

Research on the optimisation strategy of short-circuit current limitation based on quantum genetic algorithm

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Abstract: With the expansion of urban power grid, short-circuit current issue becomes more important. This study proposes an effective approach to optimise short-circuit current limiting measure configuration. Before applying short-circuit current limiting measures, the Ward equivalence is utilised to reduce power grid's scale so as to reduce the computational work in short-circuit current limiting measure configuration optimisation. In order to balance the current-limiting performance and the economic costs of short-circuit current limiting measures, a multi-objective model for optimising short-circuit current limiting measure configuration is proposed. A quantum genetic algorithm-based solving method for the optimisation model is proposed. Finally, the proposed approach is verified by the simulations on an actual power grid.

1 Introduction

Electricity is the most widely used secondary energy. In order to meet the demand of electric power, the power system, an important infrastructure of the national economy, is responsible for safe, economical, and reliable delivery of electricity to users. With social and economic development, the need of electric power increases, the physical scale of electric network expands and the power load density grows. These changes enhance the electrical connections between the various components of the power grid, which increases short-circuit current. At present, large short-circuit current has become the main factor to threat power grid's safe and economic operation. Therefore, short-circuit current limiting measure configuration optimisation is one of the hottest topics [1–3].

The short-circuit current limiting measures such as line breaking, line operating outside of substation, installing current limiting reactor, and using high-impedance transformer are the effective measures to reduce short-circuit current [4–6]. Chen *et al.* [7] regard the short-circuit current limiting measure configuration optimisation as a mixed-integer programming problem. However, due to the large physical scale of power grid, the current limiting measure configuration optimisation is a large-scale non-continuous, non-convex, and non-linear optimisation problem. Especially, after considering power grid's operating constraints, the configuration optimisation model will be more complex and difficult to solve. However, in the actual power grid, short-circuit current violation mostly happens in a few areas. In this case, the number of variables and constraints of the optimisation problem can be reduced by implementing equivalence to the part of power grid which is irrelevant to short-circuit current violation.

In addition, different short-circuit current limiting measures have different application scopes, current-limiting performances, and economic costs. Therefore, it is reasonable to balance the current-limiting performances and economic costs in short-circuit current limiting measure configuration optimisation.

This paper firstly simplifies the power grid based on the Ward equivalence method. Then the economic cost and current limiting-performance of various current limiting measures are analysed. Based on the analysis, a multi-objective optimisation model for short-circuit current limit measure configuration is proposed. In addition, a quantum genetic algorithm (QGA)-based method is proposed to solve the model. Finally, the proposed model is validated by the simulations on an actual power grid.

2 Basic principles of short-circuit current calculation

Taking a n -node power grid, shown in Fig. 1, as an example, the short-circuit impedance of node k is Z_f when a short circuit occurs at this node. According to the circuit theory, every single node of power grid and the short-circuit mode can form a two-port network. Therefore, according to the principle of superposition, the relationship between nodal voltage and current injection can be expressed as follows:

$$\dot{U} = \mathbf{Z}\dot{I} + \dot{U}^0 \quad (1)$$

where

$$\dot{U} = [\dot{U}_1 \quad \dot{U}_2 \quad \dots \quad \dot{U}_k \quad \dots \quad \dot{U}_n]^T$$

$$\dot{I} = [\dot{I}_1 \quad \dot{I}_2 \quad \dots \quad \dot{I}_k \quad \dots \quad \dot{I}_n]^T$$

$$\dot{U}^0 = [\dot{U}_1^0 \quad \dot{U}_2^0 \quad \dots \quad \dot{U}_k^0 \quad \dots \quad \dot{U}_n^0]^T$$

