REACTIVE POWER OPTIMIZAZTION METHOD INCORPORATING ECONOMIC AND ACTION NUMBER CONSTRAINTS OF CONTROL DEVICES

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ABSTRACT

The access of large-scale high penetration photovoltaic to the distribution network makes the direction of power flow frequently change, resulting in frequent switching of reactive power regulating equipment and frequent fluctuations in compensation capacity. Aiming at this problem, a new reactive power optimization method incorporating economic and action constraints of control devices is proposed. Firstly, pre-optimization is carried out based on photovoltaic and load forecasting. Then, in real-time optimization, combined sensitivity with inertia factor introduced to equipment which act too frequently, the voltage, the network loss of the whole system, the equipment life and the number of actions of control devices are comprehensively optimized. Next, improved genetic algorithm is used. Finally, an actual system case is used to illustrate the effectiveness and superiority of the proposed method for reactive power voltage optimization with the access of high penetration photovoltaic.

0 INTRODUCTION

The access of high proportion photovoltaic to the distribution network has brought new problems to the safe and stable operation of the power system[1]. The photovoltaic output fluctuates sharply with the change of the weather, which causes large voltage fluctuation of the power grid, leading to frequent action of reactive power regulating equipment. The bidirectional power flow even makes the output direction of some reactive power compensation equipment change frequently, which brings a serious impact on the safe and stable operation of the power system and the life of the equipment. Traditional reactive voltage optimization methods only considering the network loss may no longer be applicable.

Literature [2]-[3] incorporate photovoltaic inverters as reactive power compensation devices into the reactive voltage optimization process, and studied the rationality and effectiveness of the algorithm in this optimization, but do not consider the economic loss caused by actions of reactive power regulating devices. In addition, some scholars have comprehensive considerations about the economics of distribution network operation and equipment control. Literature [4] puts the number of times of control equipment into constraints, and analyzes the dynamic reactive power optimization problem within one day. Although the overall economy is optimal, the power quality of a single dispatch cycle such as the node voltage may approach the critical value on account of the long dynamic optimization period. Literature [5] puts forward a multi-objective function which consists of minimum 1 active power losses and minimum reactive power compensation cost and it uses the Multi-objective Evolutionary Algorithm Based on Decomposition to solve the model. However, in the establishment of the objective function, the regulating limitation of the reactive power regulating device is not considered, and the reactive power regulating device with less running cost is frequently switched and the loss rate is fast.

In this paper, a new reactive power optimization method is proposed. The objective function not only considers the network loss, but also considers the operating cost and switching times of the reactive power regulating equipment, achieving the optimization of the comprehensive economy. Besides, the sensitivity function and the inertia factor are used to achieve the optimal adjustment effect. Finally, the effectiveness and superiority of the proposed reactive power optimization model are verified by simulation in an actual distribution network architecture.

1 OPTIMIZATION MODEL

1.1 TRANDITIONAL OPTIMIZATION MODEL

1.1.1 Objective Function

$$\mathrm{F} = \min\left(P_{loss} + \lambda_V \sum_{i=1}^{n} \left(\frac{V_i - V_{ilim}}{V_{imax} - V_{imin}}\right)^2 \right) \tag{1}$$

Where,

$$P_{loss} = \sum_{j=1}^{n_L} \frac{R_j\left(P_j^2 + Q_j^2\right)}{U_j^2} \tag{2}$$

$$V_{ilim} = \begin{cases} V_{imin} & (V_i < V_{imin}) \\ V_i & (V_{imin} \le V_i \le V_{imax}) \\ V_{imax} & (V_i > V_{imax}) \end{cases} \tag{3}$$

Where, P_{loss} is the total network-loss of the system. n is the node set of the system. V_{imin}, V_{imax} are the lower and upper limit of the node voltage. V_i. λ_U is the penalty factor, which will take effect when node voltage exceeds its limitation.

1.1.2 Equation Constraint

$$\begin{cases} P_i = V_i \sum_{j=1}^{n} V_j (G_{ij} cos\theta + B_{ij} sin\theta) \\ Q_i = V_i \sum_{j=1}^{n} V_j (G_{ij} sin\theta - B_{ij} cos\theta) \end{cases} \tag{4}$$

Where, n is the node set of the system. P_i, Q_i are

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respectively the injected active power and reactive power of the i-th node. V_i, V_j are respectively the node voltage of the i-th and j-th node. G_{ij}, B_{ij} are respectively the conductance and susceptance between the i-th and j-th node. θ is the angle difference of the voltage vector between the two nodes.

