

Study on Coordinated Optimization of the Gird Voltage Control Strategy Considering Comprehensive Cost

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Abstract: The spoilage of the discrete reactive power devices such as shunt capacitor or on-load tap changer by control are far greater than that of the continuous reactive power devices such as generator or SVG. To reduce the comprehensive cost including the gird loss and the device spoilage, This paper proposed a novel gird voltage control coordinated optimization strategy. The comprehensive cost including the gird loss and the device spoilage is used as an objective function. The corresponding calculation method based on improved genetic algorithm is presented. The proposed strategy would be combined with the three-level voltage control mode of existing AVC systems. The simulation contrast results in IEEE-14 system show that the proposed strategy is more reasonable than the traditional control strategy without consideration of the discrete reactive power devices spoilage. Especially in the case of network load periodic change, the repeated controls of the discrete devices are effectively avoided by using the proposed strategy.

1. Introduction

The system of automatic voltage control (AVC) [1] is used to control the grid voltage and reactive power. It could regulate the reactive power equipment automatically, improves the voltage quality, reduces the loss, and ensures the safe and high-quality operation of the grid [2]. The grid reactive power equipment includes various types of continuous devices and discrete devices. The former includes various types of generators, dynamic reactive power compensation equipment and other continuous equipment. The latter includes shunt capacitor/reactor, on-load tap-changer and other discrete equipment.

The AVC system only controls continuous or discrete devices in early period. With the development, the global coordinated control mode [3] of AVC system has replaced the distributed control mode. Both of continuous and discrete equipment would be coordinated controlled. The control principle is proposed [4]. That is priority adjustment by discrete device and fine adjustment by continuous devices. This principle has become the mainstream in existing AVC system [5].

The spoilage of the discrete reactive power devices by control are far greater than that of the continuous reactive power devices. The continuous devices are controlled by power electronic components such as thyristors. The control has less effect on the reduction of continuous device life [6]. The discrete devices are controlled by mechanical components. The number of controls directly determines the discrete device life.

To reduce the comprehensive cost including the gird loss and the device spoilage, a novel gird voltage control coordinated optimization strategy is proposed in this paper. The proposed strategy would be



combined with the three-level voltage control mode of existing AVC systems [7]. The calculation method is given. And the comparative simulation calculations are performed on the IEEE14-node system to verify the effectiveness of the proposed strategy.

2. Comprehensive cost analysis of power grid

2.1 Grid gird loss cost model

Power grid [8] loss P_{loss} is mainly the line loss of power transmission, the formula of P_{loss} is given as follows:

$$P_{\text{loss}} = \sum_{i,j} G_{ij} [V_i^2 + V_j^2 - 2V_i V_j \cos(\theta_i - \theta_j)] \quad (1)$$

where, i and j are the node numbers of the grid branch ij . G_{ij} is the branch conductance. V_i , V_j , θ_i , and θ_j are the voltage amplitudes and phase angles of nodes i and j , respectively.

The cost caused by the loss of the unit network assumed to be λ . The calculation formula of the grid loss cost F_1 is given in time T as follows:

$$F_1 = \lambda \int_T \left(\sum_{i,j} G_{ij} [V_i^2 + V_j^2 - 2V_i V_j \cos(\theta_i - \theta_j)] \right) dt \quad (2)$$

2.2 Equipment spoilage model

As far as discrete equipment is concerned, the controls number of the circuit breakers and taps is much greater than the electrical parts of the equipment. Therefore, the spoilage of the discrete equipment is mainly the spoilage of circuit breakers and taps.

The service life of circuit breakers and taps is related to a number of factors such as the number of movements of mechanical components and the running time of equipment. The number of movements of mechanical components is much greater than the other factors. Therefore, the service life of circuit breakers and taps can also be represented by the number of mechanical device design operations.

Within the time T , the cost of the equipment transportation inspection caused by the k -th parallel capacitor/reactor investment/cutting operation of node n is $F_{k,n}$.

$$F_{k,n} = \frac{C_{k,n}}{N_{k,n}} \int_T |y_{k,n,t} - y_{k,n,t-1}| dt \quad (3)$$

$$F_{ml} = \frac{C_{ml}}{N_{ml}} \int_T \frac{|z_{ml,t} - z_{ml,t-1}|}{\Delta z_{ml}} dt \quad (4)$$

where, C is the life cycle cost of the corresponding discrete device, N is the number of mechanical device design actions corresponding to the discrete device, that is, the service life of the device, and y is the shunt capacitor/reactor circuit breaker status ($y=0$, the breaker is open, $y=1$, is the circuit breaker is closed), z is the variable ratio of on-load adjustable transformer, Δz_{ml} is the variation ratio value of the gear ratio of the tap changer of the on-load tap changer transformer between nodes m and l , t and $t-1$ are the current control time and the previous time.