$$\mathbf{Z} = \begin{bmatrix} Z_{11} & Z_{12} & \dots & Z_{1k} & \dots & Z_{1n} \\ Z_{21} & Z_{22} & \dots & Z_{2k} & \dots & Z_{2n} \\ \vdots & \vdots & & \vdots & & \vdots \\ Z_{k1} & Z_{k2} & \dots & Z_{kk} & \dots & Z_{kn} \\ \vdots & \vdots & & \vdots & & \vdots \\ Z_{n1} & Z_{n2} & \dots & Z_{nk} & \dots & Z_{nn} \end{bmatrix}$$

where $\dot{U}_1^0, \dot{U}_2^0, \dots, \dot{U}_n^0$ are the open-circuit voltages of all nodes before short circuit occurs. The open-circuit voltages can be obtained by power flow calculation. In actual short-circuit current calculation, the open-circuit voltage is usually set as 1.0. The elements of the impedance matrix $\mathbf{Z}$ are the self-impedance of each node and the mutual impedance between various nodes.

When a three-phase short-circuit occurs at node k , the boundary condition is

$$\begin{cases} \dot{U}_k = \dot{I}_f Z_f \\ \dot{I}_k = -\dot{I}_f \\ \dot{I}_j = 0 \quad (j = 1, 2, \dots, n; j \neq k) \end{cases} \quad (2)$$

Considering (1) and (2), short-circuit current can be calculated by

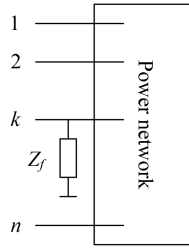


Fig. 1 Sketch of a short circuit occurred in power network

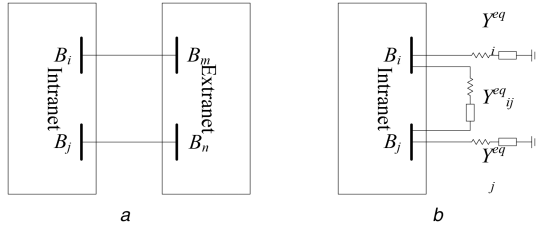


Fig. 2 Sketches of two-area power grid before and after equivalence

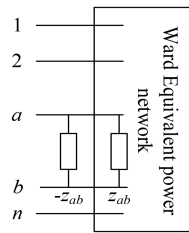


Fig. 3 Sketch of line break

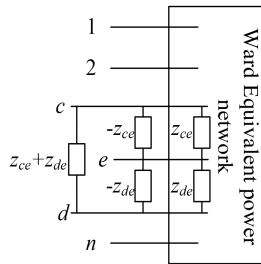


Fig. 4 Sketch of line series operating outside of substation

$$\dot{I}_f = \frac{\dot{U}_k^0}{Z_{kk} + Z_f} \quad (3)$$

According to (3), when the short-circuit impedance Z_f is given, it only needs to know the open-circuit voltage, $\dot{U}_k^0$, and the self-impedance, Z_{kk} , in order to obtain the three-phase short-circuit current at the node k .

3 Ward equivalence of power grid

As short-circuit current is relevant to all power grid operating variables, the problem of short-circuit limiting measure configuration optimisation is quite complex. However, in the actual large-scale power grid, short-circuit current violation only happens in a few areas. Therefore, a feasible approach to simple the optimisation problem is using Ward equivalence [8–10] to reduce the scale of power grid.

A two-zone interconnection power grid before and after the Ward equivalent is given in Fig. 2. The power grid includes two parts: the internal network and the outer network. The internal network is largely related to short-circuit current. Therefore, this part needs to be considered in short-circuit current limiting measures optimisation. Oppositely, the outer network is rarely related to short-circuit current and can be ignored in short-circuit current limiting measures optimisation.

The internal and outer networks are interconnected through the inner boundary nodes, $B_i \dots B_j$, and the outer boundary nodes, $B_m \dots B_n$. After Ward equivalence, the effect of the external network on short-circuit current is reflected on the injection currents and active powers of the boundary nodes.

