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Optimisation model for power system restoration with support from electric vehicles employing battery swapping

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Abstract: The energy stored in the batteries of electric vehicles (EVs) could be employed for starting generators when a blackout or a local outage occurs. Considering the feature of the battery swapping mode, an available capacity model of the batteries in a centralised charging station is first developed. Then, the authors analyse the start-up characteristics of a generator powered by batteries and propose a bi-level optimisation-based network reconfiguration model to determine the restoration paths with an objective of maximising the overall generation capability. In the upper-level optimisation model, the generator start-up sequence is optimised, whereas the restoration paths are optimised in the lower-level one. Moreover, they consider the uncertainties associated with the available capacity of the batteries. The bi-level optimisation model for the network reconfiguration is developed in the chance-constrained programming framework and solved by the well-established particle swarm optimisation algorithm. Finally, case studies are employed to demonstrate the effectiveness of the presented model. Simulation results show that a centralised EV charging station could act as a power source to effectively restore a power system without black-start (BS) generators or with insufficient cranking power from BS generators, and the presented model could be used to guide actual system restorations.

1 Introduction

Power system restoration after a blackout or a local outage is one of the most important tasks for power system operators. How to restore the power system safely and steadily after a major outage is of great significance [1, 2]. The power system restoration process is generally divided into three stages, which are black-start (BS) of generating units, system/network restoration and load restoration, respectively [3]. The main task of the system restoration stage is to energise the transmission lines for cranking the non-BS (NBS) generating units and to build a steady skeleton-network structure in power systems. Therefore, a reasonable network reconfiguration strategy is required for the rapid establishment of a skeleton network of the power system concerned, and further the restoration of system loads in the next stage.

So far, much research work has been done on developing power system restoration strategies. In [4], the consistency of BS decision-making results is presented as an important indicator for assessing the BS group decision-making results, and the preferred BS decision-making results are those with better consistency. The problem of generator start-up sequencing is described as a mixed integer linear programming problem to maximise the overall available generation capability in [5]. A network reconfiguration efficiency index for evaluating the reconfiguration solution is developed and the discrete particle swarm optimisation is employed to obtain the optimal skeleton networks with the maximum reconfiguration efficiency in [6]. A two-stage method proposed in [7] for optimising the network reconfiguration strategy overcomes the shortage of separate decision-making because the restoration sequence of generators and the restoration paths are serially optimised. It can be seen that only regular BS generators are considered as power suppliers to start the NBS generators in the restoration process.

As a new type of transportation, electric vehicles (EVs) have significant advantages in terms of easing the energy crisis, promoting the harmonious development of human beings and the environment and so on [8]. The potential impacts of EVs on power systems have been widely studied [9, 10]. In [11], the impacts of the battery charging/swapping stations are compared, and the results show that the battery swapping mode is more advantageous for public transportation in distribution systems. If the available battery capacity in the centralised charging stations reaches a certain threshold, the regional power system without BS generators or sufficient cranking power of BS generators could be restored by using the batteries in the centralised charging stations as BS power sources. So far, much research work on the available capacity of batteries in EVs charging stations has been widely reported [12, 13]. However, the research work that the batteries in a centralised charging station of EVs are employed as BS power sources to restore the regional power system after a blackout has not been studied. The users of EVs could replace the consumed batteries in the battery swapping stations, and then the replaced batteries will be delivered to centralised charging stations for charging. The capacity of the batteries in a centralised charging station could be large enough to restart NBS generators when the blackout occurs.

Given this background, we propose an optimisation strategy for network reconfiguration considering the centralised charging stations as the BS power sources. The major contributions of this paper could be summarised as follows. First, this paper develops a capacity model of centralised EV charging stations, taking the power demand, the battery inventory and logistics management into consideration. Second, the generator start-up sequence optimisation and restoration path optimisation are separately addressed in the existing papers, whereas in the proposed bi-level optimisation-based model in this paper the sequence of generators and the restoration paths are optimised simultaneously. Third, few papers study the start-up time characteristic of restoring a generating unit with the support of an EV charging station, whereas the proposed method in this paper employs the centralised

EV charging stations to restore a power system without BS generators or with insufficient cranking power of BS generators.

