Optimisation of network reconfiguration based on a two-layer unit-restarting framework for power system restoration

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Abstract: An optimisation method of network reconfiguration is proposed by introducing a two-layer unit-restarting framework for power system restoration. The unit restarting during the network reconfiguration is treated as a two-layer restoration process—network-layer unit restarting and plant-layer unit restarting. Based on the two-layer framework, the optimisation of the network reconfiguration is modelled as a multi-objective optimisation problem, in which the network-layer unit restarting, the plant-layer unit restarting and restoration of the important loads are separately modelled as three optimisation sub-problems with their own models and solving algorithms. The lexicographic optimisation method is then used to solve the multi-objective optimisation problem by integrating the solving processes of the three sub-problems. The proposed optimisation method of network reconfiguration can determine the restarting sequence of all the units and realise the coordinative optimisation of the unit restarting and restoration of the important loads. The effectiveness of the proposed method is validated by the numerical results of a restoration example based on the New England 10-unit 39-bus power system.

1 Introduction

Since 1980s, large amount of research has been carried out on power system restoration. Most of the work focused on restoration of large interconnected power systems [1–3], whereas some work specially focused on restoration of isolated power systems such as a shipboard power system [4]. After a major blackout occurs in a power system, the whole restoration process can be generally divided into three stages [2, 3]: black-start process, network reconfiguration and full load restoration. Among the three stages, the network reconfiguration is a critical intermediate stage and plays an essential role to build a strong skeleton network, in which the successful restoration of the generating units is the basis of the restoration [5, 6]. Determination of the unit restarting sequence and optimisation of the network reconfiguration have been paid much attention [7–15], whereas other issues such as application of HVDC links to system restoration [16] and development of restoration guidance simulators [17] have also been addressed. The related problems about determination of the unit restarting sequences are introduced in [7, 8]. The unit restarting sequences were optimised by using expert system method and back-tracking algorithm in [8, 9], respectively. A novel model to determine the units most suitable to restarting is presented in [10]. Based on the topological characteristics of scale-free networks, a skeleton-network reconfiguration strategy is proposed in [11, 12]. The optimisation of the restoration paths is studied by dividing the restoration process into two phases—series energising and parallel energising in [13]. The optimal target network and corresponding optimal restoring sequence are obtained at the same time by using the weighted complex network model [14] and fast elitist non-dominated sorting genetic algorithm [15].

Although significant achievements have been obtained on unit restarting and network reconfiguration, there are still some problems to be investigated further. The common shortcomings of the previous work include

1. A power plant was treated as only one generating unit, or the restarting of only one unit but not all the units was considered in a power plant.
2. It was simply thought that a unit can be restarted if the bus connected to the unit was energised in the hot-start time limit, without consideration of the cranking power constraints. Meantime, the unit’s climbing characteristics of the power output after restarted was not fully considered.
3. The load restoration was not considered in the optimisation of the network reconfiguration process.

Owing to the above problems, the available network reconfiguration methods so far largely deviate from the practical restoration process and this has reduced their application value in practical power systems.

In this paper, an optimisation method of network reconfiguration is proposed by introducing a two-layer unit-restarting framework. The unit restarting is treated as a two-layer restoration process—network-layer unit restarting and plant-layer unit restarting. Then, three optimisation
2 Optimisation strategy of network reconfiguration based on a two-layer unit restarting framework

The network reconfiguration optimisation involves the coordination of unit restarting, line re-energising and important-load restoration, where the unit restarting is the key issue to the whole restoring process and the line re-energising can be determined by the optimal recovery paths of units and loads. In fact, the unit restarting has a layered feature and can be divided into two-layers—the network-layer unit restarting and the plant-layer unit restarting. From the network layer, more power plants should be soon restored to expand the geographical distribution of the power sources for the quick construction of a skeleton network, and from the plant layer, all units in a plant should be restarted as soon as possible to provide a larger power capacity for restoration of the important loads after.

