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Analysis on micro-grid AVC control strategy based on optimization equipment action times

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ABSTRACT

In this paper, on the basis of hierarchical & zonal control strategy of conventional automatic voltage control(AVC) system, a load predication process and a diagnosis process for current electrical control status were added to enhance the predictability of the control strategy, realizing the advanced control and reducing the equipment action delay according to equipment current operation status. The newly-developed AVC system has been put in application of smart-grip in Wuhu region of Anhui province, and the experimental results shows that this new system possesses a excellent effects in increasing the qualified rate of regional network voltage and in enhancing the reactive power optimization. The new system optimized the equipment action times in terms of the whole time series, and substantially reduced the equipment damage accidents due to the over-frequent actions and thus increasing the equipment life span.

KEYWORDS

AVC; Load prediction; Advanced control; State diagnosis; Action times.

INSTRUCTION

Voltage quality is not only an important referential factor in reflecting the operation status of power system[1], but also possesses effects for the working equipment of the entire smart grid. With the rapid development of power system automation and communication technology, the AVC technology based on EMS/SCADA system gains an increasing application, which can conduct a real-time and effective reactive compensation for the power system and thus establishing a technological method in guaranteeing the safe and effective operation for the smart grid[2].

At present, the conventional power grid AVC is operated mainly for the current time sections status of power system, which takes no consideration of the historical experiment and future trends of power system[3,4]. Therefore, some problems emerge inevitably including frequent equipment switching, low utilization of equipment, non-optimized equipment action times. In reference[5], a Voltage Quality Control(VQC) thought takes consideration of load variation trend while ignores the equipment action status and the constraint of equipment max action times. In reference[6], the acceleration factors and inertia factors are adopted for the analysis of threshold-crossing time length of reactive power, time interval of continuous action and voltage. Eventually, A diagnose function method was proposed for identifying equipment operation status (permissible action and impermissible action). This method can effectively prevent transformer taps and container/reactor group from frequently switching on and off, while at the meantime, it brought over ten minute delay, making obstacles to the real-time and effective reactive voltage control of AVC.

Gaining an increasing application in current power substation, the integrated automation system help to realize real-time transformation of power network monitoring, and store the load number record of corresponding stage. In addition, the generalization of integrated automation system will realize the load prediction in ultra-short period and short period. Based on conventional hierarchical control & zonal control strategy, with comprehensive consideration of load variation trend, this paper add an diagnosis section of electrical control properties according to the current running status of transformer taps and capacitor/reactor group. An AVC strategy based optimized equipment actions times was proposed, which allows control strategies to possess predictability. The AVC strategy realizes the advanced control according to equipment operation status, optimizes equipment action times in entire time series, increases equipment use ratio, and plays an vital role in increasing equipment life span.

REACTIVE POWER OPTIMIZATION MODEL

The integrated dynamic reactive power optimization model should be established by accounting the constraints of action times of compensation devices including transformer taps and capacitor/reactor(among which, the load prediction level of overall optimization is calculated by hour as the basic unit.) In addition, the existed variable distribution properties of equipment in operation status should be taken into consideration, which in fact belongs to research topic of mixed non-linear integer programming problem.

In the system, suppose there are total number of joints is n, the number of on-load tap changer is u, the number of adjustable voltage generator is m, and the switched capacitors/reactors group are installed on joints with number of n. Every 5 min as a section, the whole-day active & reactive power change curve of entire power network bus were divided into 287 sections according to the criterion, therefore, regarding min system power loss of whole day as the purpose, the reactive power optimization model can be described as[7]:

$$\min \sum_{t=0}^{287} f(x_{1(t)}, x_{2(t)}, x_{3(t)}) \quad \textbf{(1)}$$

Equality constraints：

$$s.t.\, g(x_{1(t)}, x_{2(t)}, x_{3(t)}) = 0$$

$$t = 0,1,\cdots,287 \quad \textbf{(2)}$$

Inequality constraints：

$$x_{i(t).\min} \le x_{i(t)} \le x_{i(t).\max}$$

$$i = 1,2; t = 0,1,\cdots,287 \quad \textbf{(3)}$$

$$\sum_{t=0}^{287} | x_{1(t+1)} - x_{1(t)} | \le S_{x1} C_{x1} \quad (4)$$

In the equation: $f(x_{1(t)}, x_{2(t)}, x_{3(t)})$ is the power grid active power loss during time period of t; $g(x_{1(t)}, x_{2(t)}, x_{3(t)}) = 0$ is the node power balance equation for the time period of t, $g(x_{1(t)}, x_{2(t)}, x_{3(t)}) \in R^{(2n)}$; $x_{1(t)} = [Q_{C(t)}^T, T_{B(t)}^T]^T$, are the column vectors constructed by discrete variables in time period of t, $x_{1(t)} \in R^{(p)}$, $p = r + u$; $Q_{C(t)}$ is the reactive power output column vector of switched capacitor/reactor group in time period of t, $Q_{C(t)} \in R^{(r)}$; $T_{B(t)}$ is the change ratio column vector of on load tap changing transformer in time period of t, $T_{B(t)} \in R^{(u)}$; $x_{2(t)} = [Q_{G(t)}^T, U_{B(t)}^T]^T$ are the column vector consisted of continuous variables in time period of t, $x_{2(t)} \in R^{(q)}$, $q = m + n$; $Q_{G(t)}$ are the column vector constructed by electric generator reactive power output in time period of t, $Q_{G(t)} \in R^{(m)}$; $U_{(t)}$ are the column vectors constructed by node voltage magnitudes in time period of t, $U_{(t)} \in R^{(n)}$; $x_{3(t)} = [P_{G(t)}, \theta_{(t)}]^T$, $x_{3(t)} \in R^q$, $q = m + n$, $P_{G(t)}$ are the column vectors constructed by electric generator active power output in time period of t, $P_{G(t)} \in R^{(m)}$, $\theta_{(t)}$ are the column vectors constructed by phase difference between tested nodes and balance nodes in the period of t, $\theta_{(t)} \in R^{(n)}$, $x_{3(t)} \in R^q$。C_{x1} are the column vectors constructed by constraint values of max action times of controlling devices (on load tap changing transformer and capacitor/reactor group) in time period of t, $C_{x1} \in R^p$; S_{x1} are diagonal matrix, of which the diagonal elements are respectively related to the reactive power output of capacitor/reactor group and the adjusted step length of OLTC change ratio, $S_{x1} \in R^{(p \times p)}$.

The equation (4) shows the constraints of whole-day action times for switched capacitor/reactor group and OLTC taps. The action times of switched capacitor/reactor group(or OLTC taps) in each time period can be explained as follow: the action time can be obtained through dividing the absolute difference between reactive power outputs in ending point and starting point by related adjusting step length[8].

AVC CONTROLLING MODE

From the perspective of mathematics, in above mentioned model, there are many inequality and equality constraints and discrete variables as well, which belongs to complex non-linear programming issue. In reference[7,8,9],the prime-dual interior point method was adopted in order to obtain the global optimal solution of reactive power optimization. However in practical application, there are difference between reactive power controlling methods, and due to the non-linear effect and regional distribution,, it is difficult to acquire reactive power optimization results, and it is not suitable to adopt the solution for solving issues of the conventional micro-increment rate of network loss, which therefore damp the practical application effect, creating obstacles for engineering analysis. In the paper, the regional power network AVC use conventional hierarchical and zonal thinking for reference (Hierarchic thinking is to divide grid according to voltage levels; Zonal thinking means Based on regional characteristics of reactive power balance, by setting 220kV transformer station as center, circle the transformer station, substation and sub-equipment in the same zone) to establish the controlling model integrated with constraints of device action times for purpose of increasing voltage qualified ratio and reducing network loss. According to the distribution status of voltage reactive space of power system, the AVC system conducts the level classification and region classification through PAS network modeling. The controlling mode place priority on the mode of "regional voltage optimization control", if the controlling mode cannot meet the requirements, it will turn into the mode of "corrective control on all levels of voltage", however if still cannot meeting the requirements, the mode of "regional reactive power optimization control" can be adopted. In the case of the regional voltage is either over high or over low, the model of "regional voltage optimization control" is the first choice, which can quickly optimize the voltage level of pilot node in corrective system; If the voltage in all levels cross the limits, the model of "voltage corrective control" should be adopted to firstly secure the qualification of node voltage level. After the voltage levels of entire power network are qualified, the economical operation should be taken into consideration, adopting the model of "regional reactive power optimization control"[11], which is shown in Figure 1

According to the analysis of previous voltage adjusting situation, it is suggested to adopt the inter-working of regional voltage optimization control and local voltage control. This strategy can realize voltage qualification in the whole region by directly adjusting the equipment in central substation(220kV) for one time, which also effectively reduce the equipment action times in sub-level power substation.