The rest of this paper is organised as follows. Section 2 presents a mathematical model for assessing the available battery capacity in centralised EV charging stations. A bi-level optimisation model based on chance-constrained programming is proposed for the network reconfiguration in Section 3, which is next solved by the well-established particle swarm optimisation algorithm. The modified New England 10-unit 39-bus power system and a part of the Guangdong power grid in China are employed to demonstrate the effectiveness and essential features of the developed models and methods in Section 4. Conclusions are given in Section 5.

2 Capacity model of centralised EV charging stations

The available battery capacity in a centralised charging station is mainly affected by the battery performance, user behaviour, charging and swapping facilities and the operating modes. In terms of the battery performance, it is concluded that the greater capacity a single battery owns, the more available capacity the EV charging station can supply to the NBS generators for restarting if the number of batteries is the same. As to the user's behaviour, the daily mileage has a great impact on the battery replacement demand. From the perspective of charging and swapping facilities and their operating modes, the available battery capacity is determined by battery distribution model, the scale of charging and swapping facilities and charging policy. With the features of battery swapping model of the EVs considered, the following assumptions are made for illustrating the proposed strategy in this paper:

(i) The EVs are with the same type, so are the batteries equipped in them;
(ii) The delivery distances of the batteries between the swapping stations and the charging stations are not considered, nor are the traffic conditions. The delivery time is denoted as T;
(iii) If the battery capacity is below the threshold, the owners of EVs will consider replacing the battery immediately;
(iv) Only the battery capacity in hours is considered. The time slot in the capacity model of centralised charging stations is in hours; and
(v) The EV charging stations in the power systems are equivalent to one EV charging station. The batteries in the equivalent EV charging station are the sum of the batteries in each EV charging station. There are usually more than one EV charging station connecting into the power system concerned. However, the capacity of each EV charging station might not be great enough for the restarting of a generator when a blackout occurs. One of the effective methods is to collect the available batteries in all EV charging stations into one charging station. Therefore, the EV charging stations in the power systems could be equivalent to one EV charging station. Thus, the EV charging station mentioned in this paper is the equivalent EV charging station.

2.1 Mathematical model of electricity demand

According to the statistical data from the US Department of Transportation, the daily mileage of family cars conforms to the lognormal distribution [14]. The total mileage S_{qi} of EV q from time t_0 to t_i can be described as

$$S_{qi} = \begin{cases} S_{\text{sum}} \int_{t_0}^{t_i} f_s(t)\,\mathrm{d}t, & 0 \le t_0 \le t_i \le 24 \\ S_{\text{sum}} \left[\int_{t_0}^{24} f_s(t)\,\mathrm{d}t + \int_0^{t_i} f_s(t)\,\mathrm{d}t \right], & 0 \le t_i \le t_0 \le 24 \end{cases} \quad (1)$$

where S_{sum} is the total mileage of EV q within one day; $f_s(t)$ is the distribution function of hourly mileage in the daily mileage. In the second row of (1), t_i is not larger than t_0, which means that t_0 is the time on the first day and t_i is the time on the next day. In this case, the total mileage includes two parts: one is the mileage from time t_0 to 24 PM mid-night on the first day and the other is the mileage from time 0 AM (i.e. 24 PM mid-night on the first day) to time t_i on the next day.

Equation (2) is employed to determine whether the EV users consider to replace the battery at time t_i

$$D_{qi} = \begin{cases} 1, & W_{q0} - \dfrac{S_{qi} W_{100}}{100} \le W_f \\ 0, & W_{q0} - \dfrac{S_{qi} W_{100}}{100} > W_f \end{cases} \quad (2)$$

where W_{100} is the consumed energy of EVs after travelling 100 km; W_{q0} is the remaining battery capacity in EV q at t_0; W_f is the threshold of battery replacement for the users, which means the users will choose to replace the battery immediately when the battery capacity is below W_f; D_{qi} is denoted as an indicator for determining whether the battery of the EVs should be replaced at t_i. D_{qi} is equal to 1 if EV q needs to replace its battery at time t_i, or 0 if EV q does not.

On the basis of (1) and (2), the distribution of the number of EVs whose batteries should be replaced within one day can be obtained by Monte Carlo simulations. According to the central limit theorem, the expected value and variance of the distribution will be available, which conforms to the normal distribution.

