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Optimal Reactive Power Dispatching for Automatic Voltage Control of Hydropower Station Based on an Improved Genetic Algorithm

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Abstract: -This paper presents recent work on the control strategy and algorithm for automatic voltage control (AVC) of hydropower station with multiple units and large capacities. Under the conditions that no dynamic voltage problems are considered, a method intended primarily to control steady state voltage of HV bus by economically regulating the reactive power generation of hydropower station is proposed. An improved Genetic Algorithm (GA) is used for optimal reactive power dispatching in automatic voltage control of hydropower station. Compared with the classic GA, three basic operators in GA which are the sorting selection operator, the pattern crossover operator and the quasi-gradient mutation operator are amended in this paper. Furthermore, the result of GA is modified by mountain-climbing method. The simulating results show that the compatibility of the improved GA is better than normal optimal algorithms and classic GA, and the algorithm can also obtain global optimization and reduce the net-loss to the most extent. The numerical simulations in off-line environment on practical system with 5 units and 13 units demonstrate that the processing speed and the accuracy are completely acceptable in practical project.

Keywords: automatic voltage control; hydropower station; reactive power optimization; genetic algorithm; pattern crossover; quasi-gradient mutation

1. Introduction

Generally, HV bus of the hydropower station is a critical node of power system, which is closely related to security of the system [1]-[2]. The purpose of automatic voltage control (AVC) of hydropower station is to maintain the voltage magnitude at HV bus at its reference value by utilizing reactive power resources of generators, and to economically dispatch reactive power among generators which can be used to regulate reactive power. Under the control of AVC actions, secure and economic operation can be ensured.

Conventional methods of reactive power dispatching in power station includes average allotment, proportional allotment in terms of capacity of each generator, proportional allotment in terms of power factor of each generator, etc. Although these methods are beneficial to certain purpose, they take no economical target into consideration. Nowadays, power system is operating in a market environment that requires minimization of operating cost. The incremental costs method, which is widely used in AVC of power plants, is an effective method for this economic purpose [3]. Comparative simplicity and avoiding time-consuming iteration make this method viable in real-time application. However, the result derived from the conventional equal increment costs approach can not obtain the most optimal result when any generation constraint is violated.

In the past decade, a new optimization method known as genetic algorithm (GA) has become a candidate for many optimization applications due to its flexibility and efficiency. Nowadays, it has been widely used in many non-linear cases in power system optimization, but the application in AVC for power plants is seldom reported [4]-[8]. In this paper, GA is utilized for finding global optimal solution of reactive power economic dispatching in hydropower station. Considering the complexity of operation constraints and the requirement of real-time control of AVC for hydropower plant, the operators of classic GA is amended for improving performance of optimal reactive power dispatch in order to minimize active power losses in the station using acceptable calculation time.

The paper is organized in following way: Firstly, the AVC method including control strategy and mathematical model is presented. Next, the improvement of classic GA is proposed and its application to reactive power dispatching is elaborated. Finally, off-line numerical simulations are presented and analyzed.

2. Survey of the method for automatic voltage control (AVC) of hydropower stations

Control scheme for AVC of hydropower stations is always designed as Figure 1, which is based on an on-line voltage and reactive resource control system. It automatically coordinates the reactive power supply of generators, in the face of the continuously changing reactive power demand, to meet the objective of keeping up the HV bus voltage magnitude of each power station at its reference value as well as minimizing the real power losses in stations. The scheme is based on hierarchical control structure [3].

The essential part of the AVC system of hydropower stations is the control strategy that can achieve secure and economically optimal target simultaneously. The method used in the paper is specified in two steps.

