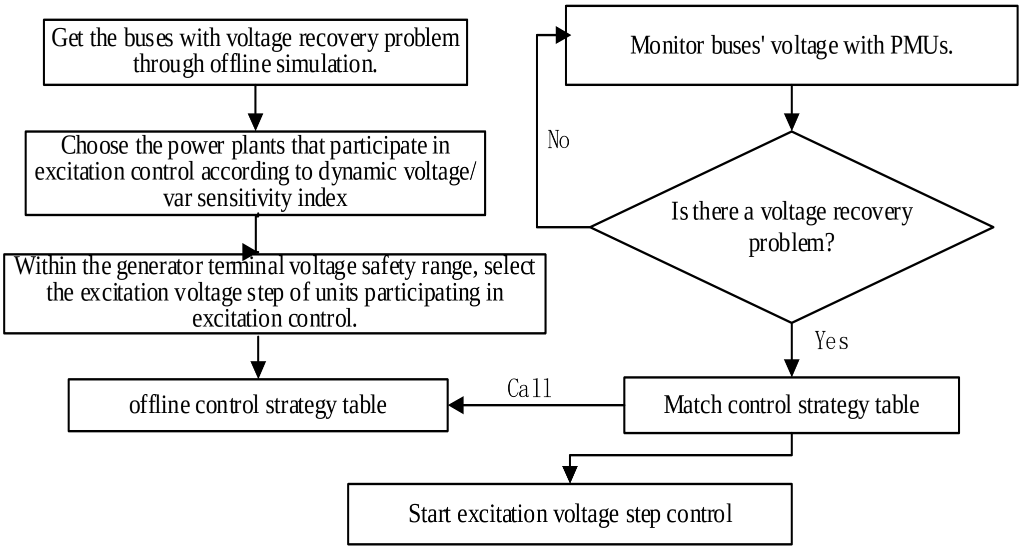

Fig. 2 Multi-machine voltage control strategy flowchart

Simulation

The multi-machine control strategy based WAMS is verified by PSD-BPA simulation. The problem of delayed voltage recovery of Guangdong grid in 2014 ultimate operation mode is analyzed as follows.

When three-phase permanent short circuit happens at the Shunde side of Shunde-Jiangmen line (fault A for short), the bus voltage of 220kV Tengsha station is as Fig.3 shows:

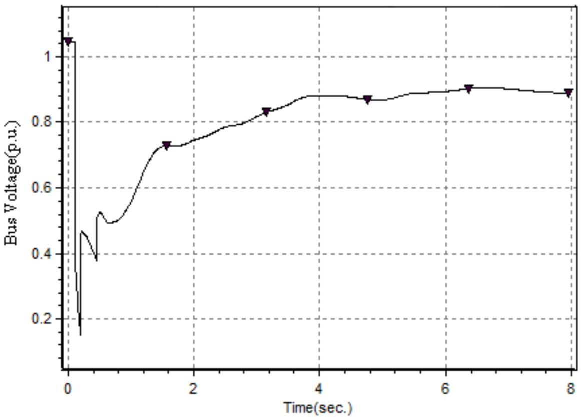

Fig. 3 Bus voltage of 220kV Tengsha Station after fault A

Fig 3 indicates that the bus voltage of Tengsha station after fault A exists delayed voltage recovery problem, and the voltage is always lower than 0.95p.u..

Units with the top 7 highest dynamic voltage/var sensitivity index near Shunde station are shown in Table 1.

A large number of simulation under different operation modes were analyzed to find the recommended threshold voltage drop index K_0=8.0p.u./s and voltage recovery index u_0=0.6p.u.. According to the WAMS real-time monitoring data, when the fault occurred (0.1 s), the bus voltage amplitude was 1.025 p.u., the voltage dropped to the minimum amplitude (0.152 p.u.) at 0.2s. When the fault was cleared (0.45 s), the bus voltage magnitude was 0.471 p.u.. According to (13), the bus voltage drop rate of 220kV Tengsha station was 8.73p.u./s, fulfilling the excitation control start criterion. At 0.4s after the failure, WAMS sent commands to start excitation voltage step control of the above seven selected units.

Excitation control step was chosen to be 4%, 3%, 2% and 1%. After the 7 units mentioned above participating in excitation voltage control, the voltage recovery time (to 0.95p.u.) of 220kV Tengsha station was shown as Table 2.