2.2 Battery swapping model

The battery charging and swapping business model is a typical vendor managed inventory model. The battery swapping stations act as the battery 'retailers' and the centralised charging station acts as the 'supplier'. The battery management centre supervises the charging status of charging machines in charging stations and the circulation and inventory in battery swapping stations based on the sharing demand and stock information. In this paper, the periodic stock-counting method is employed to monitor the battery inventory in the battery swapping stations and the (s, S) inventory policies are taken as the battery inventory management strategy [15, 16]. The detailed procedures are as follows: the operators in the battery swapping stations monitor periodically the inventory situation of batteries. When the inventory position reduces to the minimum inventory position s and below, a request will be issued to the centralised charging station for batteries with full capacity. The logistics companies will deliver enough batteries with full capacity to battery swapping stations until the battery inventory is supplied to position S and above. Meanwhile the batteries with low capacity in the battery swapping stations are transported to the centralised charging station for charging.

2.3 Battery capacity model of the centralised charging station

Before the battery capacity model of the centralised charging station is developed, we introduce the characteristic of battery charging first. The charging curve of the lithium–ion battery equipped in Nissan Altra [17] is shown in Fig. 1, where the actual battery charging characteristics are represented by the solid curve. The time spent in the initial and last battery charging phases is relatively short compared with the whole charging process. Therefore, the charging power can be approximately described as a constant in the whole battery charging process. The dotted curve in Fig. 1 denotes the simplified charging curve.

The electric energy stored in the batteries cannot be totally discharged into the power system taking the battery service life cycle into consideration [18]. When a part of the NBS generators has been restarted and the capacity provided by the charging station is limited, the charging station will be considered not to supply power for the restarting of the other NBS generators in order to avoid overusing the batteries. According to the simplified battery charging curve, we can describe the available battery

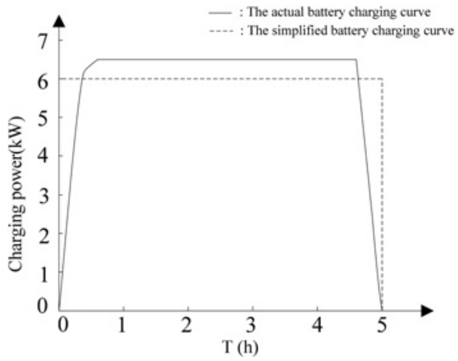

Fig. 1 *Charging curve of the lithium–ion battery*

capacity of the charging station at any time as

$$W_{\rm c}(t) = C\left(\sum_{k=1}^{K-1}\frac{k}{K}N_{\rm c}^{k}(t) + N_{\rm cc}(t)\right) \tag{3}$$

where C is the rated capacity of a single battery. K is the charging duration of battery from the state without power to that with full power. $N_{\rm c}^{k}(t)$ is the number of batteries that has been charged for k hours at time t. $N_{\rm cc}(t)$ is the number of the batteries with full power which is ready to be delivered to the swapping stations at time t.

The power injected into the power system from the charging station can be described as [19]

$$P_{\rm c}(t) = \frac{W_{\rm c}\eta_{\rm inv}}{t_{\rm disc}} \tag{4}$$

where $P_{\rm c}(t)$ is the power from vehicle to grid in kilowatts; $\eta_{\rm inv}$ is the electrical conversion efficiency of the DC–AC inverters. $t_{\rm disc}$ is the discharging time in hours.

The following constraints in the swapping and charging station should be met in order to ensure the successful restart of the NBS generators with power supplied by the batteries.

(a) Constraints in the EV swapping stations

(1) *Constraint of supply and demand:* The number of batteries stored for replacement in the swapping stations should not be less than the required number of batteries at any time

$$N_{\rm d}(t) \geq R_{\rm d}(t) \tag{5}$$

where $N_{\rm d}(t)$ is the number of batteries stored for replacement in the swapping stations at time t; $R_{\rm d}(t)$ is the required number of batteries during $[t, t+1]$.