In the two-layer framework, the unit restarting in the network-layer and the plant-layer can be carried out in parallel, and network reconfiguration is modelled as a multi-objective optimisation problem with network-layer unit restarting, plant-layer unit restarting and important-load restoration. Meantime, since the network reconfiguration is a continuous dynamic process and the previously restarted units have a strong after-effect to the succeeding restoration, it is very difficult to optimise the network reconfiguration based on an overall model of the whole process. Therefore, a global optimisation strategy of ‘modelling on discrete time steps, optimising on the whole process’ is developed to optimise the reconfiguration process. Through partitioning the time axis for the system restoration, the continuous restoring process is changed into a multi-step sequential process, thus the whole reconfiguration problem is changed into the optimisation for all the time steps to be solved coordinately. In each step, the initial condition of restoration is set according to the actual restoring state of the previous step, then, the network-layer units, the plant-layer units and the important loads to be restored are determined from the global optimisation strategy. In the proposed optimisation strategy, the reconfiguration in current step is solved from the angle of the whole process optimisation, that is, in the optimisation goal the influences of the current step restoration to succeeding unit restarting is taken into account.

In this paper, in the modelling process of the network reconfiguration optimisation, the following assumptions are made:

1. Suppose the operating regulation has set the start-up sequence of all the units in a power plant, and the first unit to be restarted is set as the network-layer unit, the other units as the plant-layer units.
2. Only one unit can be restarted at one time owing to the personnel and equipment limitation in a power plant.
3. In each restoring time step, the instant of unit restarting is determined by the dispatcher according to the system condition, but in order to facilitate the problem’s analysis, in the proposed method all the units are restarted at the end of the time step.
4. The operating time of energising transmission lines, the transient process of the unit restarting and the load restoration are not taken into account.

The assumption (4) above may need further explanation. In the network reconfiguration process, the operating time of energising a line is very short, compared with the optimisation time step (usually 15–30 min); so the time consumption of energising the recovery paths will not influence determination of the restarting sequence of units and loads. As for the transient impacts of the unit restarting and load restoration, through limiting the total power of loads picked up in one time, they can be controlled within an acceptable range without occurrence of system collapse.

3 Modelling of the network reconfiguration optimisation

Based on the reconfiguration strategy of ‘modelling on discrete time steps, optimising on the whole process’, the whole reconfiguration process is divided into a series of sequential restoring time-steps, the optimisation is modelled on each separate time step and solved with the consideration of the whole process optimisation. In this section, the optimisation model of the 4th time step is built with the step-size \( \Delta t \), and the optimisation of the time interval \( [k-1] \Delta t, k \Delta t \) is described as a representative example.

3.1 Optimisation objectives

To the multi-objective optimisation problem of network reconfiguration, the individual models according to the three optimisation objectives are first built, respectively, the overall multi-objective optimisation model can be given using the three individual models.

3.1.1 Objective of the network-layer unit restarting:
Considering the whole process optimisation, in network-layer unit restarting, not only the total MWh output of a restarted unit but also its influences to the succeeding unit restarting in the same plant should be considered. Therefore a network-layer unit with a larger MWh output after restarted and within a plant in which the plant-layer units have a larger total capacity has higher priority to be restarted, and the optimisation objective function is defined as

\[
f_1 = \sum_{i=1}^{n_G} \int_{t_1}^{t_1+\Delta t} \left( \alpha(t)c_{ij}P_{G_i(t)} \right) dt + \mu \sum_{j=2}^{n_G} P_{M_j}(t)
\]

where \( n_G \) is the number of power plants in the power system; \( n_G(i) \) is the number of units in the \( i \)-th plant \( (i = 1, 2, \ldots, n_G) \); \( T_1 \) is the total time consumption of the network reconfiguration process; \( G_i \) represents the unit \( j \) \( (j = 1, 2, \ldots, n_G(i)) \) in the \( i \)-th plant; \( c_{ij} \) is the restarting state indication of \( G_i \) (if \( G_i \) is restarted in the current time step, \( c_{ij} = 1 \), otherwise, it is 0);
\( \alpha(t) \) is a weight coefficient of unit’s MWh output in different time steps (it is given a greater value in the initial system restoring stage considering the need of important load restoration to the unit’s power output, and its value gradually reduced to a minimum value as the time elapses); \( P_{Mij} \) is the maximum output of \( G_{ij} \); \( \mu \) is distributing factor to adjust the contribution of each term to the objective function; and \( P_{Gij}(t) \) is MW output of \( G_{ij} \) at time \( t \), it is simplified as shown in Fig. 1 [9].