Using Y'_{II} to represent the initial admittance matrix corresponding to the internal nodes and using Y'_{EE} to represent the initial admittance matrix corresponding to the external nodes, so the power network to be analysed before equivalence can be represented by the following equations:

$$\begin{bmatrix} Y'_{II} & Y'_{IE} \\ Y'_{EI} & Y'_{EE} \end{bmatrix} \begin{bmatrix} V_I \\ V_E \end{bmatrix} = \begin{bmatrix} I'_I \\ I'_E \end{bmatrix} \quad (4)$$

According to (4), there are $Y'_{II}V_I + Y'_{IE}V_E = I'_I$ and $Y'_{EI}V_I + Y'_{EE}V_E = I'_E$. Therefore, after Ward equivalence, the network can be expressed as the following linear equation:

$$Y'_{II}V_I = I'_I \quad (5)$$

In the above formula, $Y'_{II} = Y'_{II} - Y'_{IE}[Y'_{EE}]^{-1}Y'_{EI}$ is the equivalent nodal admittance matrix, and $I'_I = I'_I - Y'_{IE}[Y'_{EE}]^{-1}I'_E = I'_I + I'^{eq}_I$ is the equivalent injection current vector.

4 Network analysis of current limiting

Assume there are n nodes in the equivalent grid. In this section, the change of self-impedance caused by short-circuit current limiting measure is analysed.

4.1 Line breaking

As shown in Fig. 3, the impedance of the connected line between node a and node b is Z_{ab} . The operation of breaking the line Z_{ab} can be represented by adding a line with the impedance of $-Z_{ab}$ between node a and node b in the original network [11].

After the connection between node a and node b is removed, the self-impedance of node k is

$$Z'_{kk} = Z_{kk} - \Delta Z_{kk} = Z_{kk} - \frac{(Z_{ka} - Z_{kb})(Z_{ak} - Z_{bk})}{Z_{aa} + Z_{bb} - Z_{ab}} \quad (6)$$

The self-impedance Z'_{kk} of node k can be quickly calculated. Then the short-circuit current of node k can be calculated according to (3).

4.2 Line series operating outside of substation

Line series operating outside of substation can also be represented by additional line. As shown in Fig. 4, the line ce and the line de are connected at the same node e .

The lines ce and de series operation outside of substation can be represent as adding a line with the impedance Z_{ce} of between the node c and the node e and adding a line with the impedance of Z_{de} between the node d and the node e , and then adding a line with the impedance of $Z_{ce} + Z_{de}$ between the node c and the node e .

After implementing line series operating outside of substation, the short-circuit impedance of node k can be calculated:

- Adding a line with the impedance of $-Z_{ce}$ between the node c and the node e , and then calculating $Z^{(1)}_{kk}$,
- On the basis of step (i), adding a line with the impedance of $-Z_{de}$ between the node d and the node e , and the calculating $Z^{(2)}_{kk}$,
- On the basis of step (ii), adding a line with the impedance of $Z_{ce} + Z_{de}$ between the node c and the node d , and the calculating $Z^{(3)}_{kk}$.

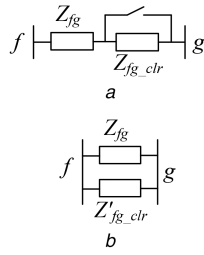


Fig. 5 The case of installing current limiting reactor

(a) Original circuit of adding current limiting reactor, (b) Equivalence circuit of adding current limiting reactor

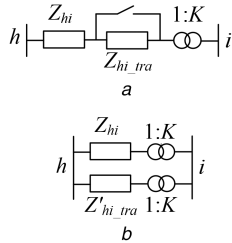


Fig. 6 The case of using high-impedance transformer

(a) Original circuit of high-impedance transformer, (b) Equivalence circuit of high-impedance transformer

$Z_{kk}^{(3)}$ is the short-circuit impedance of node k after implementing line series operating outside of substation. Therefore,

$$Z'_{kk} = Z_{kk}^{(3)} \quad (7)$$

With (7), the self-impedance change of node k , Z'_{kk} , can be quickly calculated, and then according to (3) the short-circuit current can be obtained.