(2) *Constraint of inventory in swapping stations*: This constraint presents the changes of the number of the batteries in the swapping stations in two different situations

$$N_{\rm d}(t+1) = \begin{cases} N_{\rm d}(t) - R_{\rm d}(t+1), & N_{\rm d}(t) > sN_{\rm b} \\ N_{\rm d}(t) - R_{\rm d}(t+1) + N_{\rm tr}(t), & N_{\rm d}(t) \leq sN_{\rm b} \end{cases} \tag{6}$$

where $N_{\rm b}$ is the maximal number of the batteries stored in the swapping stations and $sN_{\rm b}$ is the threshold for determining whether the distribution requirements are issued. $N_{\rm tr}(t)$ is the number of the batteries delivered from the charging station to the swapping stations. Equation (6) implies that if the number of the stored batteries for replacement in the swapping stations at time t is greater than a predetermined threshold value, the number of the stored batteries at time $t+1$ is equal to the number of batteries at time t minus the number of the replaced batteries during $[t, t+1]$; otherwise, the distribution requirements will be issued from the swapping stations to the centralised charging station and the required batteries will be successfully delivered to the swapping stations at time $t+1$.

(b) Constraint of the EV charging station

The constraint in the charging station is the equality constraint of the number of batteries

$$N_{\rm c}^{k}(t) = N_{\rm c}^{k-1}(t-1) \tag{7}$$

$$N_{\rm cc}(t) = \begin{cases} N_{\rm cc}(t-1) + N_{\rm c}^{5}(t) - N_{\rm tr}(t), & N_{\rm d}(t) < sN_{\rm b} \\ N_{\rm cc}(t-1) + N_{\rm c}^{5}(t), & N_{\rm d}(t) \geq sN_{\rm b} \end{cases} \tag{8}$$

where $N_{\rm c}^{k-1}(t-1)$ is the number of batteries that have been charged for $k-1$ h at time $t-1$. $N_{\rm cc}(t-1)$ is the number of the batteries with full charged capacities which are ready to be delivered to the swapping stations at time $t-1$. $N_{\rm c}^{5}(t)$ is the number of batteries that have been charged for 5 h at time t. Equation (7) shows that the number of batteries which have been charged for $k-1$ h at time $t-1$ is equal to that of batteries which have been charged for k h at time t. Equation (8) means that if the batteries replacement requirements are not issued at time t, the number of the available batteries that can be delivered in the charging station at time t is equal to the number of the stored batteries at $t-1$ plus the number of batteries that are just charged fully at time t. Otherwise, the number of the available batteries in the charging station at t is equal to the sum of the number of the stored batteries at $t-1$ and the batteries that are just charged fully minus the number of delivered batteries.

3 Mathematical model of the network reconfiguration

3.1 *Characteristic analysis of restarting the NBS generators by batteries*

During the power system restoration, the differences of the restoration characteristic between batteries and regular BS generators are concluded in the following two aspects. One is that the available battery capacity of the charging station reduces gradually along with the increasing of recovery time; the other is that the available battery capacity should be large enough to restore the NBS generators, which means the cranking power provided by the charging station should not be less than the required minimum start power of the NBS generators within a certain period.

Fig. 2 shows the time characteristic of the centralised charging station that acts as a BS power source to restore generator j. T_{j0} is the start time of generator j; T_{j1} is the time when generator j starts to crank; T'_{j1} is the time when the output power of generator j is not less than its start-up power; and T_{j2} is the time when the

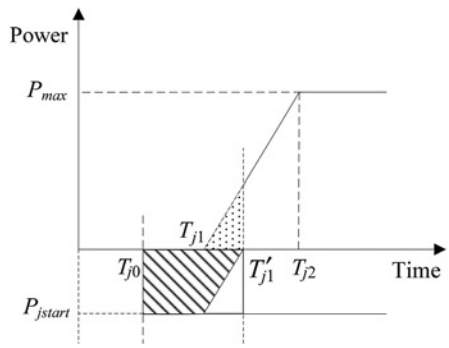

Fig. 2 *Start-up time characteristic of restoring a generating unit with the support of an EV charging station*

output power of generator j reaches its maximum value

$$P\left(\boldsymbol{T}'_{j1}\right) \geq P_{j\text{start}} > P\left(T'_{j1} - 1\right) \quad j \in \Omega_{\text{NBS}} \tag{9}$$

where $P_{j\text{start}}$ is the required minimum start-up power of generator j; $P(T'_{j1})$ is the output power of generator j at time T'_{j1}. Ω_{NBS} is the set of the NBS generators.

During the power system restoration, the following constraints should be met in the charging station.

