IET Generation, Transmission & Distribution

*Research Article*

# Optimisation model for online generators when a new generator is about to get started during power system restoration process

ISSN 1751-8687
Received on 9th April 2016
Revised on 19th August 2016
Accepted on 16th September 2016
doi: 10.1049/iet-gtd.2016.0331
www.ietdl.org

*Chongru Liu*[1] ✉, *Minhao Wu*[2], *Wei Xu*[1], *Feng Qian*[3], *Gang Luo*[3], *Qingang Duan*[3], *Haiyang Hu*[1], *Jiayu Wang*[1]

[1] *North China Electric Power University, No. 2 Beinong Road, Beijing, People's Republic of China*
[2] *State Grid Xiamen Electric Power Company, Xiamen, People's Republic of China*
[3] *Power Dispatch Control Centre of Guangdong Power Grid Corp. Ltd, No. 75 MeiHua Road, Guangzhou, Guangdong, People's Republic of China*
✉ *E-mail: chongru.liu@ncepu.edu.cn*

**Abstract:** Rapid restoration of power systems is vitally important following an outage; however, existing optimal objectives and models to start up all the generators may cause problems where by some generators are ramping while others are waiting shown in the calculation results. To address this problem considering the generator regulation characteristics, a variable-constrained maximum-value minimisation model is proposed in this study to describe the practical problem. By introducing the time variable $t$, the variable-constrained optimisation problem is converted to a constrained optimal power flow problem, which can be solved using common optimisation approaches. Applying the proposed model and method, the optimisation method is discussed considering the characteristics of generators during power system black start. Numerical results show that the algorithm is effective and can significantly reduce the restoration time. The algorithm described here is applied to the Guangdong power grid self-healing decision-making system.

## 1 Introduction

Following an outage, various operating conditions should be considered as a part of the self-healing process, which can be divided into several independent sub-problems [1], such as generator restoration path, generator restoration sequence, and so on. For each sub-problem, specific methods have been proposed to improve the efficiency of the algorithm, depending on the corresponding constraints. Self-healing strategies that are highly efficient can expedite system restoration, and enhance the overall reliability of the system. Conventionally, only hydropower and small fuel generators can operate as black-start power sources; however, the total capacity of such black-start generators is typically relatively small, and is often constrained to particular geographical locations. Fast cut back (FCB) [2] is a technology that can be used when a blackout occurs, whereby thermal power units with FCB functionality can separate from the system and operate in islanded mode as an auxiliary system. Therefore, generators with FCB functionality may be considered as black-start power sources, and can contribute to rapid recovery of the power supply. Furthermore, FCB is easy to implement in large-capacity thermal generators by transforming the steam valve of the generator.

The restoration process of power systems involves three stages: black-start, network restoration and load pick-up [3, 4]. During the black-start stage, the aim is to restart the generators from the black-start power sources. Parts of the network are changed because certain paths are required to restart the generators in the network [5]. The primary goal of the black-start stage is to recover as many generators as possible, and obtain a large potential capacity quickly.

To recover maximum power capacity, the objective can be chosen to include the maximum capacity of generators and the maximum load [6]; however, with this method, time is not considered in the optimisation process. Minimisation of the total power adjustment for all generators during each time step has been selected as an objective [7], whereby the ramping characteristics of the generators were considered to include start-up time. This model was improved upon the model proposed in [8] to coordinate the adjustment of loads by considering the weighted minimal adjustment of the active power generation and the active loads. The critical maximum time of a generator is the focus of the method described in [9]; a zoned start-up strategy was proposed, which takes both power capacity and restoration time into account. The physical characteristics of the ramping ability of the generator were not considered, however. The output characteristics of a generator have a significant effect on the output power during a black-start. Neglecting this may lead to impractical solutions.

Minimal adjustment of the total power does not imply the shortest time; however, in practice these two criteria typically yield the same results. Because of the different characteristics of generators, in particular the different ramping rates, different generators require different times to ramp up or down to the same power capacity. For this reason, the objective of the optimisation problem should be the shortest adjustment time required by the generators.

When a new generator is about to get started, the longest adjustment time required by each online generator is decided by the ramping rate and the active power internal between start time and end time. However, the upper and lower limits of the active power at the end time is a function of the final adjustment time at this step, which is described in detail in Section 3 of this paper.

Consequently, the self-healing process is a variable-constraint optimisation problem of minimising the total restart times; however, the widely used methods for optimal power flow (OPF) are unable to solve such problems. Furthermore, there is no suitable mathematical method to solve the variable-constraint optimisation problem. Therefore, the objective of the black-start optimisation problem is usually chosen as described in [7, 8]. In this way, we can sidestep the process of solving the minimisation problem using variable constraints. However, this is not equivalent to the original problem, which may lead to solutions that are impractical.

The Guangdong power grid of China is used and it is found that minimising the total adjusted power leads to solutions whereby a single generator ramps up to provide the required power capacity for the generator to start while some started generators' active power do not change. This causes long delays in starting all generators, and clearly does not represent the shortest start time for the system.