1.1.3 Inequality Constraint

$$V_{imin} \le V_i \le V_{imax} \tag{5}$$

$$T_{imin} \le T_i \le T_{imax} \tag{6}$$

$$Q_{Cimin} \le Q_{Ci} \le Q_{Cimax} \tag{7}$$

$$Q_{PVimin} \le Q_{PVi} \le Q_{PVimax} \tag{8}$$

Where, Formula (5) to (8) are the constraints of the node voltage, on-load regulating transformer tap gear, capacity of reactive power compensation device and the reactive power output of the photovoltaic plant respectively.

1.2 OPTIMIZATION MODEL CONSIDERING REGULATING COST AND ACTION TIMES

1.2.1 Multi-objective Function

When the traditional optimization is carried out, the number of equipment actions and operating costs are not considered. In order to minimize the system's active power loss and voltage over-limit, some devices operate more frequently, and the equipment loss may make the economy not optimal. Besides, too many devices participating in reactive power optimization during a certain period of time may have a bad impact on the safe and normal operation of the system.

In order to solve this problem, this paper will consider the constraints of the action times and operating costs of the devices, and the total objective function consists of the following sub-objective functions:

Optimal Adjustment Effect

$$f_1 = \max\{\sum_{i=1}^{m+n+p+q}(\sum_{j=1}^{2}\alpha_j\beta_i r_{ij})\} \tag{9}$$

Where, r_{ij} is the sensitivity of the i-th reactive voltage regulating device including network-loss sensitivity r_{i1} and voltage sensitivity r_{i2}. α_j is the corresponding weight of sensitivity, which should be determined according to the actual condition. m, n, p, q are the number of on-load regulating transformer， switchable capacitor bank, reactive power compensation device and regulating photovoltaic inverter. When the i-th device is put into use, β_i is the ratio if the device is transformer, and β_i is the per-unit values of reactive power regulating quantity if the device is the others. β_i equals zero when the device is not working.

The regulating quantity can be controlled within a certain range through this objective function, so the sensitivity of each device can be considered to be approximately unchanged during the regulation. If the quantity of regulation is large, the sensitivity can be recalculated[6].

Lowest operating cost

$$f_2 = \min(\sum_{i=1}^{m+n} d_i\beta_i + \sum_{j=1}^{p+q} t_j\beta_j) \tag{10}$$

Where

$$d_i = \frac{C_i}{\min\{N_{di}, N_{ei}\}} \tag{11}$$

$$t_j = \frac{T_j}{T_{aj}} \cdot C_j \tag{12}$$

Where, d_i is the cost of transformer or capacitor bank operating per times, and the unit is yuan per times. C_i, N_{di}, N_{ei} are respectively the total cost of device, designing mechanical times and electrical times of the fling-cut switches of the i-th on-load regulating transformer or capacitor bank. t_j is the operating cost of putting reactive power compensation device or photovoltaic inverter into use. C_j, T_j, T_{aj} are respectively the total cost of device, the time of regulating reactive power voltage once and the equipment life. In this paper, the device will be put into use once an hour. β_i is the same as above.

This sub-objective function can quantitatively describe the equipment cost invested in each reactive optimization, helping to optimize the total cost.

Minimal action equipment

$$f_3 = \min(\sum_{i=1}^{m+n+p+q} l_i\gamma_i) \tag{13}$$

Where, l_i is the inertia factor calculated below. γ_i equals one when the i-th device acts and equals zero when the i-th device is not working.

1.2.2 Constraint condition

The equation and inequality constraints are the same as formula (4) to (8) above.

In addition, the inequality constraint of the number of devices per duration should be increased to limit the total number of control devices, and to reduce the disturbance caused by device regulation to the system. The inequality constraint is as follows:

$$\sum_{i=1}^{m+n+p+q} y_i \le a \tag{14}$$

Where, a is the number of action-limiting devices.

2 TWO-STAGE OPTIMIZATION

2.1 PRE-OPTIMIZATION

The pre-optimization uses the traditional optimization model and is carried out based on load forecasting in 24 hours using improved genetic algorithm.

First, λ_i, the total number of switching times of the i-th device in the period can be counted after the optimization.