(1) Constraint of the start-up power requirement

$$\sum_{i=1}^{M} P_{i\text{gen}}(t) + P_{\text{c}}(t) - \sum_{i=1}^{M} P_{i\text{start}} u_i(t) \geq 0 \tag{10}$$

where $P_{i\text{gen}}(t)$ is the output power of generator i at time t; $P_{\text{c}}(t)$ is the power provided by the charging stations at time t; M is the number of the generators to be restored in the power systems; $u_i(t)$ is the restoration state of generator i. If the generator i is restored at or before time t, $u_i(t)$ is equal to 1; otherwise, $u_i(t)$ is equal to 0.
(2) Constraint of the start-up capacity requirement

$$W_{\text{c}}\left(T_{j0}\right) + \sum_{i=1}^{M} \int_{T_{j0}}^{T'_{j1}} u_i(t)\left(P_{i\text{gen}}(t) - P_{i\text{start}}\right) \text{d}t \geq 0 \quad j \in \Omega_{\text{NBS}} \tag{11}$$

where $W_{\text{c}}(T_{j0})$ is the battery capacity of the charging station at time T_{j0}. Equation (11) is presented to determine whether the generator j can be started at time T_{j0}. During the period of (T_{j0}, T'_{j1}), part of the consumed electric energy is provided by the EV charging station, as shown in the dark area with the solid lines in Fig. 2, and the other part is supplied by the restored generators, as shown in the dark area with the dots in Fig. 2.
(3) *Constraint of the battery capacity in the EV charging station*: This constraint illustrates the change of the battery capacity in the EV charging station in every minute (see (12))

$$W_{\text{c}}(t + \Delta t) = W_{\text{c}}(t) - \frac{1}{2}\Delta t\left(\left(\sum_{i=1}^{M} P_{i\text{start}} u_i(t) - \sum_{i=1}^{M} P_{i\text{gen}}(t)\right) + \left(\sum_{i=1}^{M} P_{i\text{start}} u_i(t + \Delta t) - \sum_{i=1}^{M} P_{i\text{gen}}(t + \Delta t)\right)\right) \quad j \in \Omega_{\text{NBS}}\ t \in \left[T_{j0},\ T'_{j1} - \Delta t\right] \tag{12}$$

where Δt is set to 1 min. This constraint should be satisfied when the EV charging station is not considered to supply power for the restarting of the other NBS generators. If the EV charging station does not supply power, the capacity of the EV charging station will be constant until the power system is completely restored.

3.2 Bi-level optimisation model

The objective of network reconfiguration is to determine the optimal restoration sequence of generators and the optimal restoration paths. We develop a bi-level optimisation-based model to achieve this objective. The start-up time of the generators is optimised for maximising the overall generation capacity of the power systems in the upper-level optimisation model, whereas in the lower-level model the optimal restoration paths are determined for delivering the cranking power to the NBS generators quickly.

3.2.1 Upper-level optimisation model: The start-up time of the NBS generators is optimised for maximising the generation capacity of the power systems. The issue can be mathematically described as

$$\max\ W_{\text{total}}\left(\boldsymbol{T}_{\text{opt}}\right) = \sum_{t=1}^{N_T} \sum_{i=1}^{M} \left[P_{i\text{gen}}(t) - P_{i\text{start}} u_i(t)\right] \tag{13}$$

(see (14))

$$\text{s.t. } P_{i\text{gen}}(t) = \begin{cases} 0, & 0 \leq t \leq t_{\text{opt}i} + t_{\text{c}i} \\ R_i\left(t - t_{\text{opt}i} + t_{\text{c}i}\right), & t_{\text{opt}i} + t_{\text{c}i} < t < t_{\text{opt}i} + t_{\text{c}i} + \dfrac{P_{i,\max}}{R_i} \\ P_{i,\max}, & t \geq t_{\text{opt}i} + t_{\text{c}i} + \dfrac{P_{i,\max}}{R_i} \end{cases} \tag{14}$$

$$0 \leq t_{\text{opt}i} \leq T^i_{\max} \tag{15}$$

$$t_{\text{opt}i} \geq t_{\text{act}i} \tag{16}$$

$$\sum_{i=1}^{M} P_{i\text{gen}}(t) + P_{\text{c}}(t) - \sum_{i=1}^{M} P_{i\text{start}} u_i(t) \geq 0 \tag{17}$$

$$W_{\text{c}}\left(T_{j0}\right) + \sum_{i=1}^{M} \int_{T_{j0}}^{T'_{j1}} u_i(t)\left(P_{i\text{gen}}(t) - P_{i\text{start}}\right) \text{d}t \geq 0 \quad j \in \Omega_{\text{NBS}} \tag{18}$$