\[
P_{Gij}(t) = \begin{cases} 0, & 0 \leq t < T_{Sij} - T_{Kij} \\ K_{Pij}(t - T_{Sij} - T_{Kij}), & T_{Sij} - T_{Kij} \leq t < T_{Sij} + T_{Kij} \\ P_{Mij}, & t \geq T_{Sij} + T_{Kij} + T_{Rij} \end{cases}
\]

where \( T_{Sij} \) is the start-up time of the unit \( G_{ij} \); \( T_{Kij} \) is the time period from the instant of unit restarting to the beginning time of unit output ramping of \( G_{ij} \); \( T_{Rij} \) is the time period from unit ramping begin to the instant reaching the maximum output of \( G_{ij} \); and \( K_{Pij} \) is the maximum ramp-rate of \( G_{ij} \).

### 3.1.2 Objective of the plant-layer unit restarting:

The objective of the plant-layer unit restarting is to maximise the total weighted MWh output that the system can provide during the network-reconfiguration period. The objective function is defined as

\[
f_2 = \sum_{j=1}^{nG} \sum_{i=1}^{nGj} \int_{t_{k}}^{t} \alpha(t)c_{ij}P_{Gij}(t)\,dt
\]

### 3.1.3 Objective of important load restoration:

The objective of important load restoration is to maximise the total weighted load amount. The objective function is defined as

\[
f_3 = \sum_{i=1}^{nL} \left( \beta_{I}c_{IL}w_{I}P_{LLs} + \beta_{II}c_{IL}w_{II}P_{LIl,s} + \beta_{III}c_{IL}w_{III}P_{LLL,s} \right)
\]

where \( n_{L} \) is the number of load buses in the system, \( \alpha_{I}, \alpha_{II}, \alpha_{III} \) are the comprehensive load weights/active power/state indication (1 for on, 0 for off) of the Class-I, Class-II, Class-III load on the load bus.

3.2 Constraints

#### 3.2.1 Start-up power constraints:
The unit start-up and load restoration require sufficient power support. In each time step, the sum of cranking power for the units to be restarted and the active power of the restored loads must be less than the start-up power that the system can provide in the current time step. The corresponding start-up power requirements for all units and loads are given by

\[
\sum_{i=1}^{nG} \sum_{j=1}^{nGj} c_{ij}P_{Gij}(t_{k}) + \sum_{i=1}^{nG} c_{ij}P_{Gij}(t_{k}) < \Delta P_{S}(k)
\]

where \( P_{Gij} \) is the cranking power required by the unit \( G_{ij} \), and \( \Delta P_{S}(k) \) is the start-up power that can be used in the \( k \)-th time step (it is determined by the active power increase of all the restarted units, including the black-start unit in the current time period).

\[
\Delta P_{S}(k) = \sum_{i=1}^{nG} \sum_{j=1}^{nGj} e_{ij}(P_{Gij}(k\Delta t) - P_{Gij}((k - 1)\Delta t))
\]

where \( e_{ij} \) is the state indication of the unit \( G_{ij} \) (if the unit has been successfully restarted, \( e_{ij} = 1 \), otherwise \( e_{ij} = 0 \)).

#### 3.2.2 Maximum power constraint to restoration of a single load:
The maximum power of a single load to be picked up should be less than the maximum power limit in the current step. Otherwise, the frequency drop caused by picking up the load will exceed the permitted frequency drop limit, and then cause low-frequency load shedding action or even system collapse. The maximum power constraint to a single load is given

\[
\begin{align*}
P_{GL_{max},ij} &< P_{L_{max}}(k) \\
P_{L_{ll},s} &< P_{L_{max}}(k) \\
P_{L_{lll},s} &< P_{L_{max}}(k)
\end{align*}
\]

where \( P_{GL_{max},ij} \) is the active power of the largest auxiliary motor of \( G_{ij} \), and \( P_{L_{max}}(k) \) is the maximum power limit to a single-load restoration in the \( k \)-th time step.