To solve these problems, in this paper an optimisation model that uses variable constraints to solve the self-healing problem is described. By introducing a time variable $t$, the variable-constrained minimum–maximum optimisation problem is converted into a constrained OPF problem that can be solved by using common optimisation approaches. The method was successfully applied to the development of a power system self-healing software package, which was applied to the Guangdong power grid of China. A number of recovery schemes using this software package are obtained.

## 2 Potential problems

The output of a generator is limited not only by the constraints but also the ramping characteristics, as shown in Fig. 1 [7].

From $t_0$ to $t_1$, the generator charges and the output of the generator $P_G$ is equal to $-R$. Before the generator reaches the minimum technical output power, the output can only increase in the section of the ramping curve $AM$. When it reaches the point $M$, the lower limit of the generator becomes $D$ and the output of the generator can either increase or decrease in the section $MB$, as shown by the arrows in Fig. 1.

The three stages of the start-up process of the generator can be expressed as follows.

(i) During the charging stage, there is

$$P_G = -R \tag{1}$$

(ii) Before the generator reaches the minimum technical output, there is

$$P_G = r_p \cdot t - R < P_G \leq D \tag{2}$$

(iii) After the generator reaches the minimum technical output, there is

$$D \leq P_G \leq C \tag{3}$$

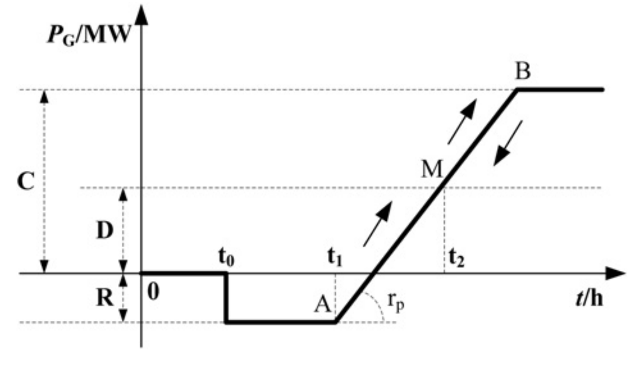

**Fig. 1** *Features of the active power of a generator. Here R is the start-up capacity. C is the upper limit of the active power. D is the minimum technical power. $t_0$ is the time to charge. $t_1$ is the crank time. $t_2$ is the minimum critical time. $r_p$ is the ramping rate. A, M and B are three points along the ramping curve*

Because the active power output is determined by the physical characteristics of the generator, the objective function of minimising the total power adjustment is not practical in assigning the active power to each of the restarted generator. As a result, the following two major problems arise.

First, if there are obvious differences among the adjustment characteristics of the restarted generators, a situation might arise where by some generators have finished adjusting and operate at a certain point, while some generators are still ramping, depending on the objective of minimising the total power adjustment. Furthermore, before a generator reaches its minimum technical output, it is impossible for it to operate at a given point.

Second, assuming that the active power output has reached the minimum technical level, the output of the generator can be controlled as desired. If rapidly adjustable units always need to wait for slowly adjustable units at each step, clearly this would obviously not lead to the optimal recovery time. This scenario would occur when the optimisation model proposed in [7] was used to calculate the restoration time for the Shenzhen grid in Guangdong Province. The Meishi power station and the Ling'ao nuclear power station were started in sequence; however, the capacity of the Meishi power station was 15 times smaller than that of the Ling'ao nuclear power station, and the Ling'ao nuclear power unit stopped adjusting several times to wait for the slower Meishi power plant before reaching the minimal output, whereas the Meishi power plant reached its upper capacity limit quickly and thereby lost the ability to regulate.

## 3 Minimisation with variable constraints

### 3.1 Objective function

Suppose that $m$ is the number of generators that have been successfully restarted during the process. Considering the physical characteristics of generators, the objective function for starting the $(m+1)$-th generator should be such as the following equation.

$$\min f(x) = \max_{k=1}^{m} \left\{ t_k = \left| \frac{P_k - P_0^k}{r_{pk}} \right| \right\} \tag{4}$$

where $P_k$ is the active power output of the $k$th generator. $P_0^k$ is the previous active power output of the $k$th generator. $r_{pk}$ is the ramping rate of the $k$th generator. The objective function represents a minimisation of the maximum possible time for adjustment of all generators.

### 3.2 Equality constraints

To start the $(m+1)$-th generator, the equality constraints are the power flow

$$\begin{cases} P_{Gi} - P_{Di} - \sum_{j=1}^{j=n} \left[ e_i \left( G_{ij} e_j - B_{ij} f_j \right) + f_i \left( G_{ij} f_j + B_{ij} e_j \right) \right] = 0 \\ Q_{Gi} - Q_{Di} - \sum_{j=1}^{j=n} \left[ f_i \left( G_{ij} e_j - B_{ij} f_j \right) - e_i \left( G_{ij} f_j + B_{ij} e_j \right) \right] = 0 \end{cases} \tag{5}$$

where the subscripts $i$ and $j$ refer to indexes of the buses. $e$ and $f$ are the real and imaginary parts of the corresponding bus voltage. $P_G$ and $Q_G$ are the active and reactive power of the corresponding generator.