2.3 Comprehensive network cost model

From the perspective of full life economic operation of the power grid, the comprehensive cost of the grid should include the Grid Gird Loss costs and equipment transportation inspection costs. According to equations (2), (3) and (4), the total cost of the grid F within the time T is calculated as follows:

$$\begin{aligned}
F = F_1 + \sum_n \sum_k F_{k,n} + \sum_m \sum_l F_{ml} = \\
\lambda \left\{ \int_T \left(\sum_{i,j} G_{ij} [V_i^2 + V_j^2 - 2V_i V_j \cos(\theta_i - \theta_j)] \right) dt \right. \\
+ \sum_n \sum_k \alpha_{k,n} \int_T |y_{k,n,t} - y_{k,n,t-1}| dt \\
\left. + \sum_m \sum_l \beta_{ml} \int_T |z_{ml,t} - z_{ml,t-1}| dt \right\}
\end{aligned} \tag{5}$$

where, $\alpha_{k,n} = C_{k,n} / (N_{k,n} \times \lambda)$ is the ratio of cost to cost per unit of network loss for the k -th group of parallel-connected capacitor/reactor single-action at node n . $\beta_{ml} = C_{ml} / (N_{ml} \times \Delta z_{ml} \times \lambda)$ is the ratio of the cost to the cost per unit network loss for a single action of the on-load tap changer tap between nodes m and l .

The formula for calculating the unit time grid comprehensive cost f is given as follows:

$$\begin{aligned}
f = \frac{\partial F}{\partial t} = \lambda \left\{ P_{loss,t} + \sum_n \sum_k \alpha_{k,n} |y_{k,n,t} - y_{k,n,t-1}| \right. \\
\left. + \sum_m \sum_l \beta_{ml} |z_{ml,t} - z_{ml,t-1}| \right\}
\end{aligned} \tag{6}$$

3. Automatic voltage control coordination optimization strategy

3.1 Coordination optimization strategy mathematical model

This paper proposes a coordinated automatic voltage control coordination optimization strategy with the goal of reducing the overall cost of the grid. The total cost f of the grid per unit time given by equation (6) is used as an objective function. The mathematical model is given as follows:

$$\begin{aligned}
\min f(x, y, z) \\
\begin{cases} g(x, y, z) = 0 \\ h^{\min} \leq h(x, y, z) \leq h^{\max} \end{cases}
\end{aligned} \tag{7}$$

where, x is the expected value of reactive power output of continuous equipment and shunt capacitor/reactor equipment, y is the shunt capacitor/reactor circuit breaker status, z is the ratio of on-load adjustable transformer, x , y , and z are the control variables of the optimized strategy; $g(x, y)$ is the boundary condition of the equation, and $h(x, y)$ is the boundary condition of the inequality.

The mathematical model of $g(x, y)$ is shown in Equation (8):

$$\begin{cases} P_i - V_i \sum_{j \in i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0 \\ \sum x_{k,i,t} - Q_i - V_i \sum_{j \in i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0 \\ x_{k,n,t} = y_{k,n,t} V_n^2 B_{kn} \\ V_m / V_l = z_{ml,t} \end{cases} \tag{8}$$

where, $x_{k,i,t}$ is the reactive power output expected value of the k -th continuous device or shunt capacitor/reactor device that is connected to node i , B_{kn} is the k -th group of node n shunt capacitor/reactor branch susceptance.

The mathematical model for $h(x, y)$ is shown in Equation (9):

$$\begin{cases} x_{k,i}^{\min} < x_{k,i,t} < x_{k,i}^{\max} \\ |x_{k,i,t} - x_{k,i,t-1}| < \Delta x_{k,i} \\ z_{ml}^{\min} < z_{ml,t} < z_{ml}^{\max} \\ |z_{ml,t} - z_{ml,t-1}| < M * \Delta z_{ml} \\ V_i^{\min} < V_i < V_i^{\max} \end{cases} \quad (9)$$

where, $x^{\max}$ and $x^{\min}$ are the reactive output upper and lower limits of the continuous device or shunt capacitor/reactor device, respectively, and Δx is the reactive power adjustable step length per unit time;; $z^{\max}$ and $z^{\min}$ are the upper and lower limits of the on-load tap changer transformer, respectively. Δz is the change ratio of the gear ratio change of the load tap changer transformer between the nodes m and l . M is the adjustable number of taps of on-load tap changer transformer tap per unit time. $V^{\max}$, $V^{\min}$ are the node voltage upper and lower limits, respectively.