4.3 Installing current limiting reactor

As shown in Fig. 5a, a current limiting reactor with an impedance value of Z_{fg_clr} is installed between the node f and the node g . The circuit of the current limiting reactor can be represented by an equivalent circuit in parallel in Fig. 5b. The relationship between the impedance Z_{fg_clr} of the parallel line and the impedance value Z'_{fg_clr} of the series limiting reactor is [12]:

$$Z'_{fg_clr} = \frac{Z_{fg}(Z_{fg} + Z_{fg_clr})}{Z_{fg_clr}} \quad (8)$$

Similar to the line breaking, the current limiting reactor between the node f and the node g can also be equivalent as a line between the node f and the node g . Therefore, after the current limiting reactor installed between the node f and node g , the short-circuit impedance of node k is

$$Z'_{kk} = Z_{kk} - \Delta Z_{kk} = Z_{kk} - \frac{(Z_{kf} - Z_{kg})(Z_{fk} - Z_{gk})}{Z_{ff} + Z_{gg} + Z'_{fg_clr}} \quad (9)$$

With (7), the self-impedance change of node k , Z'_{kk} , after current limiting reactor is installed, can be quickly calculated, and then according to (3) the short-circuit current can be obtained.

4.4 Using high-impedance transformer

High-impedance transformer can be realised by installing built-in reactor. The equivalent circuit of high-impedance transformer is shown in Fig. 6a. In this figure, Z_{hi} is the short-circuit impedance of the original transformer, Z_{hi_tra} is the impedance value of the built-in reactor, and K is the change ratio. The high-impedance transformer with built-in reactor can be modeled by a parallel equivalent circuit in Fig. 6b. The relationship between the

impedance Z'_{hi_clr} of the parallel line and the impedance value Z_{hi_clr} of the series limiting reactor is

$$Z'_{hi_tra} = \frac{Z_{hi}(Z_{hi} + Z_{hi_tra})}{Z_{hi_tra}} \quad (10)$$

Similar to the line breaking, the use of a high-impedance between the node h and the node i can also be equivalent to a line between the node h and the node i . Therefore, the short-circuit impedance of node k after using high-impedance transformer is

$$Z'_{kk} = Z_{kk} - \Delta Z_{kk} = Z_{kk} - \frac{(Z_{kh} - Z_{ki})(Z_{hk} - Z_{ik})}{Z_{hh} + Z_{ii} + Z'_{hi_tra}} \quad (11)$$

With (11), the self-impedance change of node k , Z'_{kk} , after using high-impedance transformer, can be quickly calculated, and then according to (3) the short-circuit current can be obtained.

5 Optimisation model of short-circuit current limiting measure configuration

In this section, an optimisation mode of short-circuit current limiting measure configuration is proposed. Assuming there are N lines can be disconnected, M lines can be operated outside of substation, H current limiting reactor can be installed, and G high-impedance transformer can be used.

5.1 Analysis on current-limiting performance of short-circuit current limiting measures

The main purpose of current limiting measures is to reduce the short-circuit current of the power grid, the objective function of the optimisation model of short-circuit current limiting measure configuration must reflect the decrease of short-circuit current. In this paper, the short-circuit current change before and after applying the current limiting measures is used to reflect short-circuit current reduction:

$$B = \chi \Delta \dot{I}_f = \dot{I}_f^1 - \dot{I}_f^2 \quad (12)$$

where χ means whether or not a current limit measures is used. If used, then χ is 1; otherwise χ is 0; $\dot{I}_f^1$ is the short-circuit current before using the current limiting measures; $\dot{I}_f^2$ is the short-circuit current after using current limit measures. The short-circuit currents $\dot{I}_f^1$ and $\dot{I}_f^2$ can be obtained according to the method mentioned in the previous section. Therefore, for the various current limiting measures described above, the current reduction effects can be specifically described as

- For line breaking, short-circuit current reduction effect is

$$B_1 = \chi_1 \Delta \dot{I}_{f-1} = \chi_1 (\dot{I}_{f-1}^1 - \dot{I}_{f-1}^2) \quad (13)$$

where χ_1 is whether to break the line. If the measure is implemented, χ_1 is 1; otherwise 0.