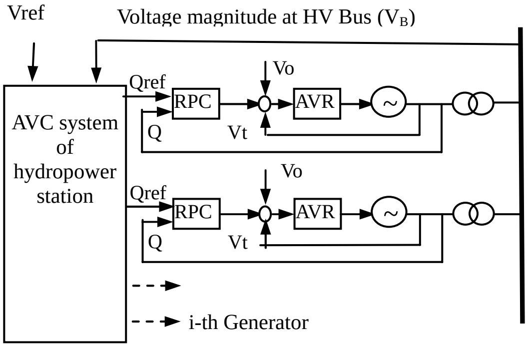

Fig.1. Schematic diagram of the AVC system of hydropower station

In the first step, on-line sensitivity approach is used to estimate reactive power injections to eliminate voltage violation of HV bus. The feasible HV outlet line models, including the model of line connecting with system and the model of line serving for local load are given respectively in the paper, and then, according to the models and on-line data, the sensitivity coefficient of the variable ΔQ (variation of required reactive power of loads resulting from voltage deviation) with respect to the variable ΔV (voltage deviation) is calculated, therefore total amount of reactive power required to inject can be worked out.

The second step is optimal dispatching of reactive power, which is in an attempt to minimize real power losses in the station. Taking account of all kinds of constraints, mathematical model of reactive power optimization is presented and an optimal algorithm is employed to this process. After performing the two processes, reactive power set-point of each generator are calculated out and sent to regulating devices of each available unit of the station, then voltage magnitude can be drawn back to its reference value, thus optimal voltage control will be realized.

3. Mathematic model for AVC

3. 1 Load model

In order to calculate sensitivity coefficient of each outlet line of the station, outlet load lines are divided into two types of models: outlet line connecting with system and outlet line serving for local load, described as follows.

3.1.1 Model of outlet line connecting with system

Suppose that the i-th outlet line is a line connecting with system, and then the reactive power transmitted on this line can be given as:

$$Q_{Li} = f(U_B, \delta_{Li}, U_{Li}) \qquad (1)$$

where:

i : Sequence number of outlet lines.

U_B: Voltage magnitude at HV bus.

U_{Li}: Voltage magnitude at accepted terminal bus of the i-th outlet line.

δ_{Li}: Phase angle difference between HV bus and accepted terminal bus of the i-th outlet line.

Then the increment of reactive power is obtained by linear approximation:

$$\Delta Q_{Li} = \frac{\partial Q_{Li}}{\partial U_B}\Delta U_B + \frac{\partial Q_{Li}}{\partial \delta_{Li}}\Delta \delta_{Li} + \frac{\partial Q_{Li}}{\partial U_{Li}}\Delta U_{Li} \qquad (2)$$

Active power transmitted on the i-th outlet line can be considered as constant during the action of voltage regulation, and then variation of phase angle can be ignored, i.e. $\Delta\delta_{Li} \approx 0$. Meanwhile, voltage magnitude at accepted terminal bus remains settled as well by the actions of local reactive power compensators, i.e. $\Delta U_{Li} \approx 0$. Then the increment of reactive power becomes:

$$\Delta Q_{Li} \approx \frac{\partial Q_{Li}}{\partial U_B}\Delta U_B \qquad (3)$$

Fig. 2 shows equivalent circuit of outlet line connecting with system.

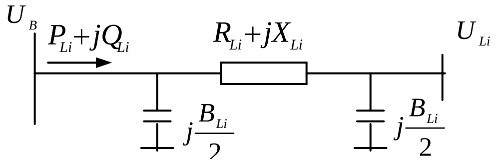

Fig.2. Equivalent circuit of the i-th outlet line connecting with system

According to Fig. 2, specific power equations of the i-th HV outlet line can be given as the decoupled load flow equations of the form:

$$Q_{Li}=\frac{U_B^2}{|Z_{11-i}|}\cos\alpha_{11-i}-\frac{U_BU_{Li}}{|Z_{12-i}|}\cos(\delta_{Li}-\alpha_{12-i}) \qquad (4)$$

$$P_{Li}=\frac{U_B^2}{|Z_{11-i}|}\sin\alpha_{11-i}-\frac{U_BU_{Li}}{|Z_{12-i}|}\sin(\delta_{Li}-\alpha_{12-i}) \qquad (5)$$

where

Z_{11-i} and α_{11-i} represents input impedance and its angle respectively, which are defined as:

$$Z_{11-i}=1/(i\frac{B_{Li}}{2}+\frac{1}{R_{Li}+X_{Li}})=R_{11-i}+jX_{11-i}$$

$$\alpha_{11-i}=tg^{-1}(\frac{R_{11-i}}{X_{11-i}})$$

Z_{12-i} and α_{12-i} represent transfer impedance and its angle respectively, which are defined as:

$$Z_{12-i}=R_{Li}+jX_{Li}$$

$$\alpha_{12-i}=tg^{-1}(\frac{R_{Li}}{X_{Li}})$$

Subject to equation (4) and (5), voltage magnitude at accepted terminal bus of the i-th outlet line is obtained as:

$$U_{Li}=((U_B-\frac{P_{Li}R_{Li}+Q'_{Li}X_{Li}}{U_B})+(\frac{P_{Li}X_{Li}-Q'_{Li}}{U_B}))^{\frac{1}{2}} \qquad (6)$$

And phase angle difference between HV bus and accepted terminal bus of the i-th outlet line is obtained as:

$$\delta_{Li}=tg^{-1}\frac{P_{Li}X_{Li}-Q'_{Li}R_{Li}}{U_B^2-P_{Li}R_{Li}-Q'_{Li}X_{Li}} \qquad (7)$$

where Q'_{Li} is defined as:

$$Q'_{Li}=Q_{Li}+\frac{B_{Li}}{2}U_B^2$$

Then the sensitivity coefficient of variational value of reactive power transmitted on the i-th outlet line with respect to the voltage deviation at HV bus is given as:

$$K_{QVi}=\frac{\partial Q_{Li}}{\partial U_B}=2U_B\frac{\cos\alpha_{11-i}}{|Z_{11-i}|}-\frac{U_{Li}}{|Z_{12-i}|}\cos(\delta_{Li}-\alpha_{12-i}) \qquad (8)$$

3. 1. 2 Model of outlet line serving for local load

Suppose that the load on the i-th outlet line is local, and then the reactive power load can then be defined as (the reactive power losses on the line can be ignored since the length of the line is quite short):

$$Q_{Li}=Q_{0-i}(\frac{U_B}{U_{B0}})^q \qquad (9)$$

where:

Q_{0-i} is nominal reactive power transmitted on the i-th outlet line.

U_{B0} is nominal voltage magnitude at HV bus.

Then the sensitivity coefficient of outlet line serving for local load is given as:

$$K_{QVi}=\frac{\partial Q_{Li}}{\partial U_B}=\frac{qQ_{0-i}}{U_B}(\frac{U_B}{U_{B0}})^{q-1} \qquad (10)$$

In this paper, the local load is treated as constant impedance model, i.e. q=2.

3. 1. 3 Final result

After sensitivity coefficient of each line is worked out, the increment of reactive power injections required to eliminate the voltage deviation at HV bus is obtained by following equation:

$$\Delta Q_B=\sum_{i=1}^{n}(K_{QVi}N_{Li})(U_{Bref}-U_B) \qquad (11)$$

where

n is total amount of outlet lines

N_{Li} are state flags of the i-th outlet line; $N_{Li}=1$ when the i-th line is connecting with bus, or $N_{Li}=0$.

U_{Bref} is set-point of the voltage magnitude at HV bus.

U_B is real-time measurement of the voltage magnitude at HV bus.

The total amount of required reactive power injections is obtained as:

$$Q_{B\Sigma}=\Delta Q_B+\sum_{i=1}^{n}Q_{Li}=(\sum_{i=1}^{n}K_{QVi}N_{Li})(U_{Bref}-U_B)+\sum_{i=1}^{n}Q_{Li} \qquad (12)$$

where

Q_{Li} are real-time measurements of the reactive power transmitted on the i-th outlet line.

If reactive power amount supplied by all generators is regulated equal to $Q_{B\Sigma}$, voltage profile can be maintained. Then voltage control problem is transformed into reactive power optimal control and dispatching problem.

3. 2 Secure constraints of generators

Secure constraints are fundamental demand of power station, which is represented by operational limitation.

The operational limitations can be expressed by inequality constraints of reactive power supply of generators, which are mainly determined by limitations of stator heat, rotor heat, terminal voltage of generator and static stability. These constraints are pertinent to current operation conditions.

Consider these factors, lower and upper bounds of control variable (reactive power generation) can be worked out according to current operation data in real-time on-line environment. Then secure constraint conditions can be provided to optimal control process. The details of methods for calculating the limitations in on-line environment will be discussed in other paper.