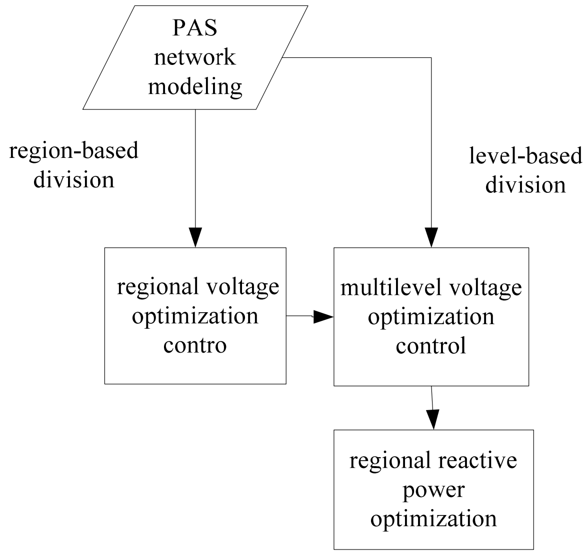

Figure 1 : Control working mode figure of AVC

ADDED PROCESS

Load prediction process

Automatic controlling system can improve the working quality in power substation. In addition, due to the characteristics of huge storage capacity and retest function, the automatic controlling system can master load data of power network more precisely and give a prediction on load variation trend of power network[12].

Assuming that the action delay value of reactive power compensation controlling device is T_S , Therefore when the reactive power voltage crosses the constraints, the duration ΔT for crossing constraint can be calculated using the predicted load curve. Also, after calculation of duration ΔT , it can estimate whether to adjust switched container/reactor group and transformer taps according to the duration value. Regarding the power quality and electromagnetic phenomenon, IEEE has already conducted specific classification[13,14], from which it can been known that the generally recognized variation range of short duration voltage is from 3s to1 min, therefore suppose T_S is 60s, and the effect of transformer taps adjustment on reactive power can be ignored, while if the duration is under 60s, there is no need for transformer taps to make any action; If the duration of reactive power and voltage crossing constraints are both under 60s, the container/reactor group are suggested to make no actions temporarily[5].

TABLE 1 : Analysis of operation criterion for equipment

Conditions	*judgment*	*Action or no action*
$\Delta T < T_S$	Emerge short time jitters in load variation, non-economical for equipment action	No action
$\Delta T > T_S$	Duration of load crossing constraints is relatively long, timely adjustment is suggested	Action

Based on the identification results on load level and load variation trend in each time period of whole day, the advanced control strategy was analyzed, which coordinated the equipment actions in all time periods, filtered voltage reactive power jitters, and reduce action times and action delay under the condition of meeting requirements of voltage reactive power operation.

Diagnosis process on equipment electrical properties

In order to prevent equipment from losing adjusting ability too early due to over frequent actions, a balance process was proposed regarding equipment action times. Regarding the balance process on equipment action times, in the reference[6], the daily max allowed action times $N_{\max}$ was divided equally into 24 sections with the consideration of practical load variation situation and voltage regulation characteristics of transformer taps and capacitor/reactor group. However in this paper, according to practical situation of power network operation, proper controlled objects and priority were selected, and the $N_{\max}$ was in weight allocation according to predicted load variation situation.

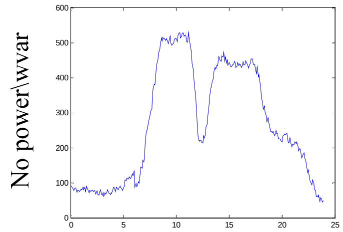

Figure 2 : Daily reactive load curve

From Figure 2, it can be seen that normally the daily reactive load can be divided into low load period and peak load period, in which the low load period is from 23:00-8:00 of the next day, while the peak load period is from 8:30 to 23:00 of the same day. In addition, in view of realizing systematic capacitive reactive power balance during low load period, multi-groups of reactors can be put into operation, therefore, the reactor group should be allocated with more action times during low load period. In this paper the weight ratio was set:4:1, which means the capacitor group (reactor group) action times account for 80% of whole day action times during the peak load period (low load period).

According to different adjusting characteristics of transformer taps, the max daily allowed action times $N_{\max}$ of transformer taps was divided equally into 24 sections.

Regarding following 3 situations:

(1) Equipment reaction time intervals was shorter than allowed min reaction time intervals, which is transmitted from the AVC system through remote interface.

(2) (2)The counter shows that The action times of a certain electrical equipment reaches the allocated action times limits during time period where it is.

(3) (3)The counter shows that total action times of the very day reaches the allowed max daily action times $N_{\max}$.

In the case of diagnosing the electrical properties of transformer taps and capacitor/reactor group, any of above mentioned situation appears, it is suggested shut equipment(i.e the diagnosis result is no action).