- For line series operating outside of substation, short-circuit current reduction effect is

$$B_2 = \chi_{11} \Delta \dot{I}_{f-11} = \chi_{11} (\dot{I}_{f-11}^1 - \dot{I}_{f-11}^2) \quad (14)$$

where, χ_{11} is whether to implementing line series operating outside of substation. If the measure is implemented, χ_{11} is 1; otherwise 0.

- For installing current limiting reactor, short-circuit current reduction effect is

$$B_3 = \chi_{clr} \Delta \dot{I}_{f_clr} = \chi_{clr} (\dot{I}_{f_clr}^1 - \dot{I}_{f_clr}^2) \quad (15)$$

where, χ_{clr} is whether to install a current limiting reactor. If the measure is implemented, χ_{clr} is 1; otherwise 0.

- For using high-impedance transformer, short-circuit current reduction effect is

$$B_4 = \chi_{\text{tra}} \Delta I_{f_tra} = \chi_{\text{tra}} (I_{f_tra}^1 - I_{f_tra}^2) \quad (16)$$

where, χ_{tra} is whether to use high-impedance transformer. If the measure is implemented, χ_{tra} is 1; otherwise 0.

5.2 Analysis on economic cost of short-circuit current limiting measures

- *Line breaking*: The economic costs of opening and closing a line are the same, and the cost is only associated with the number of opening/closing action. Therefore, the cost can be expressed as

$$C_1 = \chi_1 A_1 \quad (17)$$

where A_1 is a constant. If only considering the cost of opening/closing action, A_1 is a very small value, which mainly depends on the labour cost and power losses.

- *Line series operating outside of substation*: Line series operating outside of substation is realised by opening/closing action, so it has no difference to line breaking operation in essence. Therefore, similar to line breaking, the cost can be expressed as

$$C_2 = \chi_{1l} A_2 \quad (18)$$

where A_2 is a constant.

- *Installing current limiting reactor*: Cost of installing current limiting reactor mainly depends on the impedance value. The greater the impedance value is, the higher the cost is [12]. The cost of installing current limiting reactor can be simply calculated by

$$C_3 = \chi_{\text{clr}} (A_3 + B_3 Z_{\text{clr}}) \quad (19)$$

where A_3 and B_3 are the cost factors associated with the voltage level.

- *Using high-impedance transformer*: The investment cost of high-impedance transformer is associated with the impedance value of the built-in reactor. The greater the resistance is, the higher the cost is. Therefore, the investment cost can be calculated by

$$C_4 = \chi_{\text{tra}} (A_4 + B_4 Z_{\text{tra}}) \quad (20)$$

where, A_4 and B_4 are the cost factors associated with the voltage level.

5.3 Multi-objective optimisation model for current limiting measures

According to the current-limiting performances and economic costs analysis of short-circuit limiting measures, a multi-objective optimisation model of current limiting measure configuration is proposed:

Objective function:

$$f(P, C) = \max \sum_{i=1}^4 (\alpha_i P_i - \beta_i C_i) \quad (21)$$

Constraint conditions:

$$\sum_{i=1}^N \chi_i^1 \leq \bar{\chi}_1 \quad (22)$$

$$\sum_{i=1}^M \chi_i^1 \leq \bar{\chi}_{1l} \quad (23)$$

$$Z_{fg_clr}^i \leq \bar{Z}_{fg_clr}^i, \quad i \in (1, 2, \dots, H) \quad (24)$$

$$Z_{fg_tra}^i \leq \bar{Z}_{fg_tra}^i, \quad i \in (1, 2, \dots, G) \quad (25)$$

where α and β are the weight coefficients, $\bar{\chi}_1$ is the number of lines can be disconnected, $\bar{\chi}_{1l}$ is the number of lines allowed to be series operated outside of substation, $\bar{Z}_{fg_clr}^i$ is the largest possible limiting reactor to be installed, and $\bar{Z}_{fg_tra}^i$ is the largest possible built-in reactor in transformer.