### 3.3 Variable inequality constraints

Inequality constraints include the bus voltage limitations and the active and reactive power limitations. The power flow limitations are not considered because the load is light at the black start stage. The limitation of the transmission is mainly caused by the capacitor, charging reactive power to the light load line, which

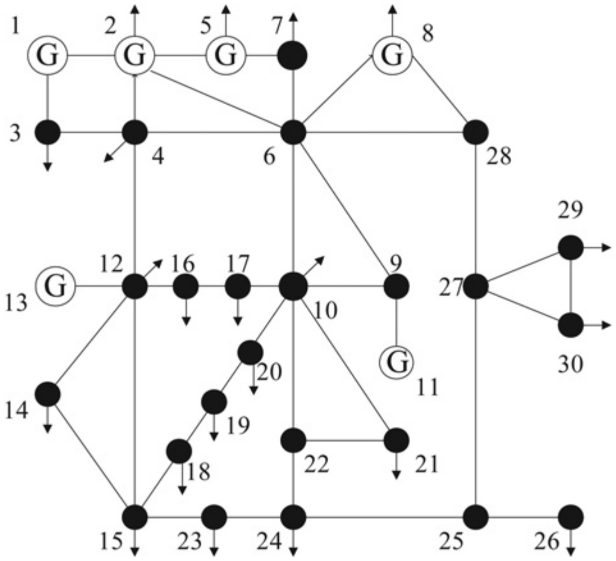

**Fig. 2** *IEEE 30-bus system*

leads to higher voltage. The voltage limitation is of importance at this stage.

Depending on the features of the active power output of the generators, (seen in Fig. 1), the active power has the following variable lower and upper limits

$$\begin{cases} \boldsymbol{U}_{\min} \le \boldsymbol{U} \le \boldsymbol{U}_{\max} \\ \boldsymbol{P}_{\min}(t) \le \boldsymbol{P}_G \le \boldsymbol{P}_{\max}(t) \\ \boldsymbol{Q}_{\min} \le \boldsymbol{Q}_G \le \boldsymbol{Q}_{\max} \end{cases} \tag{6}$$

where $P_{\min}(t)$ and $P_{\max}(t)$ are the minimum and maximum active power outputs of the generators, respectively.

Assume that the $(m+1)$-th generator starts to charge at time $t_m$ and $T_C$ is the time required to start the $(m+1)$-th generator. Once the $i$th generator has been started, the lower and upper limits of the active power outputs of the $i$th generator will satisfy (7)–(10).

When $t_m + T_C < t_{1i}$, there is,

$$P_{\min,i}(t) = P_{\max,i}(t) = -R \tag{7}$$

when $t_{0i} < t_m < t_{1i}$ and $t_m + T_C > t_{1i}$, there is

$$\begin{aligned} &P_{\min,i}(t) = -R \\ &P_{\max,i}(t) = \min\left\{-R + \mathrm{r}_{pi} \cdot \left(t_m + T_C - t_{1i}\right), \mathrm{C}\right\} \end{aligned} \tag{8}$$

when $t_{1i} < t_m < t_{2i}$, there is

$$\begin{aligned} &P_{\min,i}(t) = -P_{Gi} \\ &P_{\max,i}(t) = \min\left\{P_{Gi} + \mathrm{r}_{pi} \cdot T_C, \mathrm{C}\right\} \end{aligned} \tag{9}$$

and when $t_m > t_{2i}$, there is

$$\begin{aligned} &P_{\min,i}(t) = \max\left\{D, P_{Gi} - r_{pi} \cdot T_C\right\} \\ &P_{\max,i}(t) = \min\left\{P_{Gi} + r_{pi} \cdot T_C, \mathrm{C}\right\} \end{aligned} \tag{10}$$

where $P_{Gi}$ is the active power of the $i$th online generator in the latest step. $t_{0i}$, $t_{1i}$ and $t_{2i}$ are the corresponding time instants $t_0$, $t_1$ and $t_2$ shown in Fig. 1, for the $i$th generator. The value of $T_C$ cannot be obtained until the optimal function in (1) is solved. It is clear that the inequality constraints for the active power vary with time.

**Table 1** Generators in the IEEE 30-bus system

| Index | Bus no. | Rated capacity, p.u. | Start-up capacity, p.u. | Ramping rate, p.u./h |
|---|---|---|---|---|
| 1 | 1 | 2.61 | 0.261 | 1.50 |
| 2 | 2 | 0.40 | 0.036 | 0.21 |
| 3 | 5 | 0.20 | 0.014 | 0.09 |
| 4 | 8 | 0.20 | 0.010 | 0.10 |
| 5 | 11 | 0.20 | 0.016 | 0.08 |
| 6 | 13 | 0.20 | 0.018 | 0.15 |

### *3.4 Equivalence problem*

The optimisation problem given in (4)–(10) is a variable-constraint optimisation problem, which is not straightforward to be solved in mathematics. Therefore, it is necessary to find an efficient manner with which to convert this problem into a more general form that can be solved easily.