(see (19))

$$W_{\text{c}}(t + \Delta t) = W_{\text{c}}(t) - \frac{1}{2}\Delta t\left(\left(\sum_{i=1}^{M} P_{i\text{start}} u_i(t) - \sum_{i=1}^{M} P_{i\text{gen}}(t)\right) + \left(\sum_{i=1}^{M} P_{i\text{start}} u_i(t + \Delta t) - \sum_{i=1}^{M} P_{i\text{gen}}(t + \Delta t)\right)\right) \quad j \in \Omega_{\text{NBS}}\ t \in \left[T_{j0},\ T'_{j1} - \Delta t\right] \tag{19}$$

where $[0, N_T]$ is the period studied in this paper; the M-column vector $\boldsymbol{T}_{\text{opt}} = [t_{\text{opt}1},\ t_{\text{opt}2},\ \ldots,\ t_{\text{opt}M}]^{\text{T}}$ is the result of the upper-level optimisation, and $t_{\text{opt}i}$ is donated as the optimal start-up time of generator i; the M-column vector $\boldsymbol{T}_{\text{act}} = [t_{\text{act}1},\ t_{\text{act}2},\ \ldots,\ t_{\text{act}M}]^{\text{T}}$ is the time vector of generator i when the cranking power in the actual restoration process is received, which is obtained by the lower-level optimisation model; $W_{\text{total}}(\boldsymbol{T}_{\text{opt}})$ is the available generation capacity of the power systems when the start-up time vector of units is $\boldsymbol{T}_{\text{opt}}$. Equation (15) is the constraint of the critical maximum time interval of generators. $T^i_{\max}$ is the critical maximum time interval of generator i. $t_{\text{c}i}$ is the start-up time period of generator i from receiving the cranking power to starting to output power. R_i and $P_{i,\max}$ are the ramping rate and the maximum output power of generator i, respectively.

During power system restoration, the voltage could be kept within an acceptable range by several ways, such as connecting shunt reactors, picking up the loads with lagging power factors and adjusting transformer taps. The system frequency could be kept within the accepted limit by restoring loads gradually with a small increment [7]. Besides, a load can play different roles in different phases of the power system restoration process. Before all the generators are restarted, the available generation capacity in the power system is mainly used to restart the NBS generators and only parts of the loads are picked up for keeping the bus voltages within an acceptable range. When all the generators are restarted, the rest of the loads are gradually picked up.

3.2.2 Lower-level optimisation model: We optimise the restoration path to reduce the operating time so that the NBS generators could be provided with the cranking power within the given time. Meanwhile, the over-voltage problem in the process of power system restoration should be considered. As a result, in the lower-level model, the line weight could be decided by the line operation time and line charging capacitance. We describe the weight of line r as $w_{lr} = (1 - v)C_{lr} + vt_{lr}$, where C_{lr} is the normalised charging capacitance of line r; t_{lr} is the normalised operation time for restoring the line r; v is the adjustable coefficient. v is set to zero in the initial state; if $t_{\text{act}i}$, solved by the Dijkstra algorithm, is greater than $t_{\text{opt}i}$, the weight of lines is adjusted by gradually increasing the value of v. The adjustment of v will not stop until $t_{i\text{start}}$ is not greater than $t_{\text{opt}i}$. Once the optimal restoration path for delivering the cranking power to one generator is determined, the value of v is reset to 0, and then it can be employed to optimise the restoration path for another generator.

To minimise the number of generators that cannot be successfully restarted at the optimal start-up time, which is solved in the upper-level model, we can mathematically describe the lower-level optimisation model as

$$\min f\left(\boldsymbol{T}_{\text{opt}},\ \boldsymbol{T}_{\text{act}}\right) = \sum_{i=1}^{M} U\left(t_{\text{act}i},\ t_{\text{opt}i}\right) \tag{20}$$

$$\text{s.t.: } t_{\text{act}i} = t_{\text{res}i} + \sum_{r \in \Omega_i} t_{lr} \tag{21}$$