3. 3 Mathematical models for optimal reactive power dispatching

The network model applied to the proposed approach is shown in Fig.3.

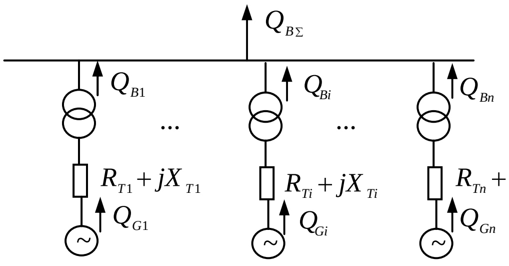

Fig.3. Network model in power station

Mathematical models of the problem contain power flow constraint equations, variable constraint conditions and objective function.

Since voltage control can be realized only by adjusting reactive power, the balance of active power can be maintained during the control actions. Therefore, only reactive power constraint equation should be considered.

$$\sum_{i=1}^{n} Q_{Bi} - Q_{B\Sigma} = 0 \qquad (13)$$

where

$Q_{B\Sigma}$ is total amount of reactive power injections required to maintain voltage profile calculated out by sensitivity approach.

Q_{Bi} are Reactive power injections supplied by the i-th generator.

N is Total amount of available generators.

The aim of reactive power optimization control is to minimize power losses. The equality constraint might be treated as penalty functions. Objective function is constructed as follow::

$$P_L = \sum_{i=1}^{n} ({P_{Bi}}^2 + {Q_{Bi}}^2) / U_B^2 \times K_{Ti} \times R_{Ti} \qquad (14)$$

where

P_{Bi} is active power injections supplied by the i-th generator.

R_{Ti} is resistance of the i-th transformer calculated to HV side.

K_{Ti} is ratio of the i-th transformer.

Inequality constraint of control variables are written as:

$$Q_{Gi\min} < Q_{Gi} < Q_{Gi\max} \quad \text{i=1, 2, ⋯ , n} \qquad (15)$$

where

$Q_{Gi\max}, Q_{Gi\min}$ are the upper and lower limit on reactive power supplied by the i-th generator, respectively.

4 Improvement of genetic algorithm for optimal reactive power dispatching

Capable of searching global optimal solution under various conditions and constraints, GA is used to solve the optimal problem of reactive power dispatching in hydropower station described in Section 3.3. Considering the real-time requirement of AVC, three main operators including selection, crossover and mutation are amended based on classic GA for improving the performance of the calculation speed and accuracy. The main process of AVC using the proposed GA method is described as follows.

4. 1 Encoding and decoding method

Within classic GA framework, the solution is modeled by means of binary strings. Such a string is made up of sub-string representing a different variable, say Qi, the output reactive power of i-th generator. Considering the constraints described in (15), the *i*-th encoded variable is:

$$m_i = \frac{Q_i - Q_{\min}}{Q_{\max} - Q_{\min}} \times 2^l, \quad i = 1, 2, \ldots, n \qquad (16)$$

Accordingly，decoding equation is:

$$Q_i = Q_{\min} + \frac{m_i}{2^l} \times (Q_{\max} - Q_{\min}) \qquad (17)$$

where

l is the length of binary code of variable, treated as genes string in chromosome. Obviously，all of the feasible results are located in the predefined constraints during the evolution process.

4. 2 Sorting selection method

Firstly, each individual of the previous generation is evaluated by fitness function:

$$f_i = F(X_i) = \sum_{j=1}^{n-1} ({P_{Bj}}^2 + {Q_{Bj}}^2) / U_B^2 \times R_{tj} + [P_n^2 + (Q_{B\Sigma} - \sum_{j=1}^{n-1} Q_{Bj})] \times R_{tn}$$

$$i = 1, 2, \cdots, k \qquad (18)$$

where

X_i is control vector of reactive power generation of units:

$$X_i = [Q_{i,1}, Q_{i,2}, \cdots, Q_{i,n}]$$

Next, the k fitness values are arranged by descending sequence with assigned sequence value from 1 to *k*. The individual with assigned value *i* is chosen for crossover by probability of $p = 10i \times k \sum_{j=1}^{k} j$.