By formulae (6)~(9), the automatic voltage control of the power grid is transformed into a problem of minimizing the overall cost of the grid per unit time, and the continuous and discrete variables with the boundary conditions are coordinated and optimized.

3.2 Coordination and optimization control system

The proposed strategy would be combined with the three-level voltage control mode of existing AVC systems, as shown in Figure 1.

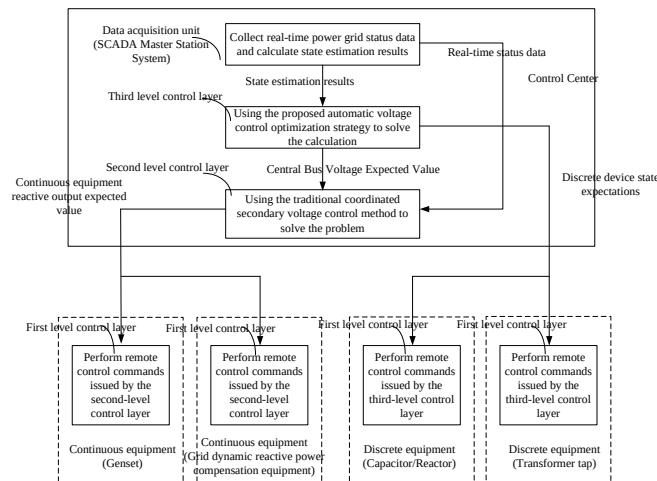


Figure 1. Schematic diagram of the coordinated optimization control system

The above optimization control system still follows the three-level voltage control mode of the existing AVC system. The third layer adopts the automatic voltage control optimization strategy of the power grid, namely formula (7). The optimized calculation determines the expected values of the discrete equipment state, namely y , z , and the expected value of the regional hub bus voltage. This set of optimization systems, based on the existing AVC system, does not require the addition of new systems and hardware, nor does it change the control mode of the existing AVC system, and is easy to implement.

4. Improved Genetic Algorithm Solving

To facilitate the calculation, the continuous variables in equation (7) are discretized. In this paper, an improved genetic algorithm is used to solve the problem and make appropriate improvements. The algorithm flow chart is shown in Figure 2.

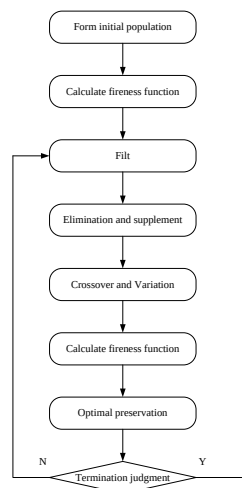


Figure 2. The process flow diagram of the improved genetic algorithm

5. Simulation Examples

This paper takes IEEE-14 node standard power grid model as an example to carry out simulation analysis. IEEE-14 node standard grid model, as shown in Figure 3, the grid model parameters see appendix A.

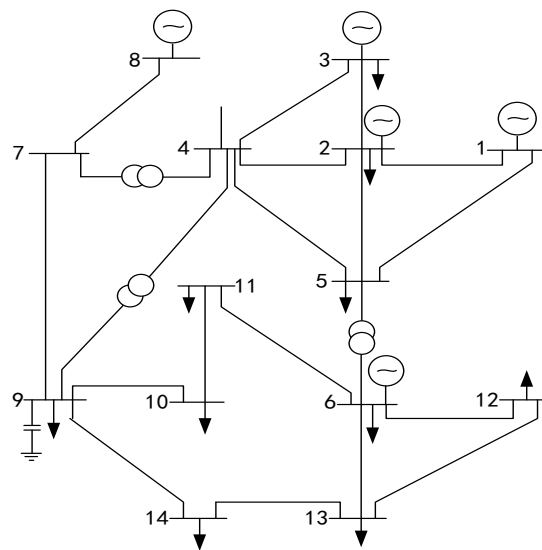


Figure 3. The model of IEEE-14 system

The No. 1 node is connected to the upper grid and is a balanced node. All nodes are P and Q nodes. The voltage amplitudes and the lower limits of the nodes are 1.1 and 0.9 respectively. No. 2 and No. 14 nodes have grid-connected generators. No. 5 nodes have dynamic reactive power compensation equipment, No. 3, No. 6 and No. 8 nodes have two parallel capacitor banks, and all transformers are no-load regulator transformers.