To convert the variable constrained problem into a fixed constraint model, a prediction time $T_{\text{pre}}$ is used to calculate the constraints of the active power $P_{\min}(T_{\text{pre}})$ and $P_{\max}(T_{\text{pre}})$. If the OPF diverges within the prediction constrains of the active power, the prediction time $T_{\text{pre}}$ will increase to expand the solution space. Because the optimisation objective is to determine the minimum start-up time, the optimal result in a smaller active power range must be the optimal solution in a larger active power range. Therefore, the variable constraints can be converted into a series of flexible fixed constraints, as shown in the following equation.

$$\begin{cases} \boldsymbol{U}_{\min} \le \boldsymbol{U} \le \boldsymbol{U}_{\max} \\ \boldsymbol{P}_{\min}(T_{\text{pre}}) \le \boldsymbol{P}_G \le \boldsymbol{P}_{\max}(T_{\text{pre}}) \\ \boldsymbol{Q}_{\min} \le \boldsymbol{Q}_G \le \boldsymbol{Q}_{\max} \end{cases} \tag{11}$$

Through given the prediction time $T_{\text{pre}}$, the variable inequality constraints is transformed to fixed inequality constraints. Furthermore, the non-differentiable objective in (4) is equivalently transformed into the following constrained differential form

$$\begin{aligned} &\min \quad f\left(P_G, Q_G, e, f, t\right) = t \\ &\text{s.t.} \quad t \ge \left|\frac{P_k - P_{0k}}{r_{pk}}\right| \end{aligned} \tag{12}$$

Because the absolute value is not convenient, a new variable $t' = t^2$ is defined. Without changing the optimisation target, the optimal solution of the problem in (12) is equivalent to the solution of the

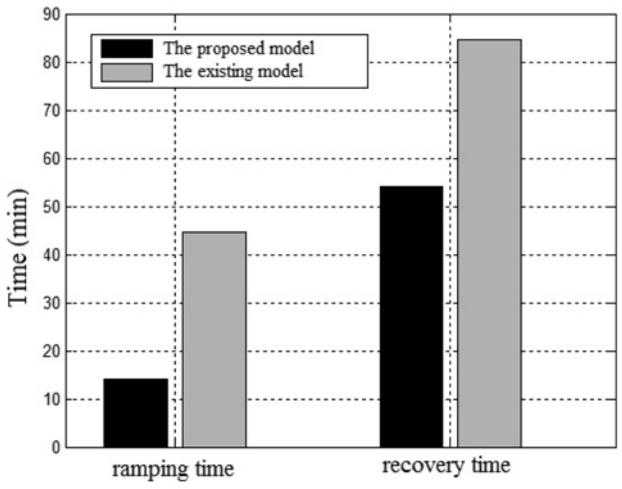

**Fig. 3** *Comparison between the results of the proposed model and the model described in [7] on the IEEE 30-bus system*

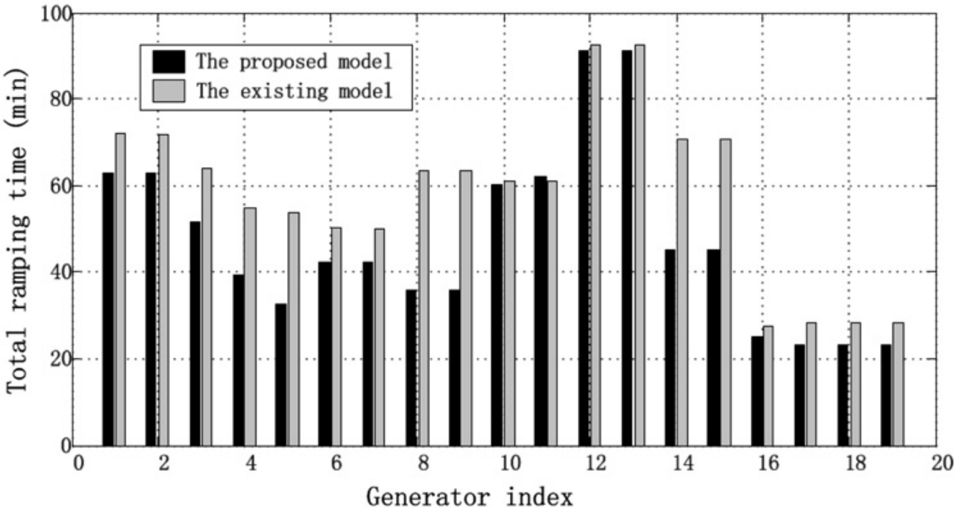

**Fig. 4** *Total ramping time obtained using the proposed model and the model described in [7] for Shantou grid*

problem in the following equation.

$$\begin{aligned} \min \quad & f(P_G, Q_G, e, f, t') = t' \\ \text{s.t.} \quad & t' \geq \left(\frac{P_k - P_{0k}}{r_{pk}}\right)^2 \end{aligned} \tag{13}$$

By introducing the variable $t'$, the objective function can be optimised in the solution space that includes both time and power. The model shown in (13) with the constrained problem in (4) and (11) is of the general OPF form, as shown in the following equation.