6 Solving method based on QGA

QGA is a probability optimisation method based on quantum computing principle and traditional genetic algorithm. Unlike traditional genetic algorithms, QGA is based on quantum computing, uses quantum bit coding to represent chromosomes, and updates generations by using quantum gate functions.

In addition, QGA has the ability of deep learning and excellent convergence speed. Therefore, QGA is promising in solving the proposed current limiting measure configuration operation model.

- *Initial population*: Assuming there are N lines can be disconnected, M lines can be series operated outside of substation, H short-circuit current limiting reactors and high-impedance transformers can be installed. The initialisation population of line breaking, line series operating outside of substation, installing current limiting reactor, and using high-impedance transformer is represented by $X(w) = \{x_1(w), x_2(w), x_3(w), x_4(w)\}$. Where $x_1(w) = \{\chi_1^1(w), \chi_1^2(w), \dots, \chi_1^N(w)\}$; $x_2(w) = \{\chi_{1l}^1(w), \chi_{1l}^2(w), \dots, \chi_{1l}^M(w)\}$; $x_3(w) = \{\chi_{\text{clr}}^1(w), \chi_{\text{clr}}^2(w), \dots, \chi_{\text{clr}}^H(w)\}$; $x_4(w) = \{\chi_{\text{tra}}^1(w), \chi_{\text{tra}}^2(w), \dots, \chi_{\text{tra}}^G(w)\}$; and $x_j(w)$ represents the j th chromosome of the w th generation. The initial probability amplitude values, $(\alpha_{ij}, \beta_{ij})$, in all population are set as $(1/\sqrt{2}, 1/\sqrt{2})$.
- *Individual measurement*: Through individual measurement, a set of solutions, $R(w) = \{\gamma_1^j(w), \gamma_2^j(w), \gamma_3^j(w), \gamma_4^j(w)\}$, can be obtained. In details, $\gamma_j^j(w)$ is the value of the j th chromosome in the w th generation. Each bit of $\gamma_j^j(w)$ is 0 or 1, which is obtained according to the probability amplitudes $|\alpha_{ij}|^2$ and $|\beta_{ij}|^2$. The measuring process is: randomly generating a number between 0 and 1, if it is greater than the probability amplitude of the square, then the measurement value is 1; otherwise 0.
- *Individual evaluation*: The fitness function is used to evaluate each individual in $R(w)$, and if the satisfactory solution or the end condition is reached, the iteration is terminated; otherwise, iteration continues.
- *Population updating*: In this paper, quantum gate $U(w)$ is used to update $X(w)$ [13, 14]. The short-circuit current limiting measure configuration optimisation based on QGA is shown in Fig. 7.

7 Numerical example

For the sake of validating the proposed method, short-circuit limiting measures are applied to an actual regional power grid. The actual regional power grid is firstly simplified by Ward equivalent method (as shown in Fig. 8). There are 19 nodes in the equivalent power grid. Due to the access of 750 kV network and large capacity generators (such as G1 and G4 etc.), the short-circuit current of node GA220 is 51.3 kA which exceeds circuit breaker's capacity (rated breaking current is 50 kA).