Node load and generator output will change over time. The AVC system controls the period of time as a unit. Please refer to appendix A for nodal load and generator output at time 0~4.

Set the ratio of the cost and unit network loss cost of the shunt capacitor bank in a single example to be 0.004, that is $\alpha_1, \alpha_3 = \alpha_2, \alpha_6 = \alpha_1, \alpha_8 = \alpha_2, \alpha_8 = 0.004$.

In the same initial state, the optimized control strategy based on comprehensive cost analysis and the traditional control strategy aiming at minimum network loss are adopted respectively, and automatic voltage control simulations are performed for the examples 1 to 4 respectively. The optimized control

strategy proposed in this paper is based on the improved genetic algorithm. The length of the continuous device gene block is 5, the number of population per generation is 20, P_c is 0.6, P_m is 0.2, and the optimal number of saved and replaced individuals is 1. The termination criterion is that the maximum value of the fitness function remains constant for five consecutive generations or reaches the maximum number of iterations of 200. The traditional control strategy adopts the control principle of "priority adjustment by discrete device and fine adjustment by continuous devices". Table 1 and Table 2 respectively show the results obtained by using two control strategies. The value at time 0 is the initial state. Figure 4 shows the number of discrete device actions when using two control strategies.

Table 1. Simulation results of the proposed strategy

	0 time	1 time	2 time	3 time	4 time
$x_{1,2}$	0.4	-0.0387	0.4	-0.1161	0.4
$x_{1,5}$	0.1	0.1	0.1	-0.0548	0.1
$x_{1,14}$	0.1	-0.0677	0.1	-0.1	0.1
$y_{1,3}$	1	1	1	1	1
$y_{2,3}$	1	1	1	1	1
$y_{1,6}$	1	1	1	0	1
$y_{2,6}$	0	0	1	1	1
$y_{1,8}$	1	0	1	0	1
$y_{2,8}$	0	0	1	0	1
P_{loss}	/	0.2061	0.2860	0.2114	0.2887
f/λ	/	0.2101	0.2980	0.2234	0.3007

Table 2. Simulation results of the traditional control strategy

	0 time	1time	2 time	3 time	4 time
$x_{1,2}$	0.4	0.4	0.4	0.4	0.4
$x_{1,5}$	0.1	0.0935	0.1	0.0935	0.1
$x_{1,14}$	0.1	-0.0032	0.1	-0.1	0.1
$y_{1,3}$	1	0	1	0	1
$y_{2,3}$	1	0	1	0	1
$y_{1,6}$	1	0	1	0	1
$y_{2,6}$	0	0	1	0	1
$y_{1,8}$	1	0	1	0	1
$y_{2,8}$	0	0	1	0	1
P_{loss}	/	0.2038	0.2860	0.2077	0.2887
f/λ	/	0.2198	0.3100	0.2317	0.3127

From Figure 4, we can see that at each time of the example, the proposed optimal control strategy is used for simulation control, and the number of discrete device actions is far less than that of the traditional control strategy.

Comparing with Tables 1 and 2, we can see that at some moments (such as time 1 and 3), the optimized control strategy is used to perform simulation control, and the network loss is greater than when the traditional control strategy is used to control the simulation. However, considering the discrete device motion loss, the optimized control strategy is used to carry out the simulation control. The total cost f of the grid at each moment is obviously less than when the traditional control strategy is used to control the simulation. And the optimized control strategy proposed is not to reduce the number of discrete device actions and over-reliance on continuous devices.

6. Conclusion

This paper propose a novel gird voltage control coordinated optimization strategy to reduce the comprehensive cost. The comprehensive cost includes the gird loss and the device spoilage. The proposed optimization strategy is combined with the existing three-level voltage control mode of the AVC system. The corresponding calculation method based on improved genetic algorithm is presented. The IEEE-14 system is used as an example to carry out simulation and comparison calculation. The simulation contrast results show that the proposed strategy is more reasonable than the traditional control strategy without considering the discrete devices spoilage. Especially in the case of gird load periodic change, the repeated controls of the discrete devices are effectively avoided by using the

proposed strategy. In future, the proposed strategy would be used in actual power grid. And we hope that the paper can provide reference for optimization of AVC system.