$$\begin{aligned} \min \quad & f(P_G, Q_G, e, f, t') = t' \\ \text{s.t.} \quad & \begin{cases} P_{Gi} - P_{Di} - \sum_{j=1}^{j=n}\left[e_i\left(G_{ij}e_j - B_{ij}f_j\right) + f_i\left(G_{ij}f_j - B_{ij}e_j\right)\right] = 0 \\ Q_{Gi} - Q_{Di} - \sum_{j=1}^{j=n}\left[f_i\left(G_{ij}e_j - B_{ij}f_j\right) + e_i\left(G_{ij}f_j - B_{ij}e_j\right)\right] = 0 \end{cases} \\ & t' \geq \left(\frac{P_k - P_{0k}}{r_{pk}}\right) \\ & \boldsymbol{U}_{\min} \leq \boldsymbol{U} \leq \boldsymbol{U}_{\max} \\ & \boldsymbol{P}_{\min}\left(T_{\text{pre}}\right) \leq \boldsymbol{P}_G \leq \boldsymbol{P}_{\max}\left(T_{\text{pre}}\right) \\ & \boldsymbol{Q}_{\min} \leq \boldsymbol{Q}_G \leq \boldsymbol{Q}_{\max} \end{aligned} \tag{14}$$

From (14), it can be seen that the original variable-constraint optimisation problem has been transformed to a normal constrained OPF problem, which can be solved using general OPF algorithms.

### 3.5 Solution of the OPF problem

The proposed OPF model in (14) can be written in general form as.

$$\begin{aligned} \text{obj,} \quad & \min f(x) \\ \text{s.t.} \quad & h(x) = 0 \\ & \underline{g} \leq g(x) \leq \bar{g} \end{aligned} \tag{15}$$

Using the algorithm presented in [10] and introducing slack variables with the interior point barrier function, the Lagrange function can be expressed as

$$\begin{aligned} L = {} & f(x) - y^{\mathrm{T}}h(x) - z^{\mathrm{T}}[g(x) - l - \underline{g}] \\ & - w^{\mathrm{T}}[g(x) + u - \bar{g}] - \mu\left(\sum_{j=1}^{c}\ln l_j + \sum_{j=1}^{c}\ln u_j\right) \end{aligned} \tag{16}$$

Linearising the function and use Newton method to establish the correction equation, there is

$$\begin{bmatrix} \boldsymbol{H} & -\nabla_x \boldsymbol{h}(\boldsymbol{x}) & -\nabla_x \boldsymbol{g}(\boldsymbol{x}) & -\nabla_x \boldsymbol{g}(\boldsymbol{x}) & \boldsymbol{0} & \boldsymbol{0} \\ \nabla_x^{\mathrm{T}} \boldsymbol{h}(\boldsymbol{x}) & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \nabla_x^{\mathrm{T}} \boldsymbol{g}(\boldsymbol{x}) & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & -\boldsymbol{I} & \boldsymbol{0} \\ \nabla_x^{\mathrm{T}} \boldsymbol{g}(\boldsymbol{x}) & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{I} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{L} & \boldsymbol{0} & \boldsymbol{Z} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{U} & \boldsymbol{0} & \boldsymbol{W} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{x} \\ \Delta \boldsymbol{y} \\ \Delta \boldsymbol{z} \\ \Delta \boldsymbol{w} \\ \Delta \boldsymbol{l} \\ \Delta \boldsymbol{u} \end{bmatrix} = -\begin{bmatrix} -\boldsymbol{L}_x \\ -\boldsymbol{L}_y \\ -\boldsymbol{L}_z \\ -\boldsymbol{L}_w \\ -\boldsymbol{L}_l^{\mu} \\ -\boldsymbol{L}_u^{\mu} \end{bmatrix}. \tag{17}$$

And

$$H = -\left[\nabla_x^2 f(x) - \nabla_x\left(\nabla_x h(x) \cdot y\right) - \nabla_x\left(\nabla_x g(x) \cdot (z + w)\right)\right] \tag{18}$$

It should be mentioned that the selection of the $(m + 1)$-th generator would affect the overall performance of the restoration strategy. In this paper, the method proposed in [11] is used to obtain the start-up sequence of generators for all the cases in each step.

## 4 Simulation results

### 4.1 IEEE 30-bus system

The IEEE-30 bus standard system is shown in Fig. 2. Branches 4–12, 6–9, 6–10 and 27–28 represent transformers, and the others represent transmission lines. There are six generators connected to buses 1, 2, 5, 8, 11 and 13, as listed in Table 1.

Generator 1 was the black-start source. The comparison between the results of the proposed model and the existing model described in [7], which uses the minimum total adjustment of the active

**Table 2** Comparison of the total power recovery

| The black-start generator | The number of the picked-up loads | | The total power recovery, p.u. | |
|---|---|---|---|---|
| | Proposed model | Existing model | Proposed model | Existing model |
| 10 | 9 | 8 | 10.46 | 9.69 |
| 11 | 11 | 9 | 11.21 | 9.78 |
| 12 | 9 | 8 | 10.42 | 9.50 |
| 13 | 9 | 8 | 10.42 | 9.50 |

power as the objective function, is shown in Fig. 3. The start-up sequence of the generators for the two methods is same, which is obtained by Liu *et al*. [11].