The short-circuit current limiting measures, line breaking, line series operating outside of substation, installing current limiting

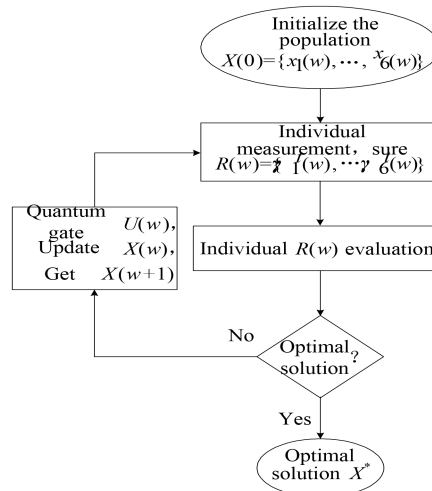


Fig. 7 Flowchart of short-circuit limiting measure configuration optimisation based on QGA

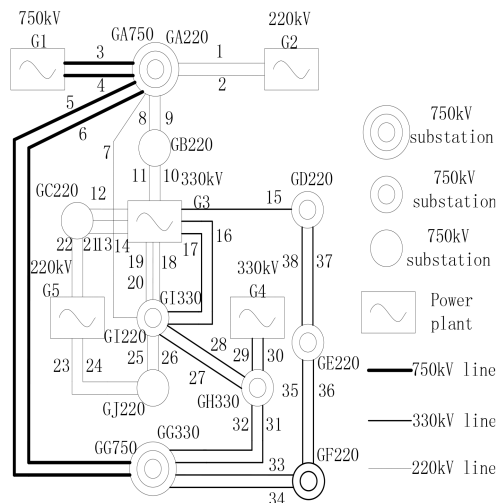


Fig. 8 Equivalent power grid after Ward equivalence

Table 1 Coefficients of the costs of short-circuit limiting measures

The cost factor	Line open circuit	Line out of the string	Current limiting reactor	High-impedance transformer
A	60	120	650	100
B	—	—	20	50

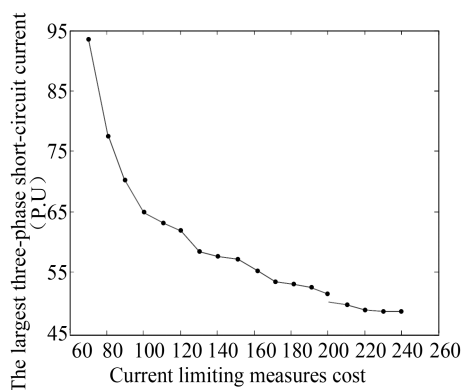


Fig. 9 Relations between limiting measure costs and short circuit

reactor, and using high-impedance transformer, are considered. In equivalent power grid, Line 7 can be disconnected; Line 1 and Line 8, Line 2 and Line 9 can be series operated outside of substation; Line 1, Line 2, Line 7, Line 8, and Line 9 can be installed with

current limiting reactor; high-impedance transformer can be used in Substation GA.

The cost coefficients corresponding to the current limiting measures are given in Table 1. The number of population of the QGA is 100, the weight coefficients α and β in the objective function are 0.01 and 0.99.

After around 40 time's iteration, the proposed algorithm converged, and the best short-circuit current limiting measures are Line 1 and Line 8 series operated outside of substation. The relationship between the economic costs of measures and the systems' maximum short-circuit current during iteration is shown in Fig. 9. As can be seen from Fig. 9, the economic cost and the systems' maximum short-circuit current have an inversely proportional relationship, i.e. the more the cost is, the better the current-limiting performance is obtained.

If Ward equivalent method is not used to simplify the power grid, the optimisation of short-circuit current limiting measures is much complex, and even the global solution cannot be obtained. Fifty times simulation has been implemented and the results are given in Table 2. As can be seen from the Table 2, without applying the Ward equivalent, the algorithm is easy to fall into local convergence.