Since proportion of the individuals with good fitness value and the individuals with bad fitness value is fixed in population, early mature due to larger fitness value of certain individuals can be avoided in early search period. During the final evolution period, optimal search will not be stopped due to small difference of fitness value in population. Therefore, accuracy can be improved.

4. 3 Pattern crossover method

Two individuals are chosen as parent chromosome string for crossover according to 4.2. In the paper, pattern crossover method is used for improving the crossover performance of the GA. A pattern string is produced in random with the same length as chromosome string. Bit change of individual are decided by corresponding bits of pattern string. Bit will be change when the corresponding bit of pattern string is 1. Two offspring chromosome strings are then produced.

Take a example as follows:

If the pattern string is 101001;
the parent string 1 is 111001;
the parent string 2 is 000010;
then
the offspring string 1 is 101011;
the offspring string 2 is 010000.

Compared with the single-bit crossover method of classic GA, pattern crossover method can exchange the information of parent strings to maximum degree. Then the search process can be accelerated for improving the speed of the GA.

4. 4 Guasi-gradient mutation method

In mutation operation of classic GA，one or several bit are chosen in random to inverse. It is generally an aimless mutation method, sometimes making individuals worse and then affecting the evolution speed of population. In this paper, a quasi-gradient directive mutation method is proposed to improve mutation operator. The main idea of this method is using the genetic information of previous generation to assist the mutation of the offspring. The detailed steps are described as follows.

The objective string should be firstly decoded to practical value, indicated as a vector：

$$X_i^t = [Q_{i,1}{}^t, Q_{i,2}^t, \cdots, Q_{i,n}^t]$$

where

t is iteration time, i is the i-th individual in population, $i = 1, \ldots, k$.

If $F(X_i^{t+1}) < F(X_i^t)$, then gradient information can be calculated:

$$g_P(X_i^{t+1}) = [dir(Q_{i,1}^{t+1}), dir(Q_{i,2}^{t+1}), \cdots, dir(Q_{i,n}^{t+1})] \quad (19)$$

where

$$dir(Q_{i,j}^{t+1}) = sign(Q_{i,j}^{t+1} - Q_{i,j}^t) = \begin{cases} 1 & Q_{i,j}^{t+1} - Q_{i,j}^t > 0 \\ 0 & Q_{i,j}^{t+1} - Q_{i,j}^t = 0 \\ -1 & Q_{i,j}^{t+1} - Q_{i,j}^t < 0 \end{cases}$$

$j = 1, 2, \ldots, n$

The mutation rule is

$$Q_{i,j}^{t+1} = Q_{i,j}^{t+1} + dir(Q_{i,j}^{t+1}) \times \left| N(0, \sigma^t) \right| \quad （20）$$

where $N(0,\sigma)$ is Gaussian function

$$\sigma^t = \beta \times F(X_i^t) \Big/ \sum_{j=1}^{k} F(X_j^t)$$

If $F(X_i^{t+1}) \geq F(X_i^t)$, the mutation rule is:

$$Q_{i,j}^{t+1} = Q_{i,j}^{t+1} + N(0, \sigma^t) \quad (21)$$

4. 5 Amendment for output results

Once fitness values of individuals adjacent to local optimal solution are much better than others', premature converge of the population may appear. Therefore the final result of the proposed GA should be corrected for obtaining global optimal solution. Mountain-climbing method is used in the paper. The string value of each variable of the pre-solution result is added and detracted by 1.If the fitness value of the new string is better than the original one, substitute the corresponding string of variable by the new string. Otherwise, modify the string value of other variables in the same way until the solution converged to maximum optimal value.

5. Numerical simulation

In order to demonstrate the usefulness of the proposed method for AVC in power station, numerical simulation using the most recent version of the program is performed on two different cases of practical hydropower stations in off-line environment. For comparing the performance of control algorithms, conventional equal incremental costs method, classic GA and improved GA proposed in the paper are applied under the same condition respectively.