With the IEEE-30 bus system, the capacity and ramping rate of generator 1 were significantly higher than those of the other units. During each step, if the system simply regulates the power of this generator to be the same as that of the other units, it results in a serious delay in restoration. The delay is caused by the waiting of generators, which has been mentioned before. Using the proposed model described here, both the generator ramp time and the total system recovery time decrease significantly, as can be seen in Fig. 3.

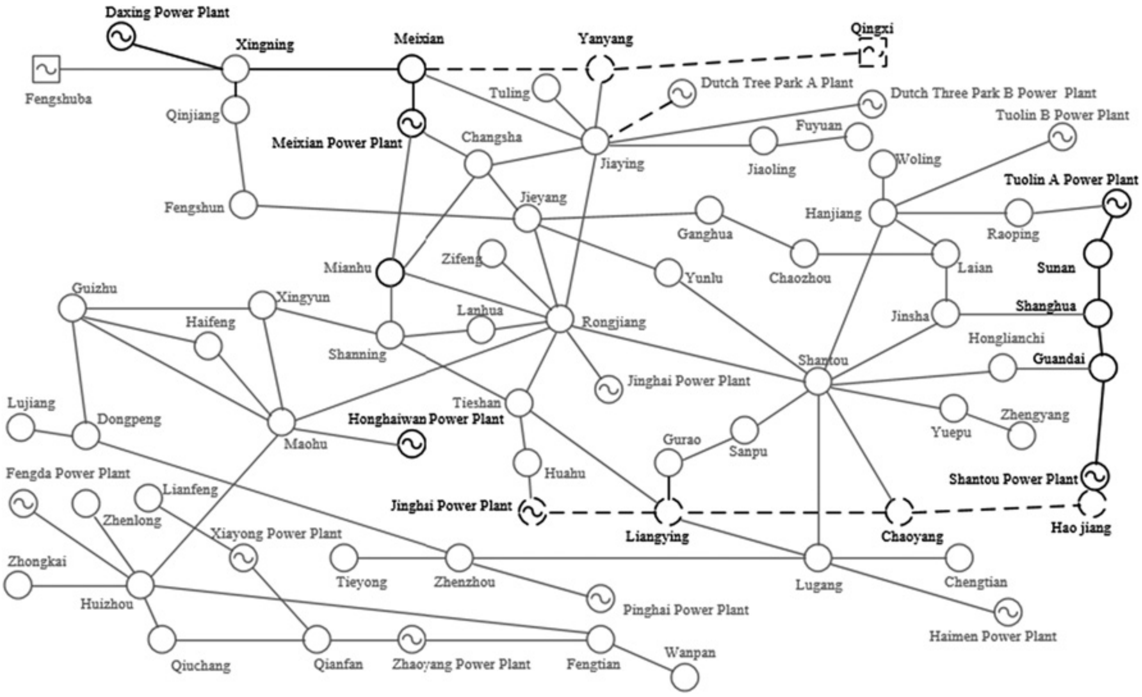

**Fig. 5** *Start-up process with Case 1. The black parts are active areas, and the dashed parts denote areas that are yet to be restarted*

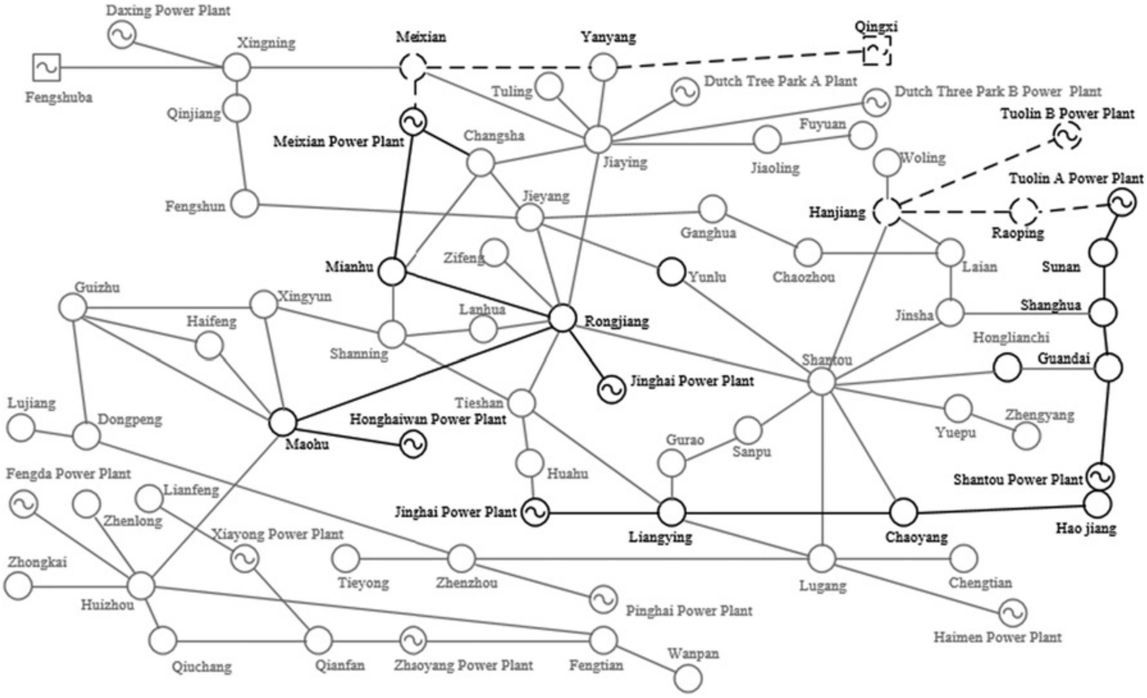

**Fig. 6** *Start-up process with Case 2. The black areas denote the active region, and the dashed areas denote the regions that are attempting to restart*