8 Conclusions

This paper proposes an effective approach to optimise configuration of short-circuit current limiting measures based on Ward equivalence and QGA. Ward equivalence is utilised to reduce power grid's scale so as to reduce the computational work in short-circuit current limiting measure configuration optimisation. In order to balance the economic cost of measures and current-

Table 2 Optimisation of the 50 simulation results of the power grid without Ward equivalent time limit flow

Current limiting measures	Current limit cost	Short-circuit current decreases, kA	The objective function value	50 times occurrences in the simulation	Frequency range of convergence
Lines 1 and 8, Lines 2 and 9 string running	240	8.54	6.0546	35	120–150
GA substation uses 14 high-impedance transformer	800	4.01	−4.0301	9	110–140
the impedance of Lines 1 and 2 in series is 1 Ω reactor	1340	4.92	−8.5292	4	110–130
the impedance of Lines 8 and 9 in series is 4 Ω reactor	1460	3.82	−10.8182	2	100–130

limiting performance, a multi-objective optimisation model for short-circuit current limiting measure configuration is proposed. A QGA-based solving method is proposed, which is effective to obtain the best configuration. Finally, the proposed approach is verified by the simulations on an actual power grid.

9 References

- [1] Gong, X., Gao, C., Long, Z., *et al.*: 'Principle of limiting asymmetric short-circuit current by installing small reactance at 500 kV autotransformer neutral point', *Electr. Power Constr.*, 2013, **34**, (11), pp. 56–60
- [2] Luo, T., Liu, L., Wang, K., *et al.*: 'Influence of UHV grid on short-circuit current of Tianjin 500 kV grid and its restrictive measures', *Electr. Power Constr.*, 2015, **36**, (8), pp. 79–83
- [3] Sun, Y., Wang, Z., Wang, Y., *et al.*: 'A fast calculation method for short circuit current of distribution network with numerous distributed resources', *Electr. Power Constr.*, 2016, **37**, (5), pp. 118–124
- [4] Ruan, Q.: 'The situation and countermeasures of short-circuit current control in shanghai power grid', *Power Syst. Technol.*, 2005, **29**, (2), pp. 78–83
- [5] Liu, S., Gu, Q., Zhang, L., *et al.*: 'Divisional power supply solutions in Tianjin 500/220 kV power grid during the period of 11th five-year plan', *Power Syst. Technol.*, 2008, **32**, (9), pp. 51–55
- [6] Yang, X., Li, L., Li, Y., *et al.*: 'The running program to limiting short-circuit current in Guangdong 500 kV power grid', *Autom. Electr. Power Syst.*, 2009, **33**, (7), pp. 104–107
- [7] Chen, L., Huang, M., Zhang, H., *et al.*: 'An optimization strategy for limiting sort circuit current', *Autom. Electr. Power Syst.*, 2009, **33**, (11), pp. 38–42
- [8] Shao, Y., Li, X., Cheng, J.: 'Studies on applying rei method to computing short-circuit fault current of distribution system of many nodes', *Proc. CSEE*, 2000, **20**, (4), pp. 64–67
- [9] Sun, Q., Cai, Z., Zhu, L., *et al.*: 'Multi-terminal equivalence method of interconnected power system and improvement based on its error analysis', *Power Syst. Technol.*, 2008, **32**, (23), pp. 67–71
- [10] Yan, W., Li, S., Chen, J., *et al.*: 'Parameter estimation for two-port external network static equivalent model on the basis of internal network measured information', *Proc. CSEE*, 2011, **31**, (13), pp. 101–106
- [11] Feng, S., Yu, Y.-J., Wang, L., *et al.*: 'A method of fast short-circuit current calculation for topology adjustment', *Power Syst. Prot. Control*, 2014, **42**, (8), pp. 28–33
- [12] Chen, L.: 'Research on optimal strategies of short-circuit current limiter development for large-scale power systems'. PhD thesis, Zhejiang University, 2011
- [13] Han, K.H., Kim, J.H.: 'Genetic quantum algorithm and its application to combinatorial optimization problem'. Proc. 2000 Congress on Evolutionary Computation, La Jolla, USA, July 2000, pp. 1354–1360
- [14] Han, K.H., Park, K.H., Lee, C.H., *et al.*: 'Parallel quantum inspired genetic algorithm for combinatorial optimization problem'. Proceeding of the 2001 IEEE Congress on Evolutionary Computation, Seoul, Korea, May 2001, pp. 1442–1429