In Case 1, a hydropower station is with 5 generator units, the 3rd generator of which do not take part in real-time reactive power dispatch for some reasons, and 4 HV outlet lines including 2 lines connecting with system network and 2 lines serving for local load. State description before AVC action and state after AVC action of the system are shown in Table 1. The conventional incremental costs method is a fastest one, but the result losses in the hydropower station are relatively larger than GA based method. With the proposed GA method, the control system consumes less time than with the classic GA method, Furthermore the voltage at HV Bus is closer to target, and the power losses is smaller.

In Case 2, a hydropower station is with 13 generator units, and 8 HV outlet lines including 5 lines connecting with system network and 3 lines serving for local load. Simulation result of Case 2 is shown in Table 2. With the conventional incremental costs method, 3 generators will reach the generation limit under the operating condition. With the proposed improved GA, the control system for AVC has the best performance. It can be seen from Table 1 and Table 2 that the consumed time of the proposed method is less than 1s. This calculation speed can satisfy the requirement of real-time steady state voltage control of hydropower station.

Table 1 Comparison of three algorithms for AVC of hydropower station with 5-units

		Deviation of HV Bus	Reactive power generation of each units					Total losses	Iteration times	consumed Time
			Q_{G1}	Q_{G2}	Q_{G3}	Q_{G4}	Q_{G5}			
Before AVC action		−1.5%	0.161	0.153	0.191	0.146	0.132			
After AVC Action	Eequal incremental costs method	0.41%	0.231	0.263	0.191	0.226	0.246	0.643	None	Less than 0.01ms
	Classic GA	0.27%	0.247	0.251	0.191	0.264	0.238	0.554	30-40	About 0.4s
	Proposed improved GA	0.23%	0.255	0.249	0.191	0.250	0.210	0.541	Less than 25	About 0.3s

Table 2 Comparison of three algorithms for AVC of hydropower station with 13-units

		Deviation of HV Bus	Total losses	Units reaching the generation bound	Time consumed
After AVC actions	Equal incremental costs method	0.37%	1.26	3 generators	Less than 0.01ms
	Classic GA	0.14%	1.03	none	About 1.2s
	Proposed improved GA	0.12%	0.96	none	About 0.8s

6. Conclusions

The control strategy and improved optimal algorithm based on GA for automatic voltage control system of hydropower stations are proposed in the paper. By amending the operators of classic GA, the performance of optimal voltage control is improved in economic aspect. A software package based on the proposed approach has been developed. Using the developed AVC program, the numerical simulations in off-line environment on practical system are presented. Results and analyses demonstrate the advantage of the proposed control scheme.

Reference

[1]J. P. Paul, J. Y. Leost and J. M. Tesseron: Survey of the Secondary Voltage Control in France: Present Realization and Investigation", IEEE Trans. on Power System, Vol.2, No.2, 1987, pp505-511

[2]M. D. Ilic, X. Liu and etc.: Improved Secondary and New Tertiary Voltage Control, IEEE Trans. on Power System, Vol.10, No.4, 1995, pp1851-1858

[3]Gehao Sheng, Guangyu Tu. A Method for Automatic Voltage Control of Cascaded Hydroelectric Power Stations, Proceedings of 5th International Conference on Advanced Power System Control, Operation and Management, Hong Kong, 2000.

[4] Q. H. Wu, J. T. Ma, Power System Optimal Reactive Power Dispatch Using Evolutionary Programming, IEEE Transaction on Power System, Vol. 10, No.2, 1995.

[5]Gerald B. Sheble, KristinBrittig. Refined Genetic Algorithm-Economic Dispatch Example. IEEE Transactions on Power Systems, Vol.10. No.1. ,1995

[6]Kenji lba. Reactive Power Optimization by Genetic Algorithm. IEEE Transactions on Power Systems. Vol.9.No.2.May 1994.

[7]J. G. Vlachogiannis and N. D. Hatziargyriou, Reinforcement Learning for Reactive Power Control, IEEE Trans. on Power System, Vol.19, No.3, 2004, pp1317-1322

[8]A. G. Bakirtzis, P. N. Biskas, C. E. Zoumas, and V. Petridis, Optimal power flow by enhanced genetic algorithm, IEEE Trans. on Power System,,vol. 17, No.2 2002 pp. 229–236.