**Table 3** Results of the recovery time of case 2

| Index | Generator operating in islanding mode | Time for system recovery, min |
|---|---|---|
| 1 | Daxing | 523 |
| 2 | Meixian | 578 |
| 3 | Honghaiwan | 420 |
| 4 | Jinghai | 497 |
| 5 | Shantou | 510 |
| 6 | Tuolin | 604 |
| 7 | Fanshuyuan | 588 |

**Table 4** Results of the average recovery time for each area of Guangdong gird using the two models

| Area | Generators | Conventional model, min | Proposed model, min | Saving time, % |
|---|---|---|---|---|
| Dongguan | 7 | 88.07 | 85.16 | 3.30 |
| Guangzhou | 20 | 49.81 | 42.84 | 13.99 |
| Jiangmen | 9 | 21.48 | 20.14 | 6.24 |
| Meizhou | 10 | 15.67 | 13.25 | 15.44 |
| Shaoguan | 8 | 134.26 | 99.95 | 25.55 |
| Shantou | 19 | 58.11 | 47.14 | 18.88 |
| Zhongshan | 7 | 93.42 | 77.57 | 16.97 |
| Zhuhai | 6 | 49.50 | 23.40 | 52.73 |

## 4.2 Shantou grid system

To compare the results of the proposed model with the model described in [7], Shantou grid was used as a test system which serves one of the major cities of Guangdong Province in China. Shantou grid has 191 buses, 19 generators, 120 AC lines and 141 transformers. The parameters of the generators differ from each other.

On the premise of same start-up sequence of the generators, each generator was considered as the black-start unit to start other 18 generators in the system for each case. The total ramping time of the generators in the 19 cases is shown in Fig. 4.

In most cases, the proposed model shows a clear improvement over the model described in [7], while total ramping time were similar when the 10–13th generators were considered as the black-start units. A more detailed comparison, shown in Table 2, reveals that significantly more loads were picked up using the proposed model. For the cases in which the picked-up loads of the two model were similar, the proposed model provides better recovery path and less recovery time.

## 4.3 East Guangdong grid

During the black-start stage, self-excitation and charging over voltage are likely to occur because of the excess reactive power. To avoid these phenomena, the proper load should be injected to balance the reactive power during the recovery. Therefore, the generators should produce more active power for the injected load; however, this would slow the recovery process.

By using the proposed optimisation method and the proposed Power-System Self-Healing software package, two more cases in the East Guangdong grid are calculated. It is assumed that the Shantou, Meixian and Honghaiwan power stations are able to self-start.

*Case 1:* The system is in a state of complete outage and only three generators have the ability to self-start.

Because the Honghaiwan power station is connected to the 500 kV network, the initial equivalent electrical susceptance of the Honghaiwan–Maohu–Rongjiang overhead line is large. When the system is initially in an outage state, a long time is needed to start this line because more load should be injected to balance the reactive power, which would lead more active power injected. As shown in Fig. 5, the power generation capability of Honghaiwan station cannot be fully used to aid in system restoration.

*Case 2:* Assume that the Honghaiwan power station can operate in islanded mode. When a fault occurs, the Honghaiwan station can operate with a reduced output power and provide energy to the Maohu and Rongjiang stations, maintaining service to a small amount of loads.

The results calculated using the software package developed is shown in Fig. 6.

There are seven thermal power plants with large capacity in the East Guangdong grid. Assuming each of these generators can operate in island mode, the results of the time required to recover the entire system are listed in Table 3.

## 4.4 Guangdong grid system

A comparison of the results obtained for the eight large areas in the Guangdong grid reveals that the optimisation model described in this