According to [18], \( P_{L_{max}}(k) \) can be calculated roughly by the frequency response rates of the restarted units as

\[
P_{L_{max}}(k) = \left[ \begin{array}{c} 0 \\
\frac{\omega_{H}}{\omega_{H} + 1} \frac{\omega_{H}}{\omega_{H} + 1} \end{array} \right] P_{G_{ij}}(t_{k})
\]
shown in (9) 

\[ P_{\text{L, max}}(k) = \Delta f_{\text{max}} \sum_{j=1}^{n_0} \sum_{l=1}^{n_{0j}} c_{ij} \frac{P_{S,ij}}{d_{ij}} \]  

(9) 

where \( \Delta f_{\text{max}} \) is the permitted frequency drop, \( d_{ij} \) is the frequency response rate of \( G_{ij} \) under current loading condition. The value of \( d_{ij} \) is dominated by the dynamic characteristics of the prime movers.

Based on the typical frequency response rates of steam-turbine unit at loading rate of 5, 40 and 75% given by [18], the units’ frequency response rates under different load conditions are calculated by using a piece-wise linear method. In each time step, the units’ loading rates gradually increase, so the frequency response rates at the beginning time of the 4th time step is used in calculation of \( P_{\text{L, max}}(k) \) to obtain a conservative result.

3.2.3 Start-up time limitation: Mostly, the units to be restarted are thermal generating units. A unit with drum-type boilers has a maximum critical time limit for hot-start, if the hot-start condition is lost; the unit has to be restarted in a cold-state after a considerable time delay (usually several hours). A unit with supercritical boiler has a minimum critical cold-start time limit; it cannot be started before the time limit.

The maximum critical hot-start time limit constraint for the hot-start unit \( G_{ij} \) is given by

\[ 0 < T_{S,ij} < T_{\text{CH,ij}} \]  

(10) 

where \( T_{\text{CH,ij}} \) is the maximum critical hot-start time limit of \( G_{ij} \) considering a reasonable margin.

Similarly, the minimum critical cold-start time interval for the cold-start unit \( G_{ij} \) is given by

\[ T_{S,ij} > T_{\text{CC,ij}} \]  

(11) 

where \( T_{\text{CC,ij}} \) is the minimum critical cold-start interval of \( G_{ij} \).

3.2.4 System operating constraints: They are mainly the constraints of power flow, minimum and maximum system frequency, upper or lower-power limits of the units, bus voltage limits and the power limits of transmission lines. The system operating limits can be conceptually expressed by equations and inequalities as follows

\[ \begin{align*}
  g(x, u) &= 0 \\
  g(x, u) &< 0
\end{align*} \]  

(12)

where \( x \) is a vector of the system state variables and \( u \) of the system control variables.

4 Solving methodology of the multi-objective optimisation problem

In the established multi-objective optimisation model, network-layer unit restarting, plant-layer unit restarting and important-load restoration have different priorities and a hierarchical structural relationship and the constraint sets, such as the start-up power constraint, the power flow constraint are interdependent. The lexicographic method is used to solve the multi-objective problem. In the constraint set, the single-load maximum-power constraint and unit start-up time constraint can be settled by preselection of units and loads, and the system-operating constraint can be checked by power flow analysis of the optimal reconfigured network in each time step. Therefore the network-reconfiguration optimisation can be changed into a typical multi-constraint knapsack problem with the start-up power constraint. The lexicographic method and backtracking/greedy algorithm can be effectively combined to solve the network-reconfiguration problem.

4.1 Optimisation of network-layer unit restarting and plant-layer unit restarting

4.1.1 Preselection of units to be restarted: In each time step, the units satisfying the single-load maximum power constraint and unit start-up time constraint are preselected as the candidate units to be restarted, and then the preferential units to be restarted in current time step are determined through optimisation in the candidate unit set.

1. Preselection of network-layer units to be restarted

In the network reconfiguration, a main operating task is to energise recovery paths to deliver cranking power to network-layer units. In this paper, the Dijkstra algorithm [19] is used to obtain the units’ shortest recovery paths, whereas the charging reactive powers of transmission lines under rated voltage with high-voltage and low-voltage compensating reactors are used as the distance measurements.

The preselection of network-layer units is done in the following steps: (a) The distance value of the restored lines are set to a very small positive number \( \epsilon \) according to the system actual state of the previous time step; (b) The un-restarted units satisfying the start-up time constraint and with \( P_{\text{CL, max},k} \) less than \( P_{\text{L, max}}(k) \) are put into an array \( W_k \); (c) The distance of the recovery path \( d_{\text{G1}} \) of the units in \( W_k \) is obtained by using the Dijkstra algorithm; and (d) The units’ recovery-path distance \( d_{\text{G1}} \) of a unit is less than \( d_{\text{max}} \), then it is selected as the optional restarted network-layer unit and is put into an array \( W \); where \( d_{\text{max}} \) is the line’s largest charging reactive power permitted, which is determined by the over-voltage permitted at the line end when energising the no-load transmission line.