Next, the action restriction coefficient Φ_i can be calculated. For the on-load regulating transformers or capacitor banks:

$$\Phi_i = \frac{N_{di} - N_{dzi}}{365(Y_i - Y_{dzi})} \tag{15}$$

Where, N_{di} is the designing mechanical times. N_{dzi} is the number of times that the device has been activated. Y_i is the equipment service life and Y_{dzi} is the number of years the device has been in use.

For reactive power compensation devices or photovoltaic inverters:

$$\Phi_i = 365(Y_i - Y_{dzi}) \tag{16}$$

Finally, the inertia factor l_i can be calculated. For the on-load regulating transformers or capacitor banks:

$$l_i = (\frac{\lambda_i}{\Phi_i})^2 \tag{17}$$

For the reactive power compensation devices and photovoltaic inverters:

$$l_i = (\frac{\lambda_{i*1}}{24\Phi_i})^2 \tag{18}$$

2.2 REAL-TIME OPTIMIZATION

The real-time optimization uses the optimization model considering regulating cost and action times of devices.

Multi-objective Decision

The three sub-objectives are combined into one total objective function using fuzzy complementary analytic hierarchy process [7].

The fuzzy scale α_{ij} equals 0.5，0.6，0.7，0.8，0.9 if the comparing result of element A_i and A_j is five different levels and the corresponding α_{ji} equals 0.5，0.4，0.3，0.2，0.1. The judgment matrix formed by the fuzzy complementary scale is: $\mathbf{A} = \left(\alpha_{ij}\right)_{m\times m}$.m is the number of comparing elements. Sum the matrix by row and obtain $T_i = \sum_{j=1}^{m} \alpha_{ij}, i = 1,2,\dots,m$, which can be transformed to $T_{ij} = \frac{T_i - T_j}{2(m-1)} + 0.5$. Then the fuzzy consistency matrix **T** can be obtained:$\mathbf{T} = (T_{ij})_{m\times m}$. Then the normalizing rank aggregation is carried out for **T** and the feature vector can be obtained: $\boldsymbol{\nu} = (\nu_1, \nu_2, \dots, \nu_m)^T$. If

$$\nu_i = \frac{\sum_{j=1}^{m} \alpha_{ij} + \frac{m}{2} - 1}{m(m-1)}, i = 1,2,\dots,m \tag{19}$$

ν_i is the weight calculated for the multi-objective decision. The comprehensive total objective is:

$$\mathrm{f} = -\nu_1 \mathrm{f}_1 + \nu_2 \mathrm{f}_1 + \nu_3 \mathrm{f}_3 \tag{20}$$

2.3 IMPROVED GENETIC ALGORITHM

2.3.1 Improvement

(1) In order to make crossover and mutation operations more convenient, hybrid encoding[8]is used for regulating transformers and capacitor banks.

(2) The values of crossover rate R_c and mutation rate R_m in this paper are as follows:

$$R_c = R_{c0} + \mu_1 N_n' - \mu_2 f' \tag{21}$$

$$R_m = R_{m0} - \mu_3 N_n' + \mu_4 f' \tag{22}$$

Where, R_{c0} and R_{m0} are the basic value. μ_i is the coefficient. $N_n' = N_n/M$, $f' = f_{min}/f_{max}$, N_n is the number of different individuals in each generation, M is the number of groups. f_{min} and f_{max} are the minimum and maximum fitness.

2.3.2 Evaluation of Random Solution

Since the genetic algorithm is a stochastic optimization algorithm, the time and optimization result of each optimization are not necessarily the same. Therefore, this paper further evaluates the optimal solution obtained by the algorithm.

This paper sets a regulating threshold:

$$(\Delta P_{loss}\% \le \xi) \cap (\Delta \sum |\Delta U|\% \le \sigma) \tag{23}$$

Where, $\Delta P_{loss}\%$ is the percentage of reduction of net loss before and after optimization. $\Delta \sum |\Delta U|\%$ is the voltage deviation correction before and after optimization. ξ and σ are the constant.

When the optimization effect is better than the threshold, the system issues control commands based on the calculated results. If not, part of the correlation such as the iterative termination criterion in the genetic algorithm will be adjusted.