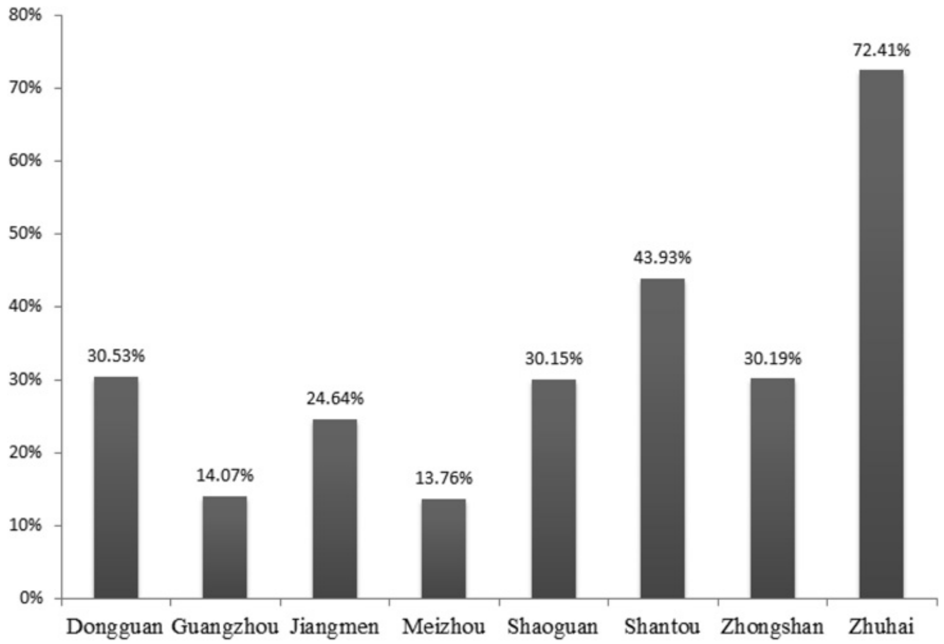

**Fig. 7** *Maximum time saving for each area of the Guangdong grid by the proposed model, compared with the conventional model described in [7]*

paper can improve the power distribution and significantly accelerate recovery. The results of the average recovery time for each area using the two models are listed in Table 4.

Using the proposed model, the contribution to the acceleration of the restoration process of the system is greater when the ramping rate of the black-start generator is higher. The maximum time saving for each area is shown in Fig. 7.

## 5 Conclusions

A optimisation model with variable constraints is proposed to describe power system restoration in this paper. A power system self-healing software package is developed, which has been applied to the Guangdong grid, and the effectiveness of this software toolset was investigated. The main contributions of this paper are as follows.

(i) Considering the physical characteristics of generators, an optimisation model that minimises the maximum possible time for system restart was established using variable constraints to solve the self-healing problem.
(ii) By introducing the time variable $t$, the variable constrained minimum-maximum optimisation problem is converted into a constrained OPF problem that can be solved by using common optimisation approaches.
(iii) The proposed method was shown to significantly reduce the start-up time for the black-start stage. The method has been successfully used with the power system self-healing software toolset for Guangdong power grid.

It should be mentioned that, in this paper, the load picking up manner and the behaviour of the load is not considered. The details on the devices operation time, such as the response time of reactive power controllers, the response time of breaker, the charging time of transformer, etc. are not considered.

## 6 Acknowledgments

This work was supported by Program for New Century Excellent Talents in University (NCET-12-0846) and supported by '111' Project (B08013) of China and supported by Research on Intelligent Separation Control and Self-Healing Restoration of AC-DC Hybrid Power Systems (Self-Healing Restoration).

## 7 References

1 Qiulan, W.: 'Theory study for self-healing of large power grid', *Autom. Electr. Power Syst.*, 2009, **33, no.**, pp. 29–32
2 Jinhuan, Y.: 'Discussion on several issues concerning FCB', *Electr. Power*, 2007, **40**, (5), pp. 59–62
3 Adibi, M., Clelland, P., Fink, L., *et al.*: 'Power system restoration - A task force report', *IEEE Trans. Power Syst.*, 1987, **2**, (2), pp. 271–277
4 Yunhai, Z., Yong, M., Bin, Y.: 'Decision support system for black-start', *Autom. Electr. Power Syst.*, 2001, **25, no.**, pp. 43–46
5 Lindstrom, R.R.: 'Simulation and field tests of the black start of a large coal-fired generating station utilizing small remote hydro generation', *IEEE Trans. Power Syst.*, 1990, **5**, (1), pp. 162–168
6 Ketabi, A., Asmar, H., Ranjbar, A.M., *et al.*: 'An approach for optimal units start-up during bulk power system restoration'. 2001 Large Engineering Systems Conf. on Power Engineering, 2001. LESCOPE '01., 2001, vol., no., pp. 190–194
7 Hou, Y., Liu, C.-C., Sun, K., *et al.*: 'Computation of milestones for decision support during system restoration', *IEEE Trans. Power Syst.*, 2011, **26**, (3), pp. 1399–1409
8 Zhong, H.-r., Gu, X.-p.: 'Determination of optimal unit start-up sequences based on fuzzy AHP in power system restoration'. 2011 fourth Int. Conf. on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 6–9 July 2011, pp. 1541–1545
9 Zhong, H., Gu, X.P., Zhu, X.: 'Optimization method for unit restarting during power system black-start restoration'. Power and Energy Engineering Conf. (APPEEC), 2012, Asia-Pacific, 27-29 March 2012, pp. 1–4
10 Linfeng, Y., Jinbao, J., Daolan, H.: 'Multiple centrality corrections interior point optimal power flow algorithm based on optimal centering parameter', *Proc. CSEE*, 2012, **32**, (4), pp. 136–144
11 Liu, C., Wu, M., Deng, Y.: 'Start-up sequence of generators in power system restoration avoiding the backtracking algorithm'. 2013 IEEE Power and Energy Society General Meeting, Vancouver, Canada, 21–25 July 2013