CASE ANALYSIS

The added load prediction process and diagnose process of equipment status were adopted in the designment & development of power network AVC system in Wuhu city, Anhui province. The flow diagram of AVC system is shown as follow:

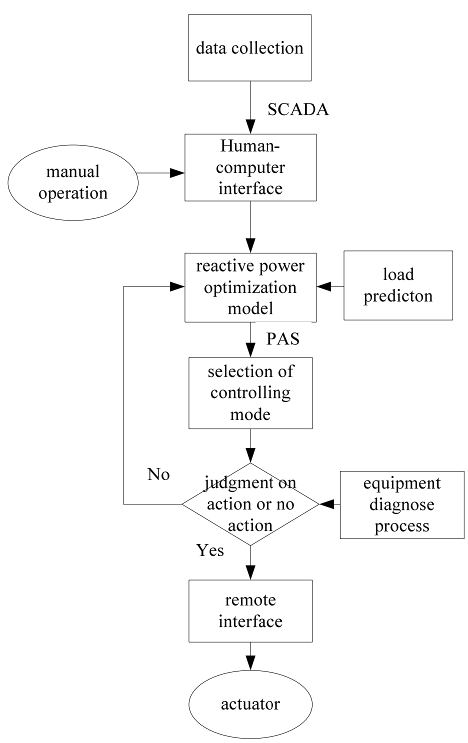

Figure 3 : The AVC system flow diagram of wuhu power grid

Integrated with OPEN 3000 EMS platform, the AVC system obtains real time collected data. Through combining the load prediction value during ultra-short period, obtaining controlling mode by PAS network modeling, with the purpose of the max voltage qualified rate and lowest power network loss, taking busbar voltage, qualified power and lowest action times of transformer taps and capacitor/reactor as constraint conditions, through calculation and analysis on issue of whole power network reactive power optimization, it distributes real-time controlling strategy. And through combining the remote adjusting function of SCADA system, the AVC can conduct closed-loop control regarding the transformer taps and capacitor/reactor of the system.

TABLE 2 : Results analysis of power grid operation before AVC input

Time	Qualified rate of whole day voltage（%）	Qualified rate of whole day power factor（%）	Whole day equipment action time
Monday	99.12	99.52	210
Tuesday	100	99.89	213
Wednesday	98.91	99.21	221
Thursday	99.54	99.76	215
Friday	100	100	213
Saturday	99.35	99.78	220
Sunday	98.54	99.15	218

TABLE 3 : Results analysis of power grid operation after AVC input

Time	Qualified rate of whole day voltage（%）	Qualified rate of whole day power factor（%）	Whole day equipment action time
Monday	100	100	153
Tuesday	100	99.89	155
Wednesday	99.31	99.71	155
Thursday	99.32	100	154
Friday	100	100	151
Saturday	99.75	100	157
Sunday	99.32	99.61	161

According to TABLE 1 and TABLE 2, due to the advanced controlling strategy of load prediction in the paper, the "jitters" of short time load variation can be effectively filtered and the equipment action times can be substantially reduces. Before AVC system input, the weekly average action times of electrical equipment is 215, while after input of AVC system the weekly average action times is 155, therefore the optimized proportion reaches 30%. Since the diagnose process on electrical equipment was added in the paper, it can allocate proper action times according to practical load variation situation and the voltage adjusting characteristic of transformer taps and capacitor/reactor group. And by taking timely locking measurement on equipment, it can effectively realize security equipment operation. Before input of AVC system in 2012, there are totally 13 power network damage cases in Wuhu region including capacitor damage, capacity switcher damage, reactor damage, capacitor secondary coil burn. While after AVC system input in 2013, the annual total power network damage case is only 2 in Wuhu region.

In addition,the qualified rate of voltage and power factor in Wuhu power network has been obviously increased also due to the system load prediction results being integrated into the control strategy. Non-delay control system is determined according to the load variation trend, and thus increasing the qualified rate of voltage and power factors.。

CONCLUSION

Through specific analysis on load prediction, A reactive power advanced control strategy was proposed in this paper, which realize the self-classification of load variation according to load prediction of power network, and further determine the weight coefficients of daily allowed max action times $N_{\max}$ in different periods of a day according to different load trends. Meanwhile, by adopting counter, the system action times were limited. and Through integrating controlling properties in real time operation status of equipment, the database of alarming cases and protection cases was established, which realized the timely automatic shut-off movement for electrical equipment out of control. The strategy avoided the over-frequent actions of primary equipment, optimized the action times of electrical equipment, reduced the risk of equipment damage, prolonged the equipment life span, all of which reflects the advancibility and intellectuality of system.

Taking application of the strategy into Wuhu power network, it demonstrated that the reliability and stability of the system in practical field, which can promote the development of power network.

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