2. Preselection of plant-layer units to be restarted

A plant-layer unit that satisfied all the following four constraints is selected as the optional restarted unit in the current time step and is put into an array \( P \).

(a) All the units to be started before this unit in the unit-starting queue of the same plant have been restarted; (b) There are no other units in starting process in the same plant in the current time step; (c) The unit’s \( P_{\text{CL, max},k} \) is less than \( P_{\text{L, max}}(k) \); (d) The units’ start-up time constraint is satisfied.

4.1.2 Unit restarting optimisation based on the backtracking algorithm: The optimisation problems of network-layer unit restarting and plant-layer unit restarting are solved, respectively, by the backtracking algorithm [20]. In each time step, according to the actual system state of the previous step, the start-up power which the system can provide in the current step is calculated. Based on the previously restored system, the next unit to be restarted is searched, and then the cranking power constraint to start this unit is checked. If the cranking power constraint is satisfied, the objective function value (the total weighted MWh output that all the selected units can provide during
the whole reconfiguration period) is calculated. After that, whether the objective function value is larger than the original one is judged, if larger, this unit restarting scheme is discarded and the searching process is continued to find another unit directly. If the cranking power constraint is not satisfied, the current unit is discarded and the searching process returns to the previous unit to take a new route to search for another unit. After all the units in the layer are searched, then the searching process goes back to the previous unit and repeats the search until all unit restarting scheme have been visited. After the whole searching process is completed, the optimal combination of units to be restarted can be found.

4.2 Optimised restoration of important loads

4.2.1 Determination of comprehensive weight coefficients of loads: In load restoration, the Class-I loads are first restored, the Class-II and III loads are then recovered. In the network-reconfiguration process, the restoration of a Class-I load usually requires to energise the load restoration path, but the restoration of the Class-II and III loads does not, with the load bus energised in the restoration of the Class-I loads. Therefore in restoration of the Class-I loads, the operating cost, operating reliability, load importance and the load’s influence to succeeding network-reconfiguration should be considered comprehensively, whereas in restoration of the Class-II and III loads, only load importance and their influence to succeeding network-reconfiguration are considered. The comprehensive weights of all the loads on different load switches are calculated by using the analytic hierarchy process (AHP) algorithm in [19]. The AHP model for Class-I loads is constructed with eight evaluating indexes of \(C_1 - C_8\) as shown in Fig. 2.

For each of Class-I loads, the eight evaluating indexes are first normalised, and the comprehensive weight coefficient can be then obtained by weighted summations from the index layer to the goal layer. The detailed procedure of the AHP algorithm can be found in [19]. For the Class-II and III loads, the calculating process of the weight coefficients is similar and much simpler, with only two indexes considered.

4.2.2 Load restoration optimisation based on the greedy algorithm: All the un-restored loads, except the loads whose capacities are larger than the allowed single-load capacity \(P_{L_{\text{max}}}(k)\), are taken as the candidate loads to be restored in the current time-step \(k\). The start-up power constraint is modified as \(\sum_{n=1}^{N} c_{II} P_{L_{II}}(k) + c_{III} P_{L_{III}}(k) + c_{I} P_{L_{I}}(k) < \Delta P_{S}(k)\), where \(\Delta P_{S}(k)\) is the remaining available start-up power after the unit restarting power is deducted in the current time step.

The load restoration optimisation in each time step can be treated as a one-dimensional knapsack problem with the objective function \(f\) and the start-up power constraint. As the number of load buses is usually large, and each load bus has three load switches for the three load classes, the greedy algorithm [20] is used to solve this knapsack problem for obtaining a solution quickly. The loads and transmission lines to be restored are determined from the optimisation results. After getting the restoring plans, the system operation constraints are checked by power flow calculation of the reconfigured network in the current time step. If all the constraints are satisfied, then specific restoring instants of the loads and transmission lines can be determined by the dispatcher according to actual situation. If any constraint is not satisfied, the load restoration optimisation has to be carried out again by appropriately increasing the comprehensive weight coefficients of the loads on the energised paths, until all operating constraints are satisfied.