2.4 FLOW CHART OF OPTIMIZAZTION

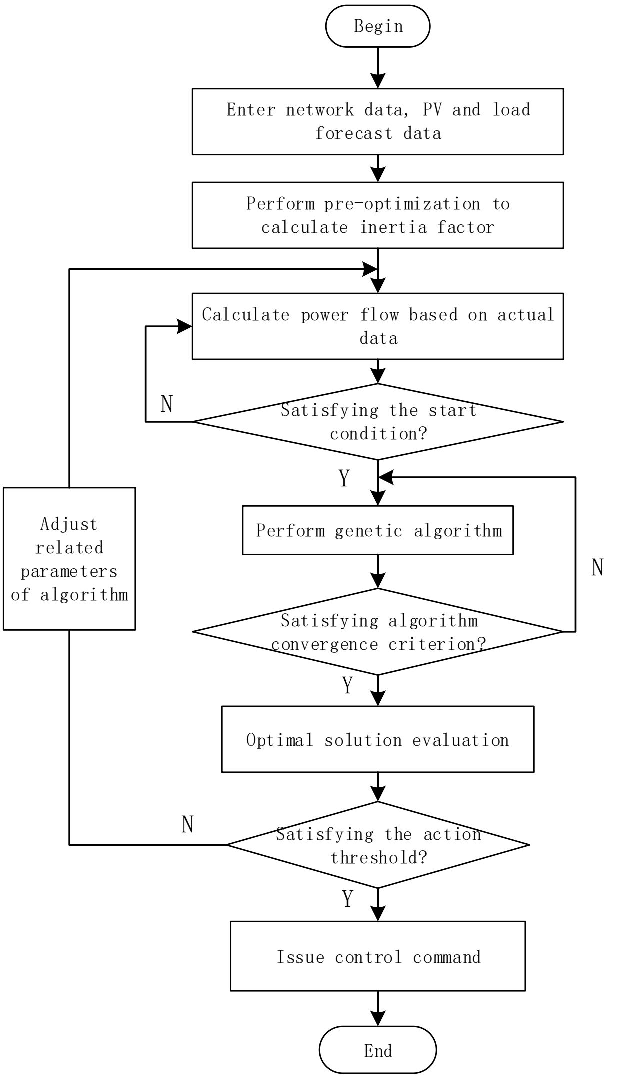

Fig.1. Flow chart of optimization

3 CASE ANALYSIS

Take the actual power grid in a certain area as the case system.

The number of nodes in the actual regional power grid is 41, the number of regulating transformers is 8, the number of switchable capacitor banks is 9, and the number of adjustable reactive power photovoltaic power plants is 7, and each photovoltaic power plant is equipped with Static Var Generator(SVG).

The equivalent 41-node topology is shown below:

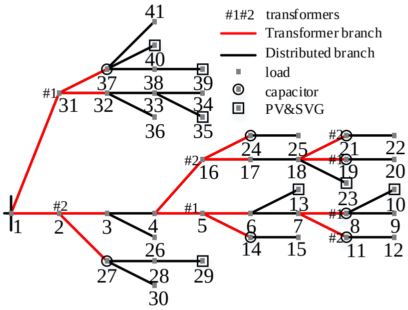

Fig. 1. Equivalent network topology

First pre-optimize which is also the traditional reactvie power optimization is carried out and then optimize in real time. The real-time optimization is usually carried out in a period of time and this paper takes it as one hour. The optimized transformer gear position information, capacitor bank switching information, SVG output and photovoltaic power plant output are shown in the following tables.

Tab. 1. Transformer gear after optimization

Transformer name	Gear
220kV Shuanglong 1#	-1
220kV Shuanglong 2#	-1
110kV Shigang 1#	3
110kV Shigang 2#	2
35kV Qianfeng 1#	0
35kV Qianfeng 2#	1
35kV Lvliang 1#	0
35kV Lvliang 2#	2

Tab. 2. Switching of capacitor banks after optimization

Capacitor name	Number of input groups	Reactive power of each group/ Mvar
Shuanglong 1# 35kV side capacitor	0	10
Shuanglong 2# 35kV side capacitor	0	7
Shigang 1# 10kV side capacitor	0	3.6
Shigang 2# 10kVside capacitor	0	1
Qianfeng 1# 10kV side capacitor	0	2
Qianfeng 2# 10kV side capacitor	0	2
Lvliang 1# 10kV side capacitor	0	3
Lvliang 2# 10kV side capacitor	0	2
Zhenhe photovoltaic 20MW side capacitor	1	1.3