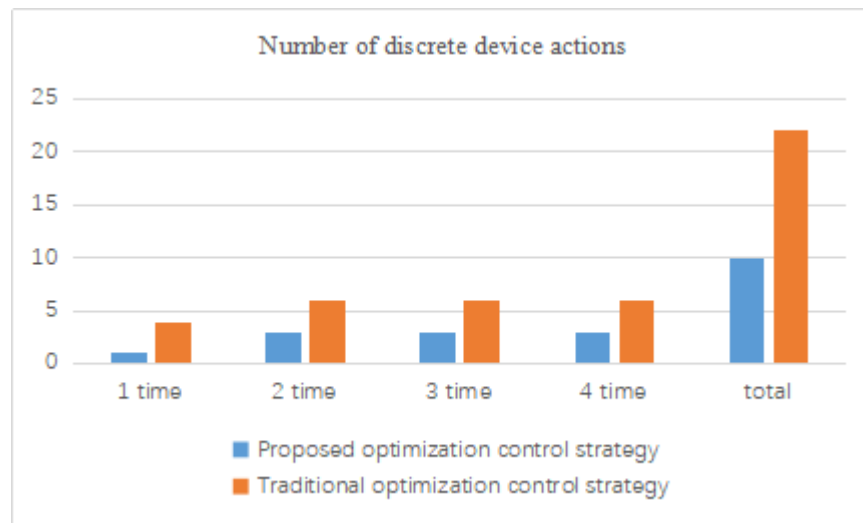


Figure 4. The comparison of the the proposed strategy and the traditional control strategy

7. Reference

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Appendix A

Table A1. The node load and generator output in 0 moment

Node number	Active load	Reactive load	Generator output
2	-0.217	0.1	0.4
3	-0.942	0	/
4	-0.478	0.039	/
5	0.124	-0.016	/
6	-0.112	0	/
7	0	0	/
8	0	0.1	/
9	-0.295	-0.1	/
10	-0.09	-0.058	/
11	-0.035	-0.018	/
12	-0.061	-0.016	/
13	-0.135	-0.058	/
14	-0.149	-0.05	0.2

Table A2. The node load and generator output in 1st moment

Node number	Active load	Reactive load	Generator output
2	-0.217	0.1	0.4
3	-0.942	0	/
4	-0.478	0.039	/
5	0.124	-0.016	/
6	-0.112	0	/
7	0	0	/
8	0	0.1	/
9	-0.295	-0.1	/
10	-0.09	-0.058	/
11	-0.035	-0.018	/
12	-0.061	-0.016	/
13	-0.135	-0.058	/
14	-0.149	-0.05	0.2

Table A3. The node load and generator output in 2nd moment

Node number	Active load	Reactive load	Generator output
2	-0.217	-0.2	0
3	-0.942	-0.2	/
4	-0.478	0.039	/
5	-0.076	-0.016	/
6	-0.112	-0.1	/
7	0	0	/
8	0	-0.1	/
9	-0.295	-0.3	/
10	-0.09	-0.058	/
11	-0.035	-0.018	/
12	-0.061	-0.016	/
13	-0.135	-0.058	/
14	-0.149	-0.05	0

Table A4. The node load and generator output in 3rd moment

Node number	Active load	Reactive load	Generator output
2	-0.217	-0.0932	0.4
3	-0.942	-0.1392	/
4	-0.478	0.2	/
5	0.124	0	/
6	-0.112	-0.1477	/
7	0	0	/
8	0	-0.0238	/
9	-0.295	-0.166	/
10	-0.09	0.1	/
11	-0.035	0.1	/
12	-0.061	-0.016	/
13	-0.135	-0.058	/
14	-0.149	0.1	0.2

Table A5. The node load and generator output in 4th moment

Node number	Active load	Reactive load	Generator output
2	-0.217	-0.0932	0
3	-0.942	-0.1392	/

4	-0.478	0	/
5	-0.076	-0.2	/
6	-0.112	-0.1477	/
7	0	0	/
8	0	-0.0238	/
9	-0.295	-0.166	/
10	-0.09	-0.1	/
11	-0.035	-0.1	/
12	-0.061	-0.016	/
13	-0.135	-0.058	/
14	-0.149	-0.1	0