4.3 Network reconfiguration optimisation based on the lexicographic method

The lexicographic method is a multi-objective optimisation method, in which all the objectives are ranked in a descending order of the objective importance, and then all

![Fig. 2](https://www.ietdl.org)
the objectives are sequentially optimised based on the given order with the previous optimisation results reserved when the next optimisation objective is solved, until all the objectives are optimised [21]. In network reconfiguration, optimisation of network-layer unit restarting is taken as the first objective, optimisation of plant-layer unit restarting the second objective and optimisation of the important-load restoration the third objective. In each time step, the initial state of the reconfigured system can be determined according to the optimisation results of the previous time step. Network-layer unit restarting is optimised at first and the feasible optimisation domain for the next objective is modified (such as the remaining available start-up power, the energised buses and the loads at the unit buses) according to the optimisation results. Then, plant-layer unit restarting is optimised. On the basis of unit-restarting optimisation, important-load restoration is optimised as the last optimised objective. Through the optimisation calculations in the sequential time-steps considering the whole-process optimisation, the whole network-reconfiguration process is optimised until the preset reconfiguration target is reached (in this paper, the reconfiguration target is all the units satisfying the hot-start limits have been restarted).

At the beginning of the reconfiguration optimisation, the network-reconfiguration time period $T_1$ is unknown; so $T_1$ is set to 3 h at first (considering the usual condition), and then, the network reconfiguration is optimised and the real-time consumption $T$ for the network reconfiguration is obtained. If $T$ is equal to $T_1$, the optimisation process is completed. Otherwise, $T_1$ is set to $T$, and the reconfiguration optimisation is repeated until the newly obtained $T$ is equal to $T_1$. The optimisation process of the network reconfiguration is shown in Fig. 3.

5 Case study and result analysis

5.1 Example power system and system parameters

The New England 10-unit 39-bus power system shown in Fig. 4 is used to verify the effectiveness of the proposed network reconfiguration method. The optimisation program was developed with the programming tools of MATLAB on a personal computer. There are totally ten power plants in the power system. As the plant at bus 39 is an equivalent generating unit of the external power system, it is not considered in the network reconfiguration optimisation. The unit at bus 30 is used as the black-start unit, and it is successfully restarted at the instant 0 h as the beginning time of the network reconfiguration. The numbers and parameters of the units in the nine power plants are assumed as that in Table 1. The units at bus 31 are subjected to a minimum critical cold-start time constraint, and the others are subjected to a maximum critical hot-start time limit. The time-step-size $\Delta t$ is set to 0.25 h, $\mu$ is given a value of 0.1, the parameter $\alpha$ is given a value of 1.5 from the restoring period of 0 to 1 h, 1.0 from 1 to 2 h, 0.8 from 2 h to $T_1$, and $\beta_1 = 10$, $\beta_II = 5$, $\beta_III = 1$. The active power at each load bus is given the value in normal system operating condition, of which the Class-I load ratio is set to 10–20%, the Class-II load is set to 25–45% and the actual ratios of the Class-I and II loads are generated randomly in the range. The ratio of the Class-III load is determined according to the ratios of the Class-I and II loads. The power factor for all the loads is set to 0.8.

Fig. 3 Flowchart of the network reconfiguration optimisation

Fig. 4 New England 10-unit 39-bus power system
5.2 Results of the network reconfiguration optimisation

Through optimising the network reconfiguration process of the used example by using the proposed method, the units to be restarted and loads to be restored in each time step are obtained, as shown in Table 2. The reconfigured skeleton-network for the studied power system is shown in Fig. 5.

5.3 Result analysis

As seen from Table 2, the total reconfiguration time is 2.5 h (10 time steps, 0.25 h for each step). The network-layer units were restarted in the first three time steps. As the constraint of ‘each power station can restart only one unit at one time’, no plant-layer units satisfied the restarting constraint in this period, and the remaining start-up power is used to restore the important loads on buses 12 and 26. From the fourth step, plant-layer units began to be restarted gradually, and the star-up power the system could provide increased continually with more restarted units, so the important loads could be restored step by step. In the tenth step, all the units meeting the hot-start requirements were successfully restarted, so the optimisation process was completed, whereas most of the Class-I loads in the system were also restored. The power flow analysis of the optimised reconfigured network is carried out in each time step.