Table. 1 Top 7 units based on sensitivity

Units	μ_{li} [MW • kV • MVar^{-1}]
Zhuhai B	64.691
Hengmen B	36.309
Hongwan	30.696
Nanlang	28.809
Zhuhai A	23.094
Tonggu B	21.834
Yangjiang(nuclear)	20.627

Table. 2 Bus voltage recovery time of 220kV Tengsha station after excitation control

Excitation Control Step	Voltage Recovery Time(to 0.95pu)[s]
4%	3.76
3%	3.89
2%	3.94
1%	4.71

Table 2 shows that when the excitation voltage control step is 4%, the voltage recovery time (to 0.95p.u.) of 220kV Tengsha station is shortest, which indicates that the higher the excitation voltage control step, the shorter the voltage recovery time. But if the control step were high enough, terminal voltage of unit might be a bit high, as Fig 4 shows.

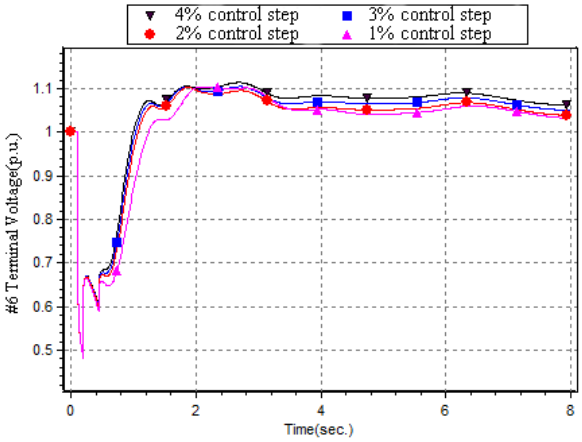

Fig. 4 Terminal voltage of Tonggu B No.6 under different step control

In Fig 4, when the excitation voltage control step is 4% or 3%, the #6 generator' voltage of Tonggu B plant exceeds 1.05p.u. to the end. Therefore, taking into account the safety range of generator terminal voltage, the excitation voltage control step should be appropriately low down. However, in order to ensure the quality of recovery after voltage control, the excitation voltage control step is set to be 2%.

To verify the above conclusion, let the excitation voltage control step of the power plant units of Table 1 to be 2%, simulation results are shown in Fig 5. Before the implementation of excitation control, the bus voltage of Tengsha station is always lower than 0.95p.u., but after the implementation of excitation control, the time of 220kV bus voltage recovery to 0.95p.u. of Tengsha station is 3.94s, significantly improving the voltage recovery and enhancing the system dynamic voltage stability. In practical engineering applications, PMUs are used to monitor system bus voltage, when fault occurs and the bus voltage drops to meet preset criteria, WAMS sends commands to certain power plants to participate in the excitation control.

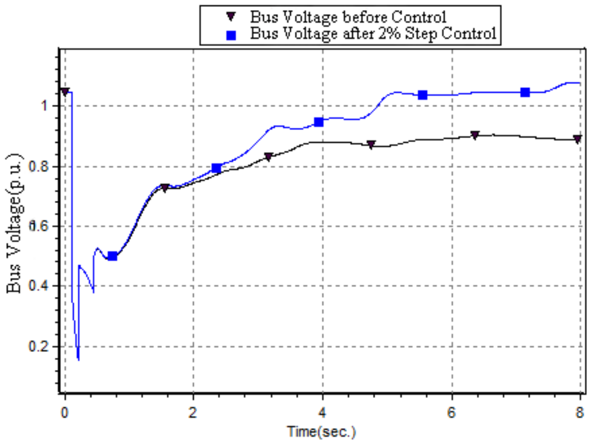

Fig. 5 Bus voltage recovery curve of 220kV Tengsha station under 2% excitation voltage step control

Conclusion

To improve the problem of delayed voltage recovery after fault, a dynamic sensitivity index of key bus voltage to power unit reactive power after fault is defined and a multi-machine voltage control strategy based WAMS is proposed. The problem of delayed voltage recovery of Guangdong grid in 2014 ultimate operation model is analyzed by using PSD-BPA, and simulation results show that the proposed strategy is effective for rational selection of plants involved in reactive power control after grid fault, revealing important application value for improving bus voltage recovery.

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