Tab. 3. Reactive power output of photovoltaic power station and its SVG

Photovoltaic name	Active power/MW	Reactive power/Mvar	SVG Reactive power/Mvar
110kV Zhenhe 100MW	85.88887	1.6546	2.5032
35kV Zhenhua 20MW	14.759999	-1.0456	-1.8557
35kV Zhenhe20MW	13.3112	0	0.2112
35kV Asian New Energy 18.8MW	11.63904	-1.4401	-0.0647
35kV Jixin 23MW	19.2672	-0.9285	-0.5626
35kV Qianfeng Zhaohui 31MW	24.94656	-0.0999	-4.9488
10kV Zhaohui 1# 8MW	4.724637	4.7195	1.7694

Th real-time reactive power optimization considering the economic and the number of action times of device presented in this paper is compared with traditional reactive power optimization. Figure 1 shows the action times of the capacitor bank, the on-load regulating transformer tap, the inverter and the SVG after the two optimization methods in this period. It can been seen from the data in the figure that the number of switching times of the capacitor banks is reduced obviously after the real-time optimization and the action times of other device is also reduced.

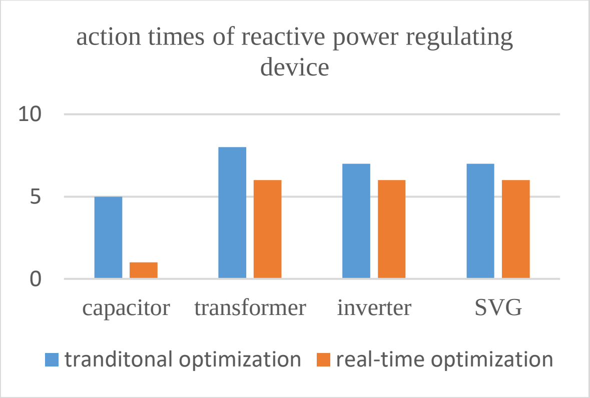

Fig. 2. Action times of reactive power regulating device

Tab. 4. Equipment loss and network-loss after two optimization methods

	Real-time optimization	**Traditional optimization**
Equipment loss	2369.4yuan	2704.2yuan
Network-loss	0.10772pu	0.10723pu

After calculation, compared with traditional reactive power optimization, the equipment loss cost was reduced from 2703.2 yuan to 2,369.4 yuan by 12.35%. The active network loss increased slightly. The reactive device such as the capacitor bank is not fully invested due to the action constraint, so that a large amount of reactive power flows in the network, resulting in a relatively large network loss at this time.

The power flow calculation is performed by simulation, and the voltage distribution of each node after traditional optimization and real-time optimization is shown in the figure followed.

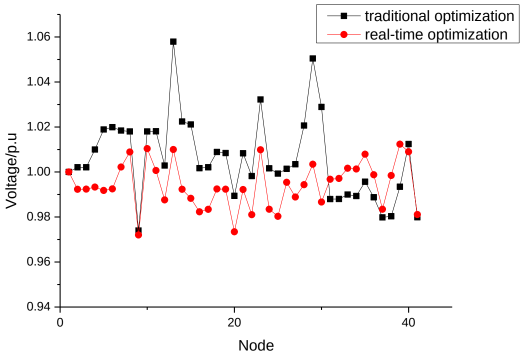

Fig. 3. Distribution of node voltage after two optimization methods

It can be seen from the figure that compared with the traditional reactive power optimization method,the real-time optimization controls the node voltage by sensitivity, on account of which the distribution of the grid voltage of the whole region is improved obviously, and the average voltage offset of the whole network is reduced from 0.0106pu to 0.009818pu.

4 CONCLUSION

This paper proposes a reactive power optimization method that considers the cost of equipment and the limitation of the number of actions. Firstly, through load forecasting and photovoltaic forecasting, the improved genetic algorithm is used for pre-optimization. Based on the result, the voltage, network loss, equipment life and number of actions of the whole system are comprehensively optimized by combining sensitivity and inertia.

The simulation of the grid structure of an actual area demonstrate the effectiveness and superiority of the proposed method. The simulation results show that although the system network loss is slightly increased, it has obvious improvement effect on equipment life and system stability, and is more economical than the simple net loss target.

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