In the first time step, the black-start source provided cranking power to the network-layer units on the buses 32, 33 and 38; so all the restoring paths for these units were energised and all the Class-I, II and III loads at bus 12 were also restored (because restoration of the Class-I load at bus 31 requires to energise three new lines with over-voltage occurrence, and the remaining start-up power is less than the Class-I load power at any other bus), through power flow calculation, the maximum voltage was at bus 29 with a value of 1.072 p.u. In the second step, the restored system provided cranking power to the network-layer units on the buses 35, 36 and 37, and no loads were restored, the maximum voltage was still at bus 29 with a value of 1.09 p.u. In the third time step, the restored system provided cranking power to the network-layer units on bus 34, and the Class-I load at bus 26 was restored, and the maximum

Table 1 Parameters of the units in the nine power plants

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Unit ID</th>
<th>$P_{NI}$, MW</th>
<th>$P_{cr}$, MW</th>
<th>$K_{P}$, MW/h</th>
<th>$T_{K}$, h</th>
<th>$T_{R}$, h</th>
<th>$T_{CC}$, h</th>
<th>$T_{CH}$, h</th>
</tr>
</thead>
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<td>30</td>
<td>30-1</td>
<td>200</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
</tr>
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<td>160</td>
<td>0.50</td>
<td>3.75</td>
<td>4</td>
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</tr>
<tr>
<td></td>
<td>31-2</td>
<td>600</td>
<td>30.0</td>
<td>160</td>
<td>0.50</td>
<td>3.75</td>
<td>4</td>
<td>N/A</td>
</tr>
<tr>
<td>32</td>
<td>32-1</td>
<td>250</td>
<td>12.5</td>
<td>108</td>
<td>0.67</td>
<td>2.31</td>
<td>N/A</td>
<td>2.75</td>
</tr>
<tr>
<td></td>
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<td>250</td>
<td>12.5</td>
<td>108</td>
<td>0.67</td>
<td>2.31</td>
<td>N/A</td>
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Table 2 Optimised sequence of unit and load restoration

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</table>
system voltage was still at bus 29 but the voltage decreased to 1.068 p.u. with further load restoration. From the fourth step, as the plant-layer units were gradually restarted and a part of loads were further restored, the maximum system voltage was well controlled under 1.05 p.u. In the whole reconfiguration process, the maximum voltage is 1.09 p.u., and all the system operating constraints are satisfied.

Based on the two-layer unit-restarting framework, the network-layer units were restarted in the first three time steps, and all the recovery paths for these units were energised. After that, the plant-layer units were restarted step by step till all the units meeting the hot-start requirements were successfully restarted. By the proposed strategy, a quick network reconfiguration is realised through restarting the network-layer units soon and the restart of all the units is considered, by introducing the layered optimisation method, whereas the previous methods simply treated a power plant as a single unit, which was obviously not conform to the practical restoring process. Furthermore, the restoration of important loads is optimised to coordinate with the unit restarting, and so the coordinative optimisation of unit restarting, line re-energising and important-load restoration is realised.

6 Conclusions

A novel network-reconfiguration optimisation method based on a two-layer unit-restarting framework for power system restoration is proposed. By dividing all the units into network-layer units and plant-layer units, the coordinative optimisation of network-layer unit restarting, plant-layer unit restarting and restoration of important loads is realised through a reconfiguration strategy of ‘modelling on discrete time steps, optimising on the whole process’, by means of the lexicographic multi-objective optimisation algorithm. The proposed method can eliminate the shortcomings of the previous network-reconfiguration methods in which a power plant is treated as a single unit or only one unit of each plant is considered. At the same time, the unit ramping characteristics of power output and the system operating constraints are well considered in the restoring process. The proposed network-reconfiguration method can be used for determining restoration plans after a major blackout of a power system.

7 Acknowledgments

The work in the paper is supported by a project of National Natural Science Foundation of Hebei Province (E2011502025), and a Project of National Natural Science Foundation of China (51077052).

8 References

Q1 Please provide expansion for the abbreviation HVDC.
Q2 IEE style for matrices and vectors is to use bold italics. Please check that we have identified all instances correctly.