$$D_i = \inf_{X^i} \left\{ \sum_{r=1}^{N_L^i} x_r^i w_{lr} \right\} \tag{22}$$

$$\Omega_i = \left\{ r | x_r^i = 1 \right\} \tag{23}$$

where $t_{\text{res}i}$ is the start-up time of the node which is the 'nearest' to the generator i in the restored power systems before the generator i is cranked. The 'nearest' node to the generator i is the intersection of the restored power systems and the optimal restoration lines. Ω_i is the set of the optimal restoration lines that supply cranking power to generator i. D_i is the shortest distance between the generator i and the restored power system in which the weight of the transmission lines are set to 0. $\boldsymbol{X}^i$ is the Boolean variable vector and is denoted as the status of the lines while restoring the generator i. Its element x_r^i is 0 if the line r is not selected to supply the cranking power to generator i; otherwise, x_r^i is equal to 1. N_L^i is the number of the candidate lines to be restored for restarting generator i. $U(x, y)$ is defined as a binary function. If $x \geq y$, $U(x, y)$ is equal to 1; otherwise, $U(x, y)$ is equal to 0.

3.3 Bi-level optimisation model based on chance-constrained programming

The bi-level optimisation model developed in Section 3.2 can optimise the restoration sequence of generators and the restoration paths simultaneously. The upper-level optimisation model determines the start-up sequence of the generators so as to maximise the overall generation capacity of the power system, whereas the lower-level model optimises the restoration paths delivering the cranking power to the NBS generators quickly. The upper-level and lower-level optimisation models are connected by two vectors $\boldsymbol{T}_{\text{act}}$ and $\boldsymbol{T}_{\text{opt}}$, which are affected by the available battery capacity in the EV charging stations. However, the available battery capacity in the EV charging station is uncertain, so the bi-level optimisation-based model for the network reconfiguration should be considered as a stochastic optimisation problem. As an important branch of stochastic optimisation, chance-constrained programming mainly focuses on the condition that random variables are in the constraints, and the decision has to be made before the random variables are determined. The chance-constrained programming method has been widely used in many fields including the power systems due to its advantage over dealing with the uncertainty in programming problems [20].

The established mathematical model combines the chance-constrained programming method with the bi-level optimisation-based model for the network reconfiguration, so the generation capacity of the power systems could be maximised and the results could be maintained at certain confidence level. We employ the chance-constrained programming method to deal with the uncertainty of the available battery capacity in the EV charging station, and the reasonable system restoration strategy can be determined by the bi-level optimisation-based model after the uncertain factors are transferred to the determined values by Monte Carlo simulation. Thus, the optimisation problem can be described as

$$\max\ \overline{W} \tag{24}$$

$$\text{s.t. } \Pr\left\{ W_{\text{total}} \geq \overline{W} \right\} \geq \beta \tag{25}$$

$$W_{\text{total}} = \sup_{\mathbf{T}_{\text{opt}}} \left\{ \sum_{t=1}^{N_T} \sum_{i=1}^{N_{\text{res}}} \left[P_{i\text{gen}}(t) - P_{i\text{start}} u_i(t) \right] - aF \right\} \tag{26}$$

$$F = \inf_{\left(\boldsymbol{T}_{\text{opt}},\, \boldsymbol{T}_{\text{act}}\right)} \left\{ \sum_{i=1}^{N_{\text{res}}} U\left(t_{\text{act}i},\ t_{\text{opt}i}\right) \right\} \tag{27}$$

where $\overline{W}$ is the maximal generation capacity of the power systems at the confidence level of β; W_{total} is the available generation capacity of the power systems after the blackout within the studied period; $\sup_x\{f(x)\}$ and $\inf_x\{f(x)\}$ are the supremum and infimum of function $f(x)$ in its domain, respectively.

3.4 Solving approach for the proposed model

We employ the well-established particle swarm optimisation algorithm to solve the formulated optimisation model. This algorithm exhibits good performance in finding the global solution. The basic idea to solve the proposed model is presented as follows. First, the initial population including M_p particles which represent the start-up sequence of NBS generators is randomly generated. The fitness function of the particle swarm optimisation algorithm is set as the available generation capacity if the generators to be restored can be started by the available battery capacity in the EV charging station; otherwise, it is equal to zero. Finally, for the given start-up sequence, the optimal start-up time and restoration paths can be obtained by the iterations between the upper- and lower-level models. The iterations are repeated until the objective function of the lower-level model is 0. Moreover, the Monte Carlo simulation would be used to verify whether the chance constraints are satisfied.

Fig. 3 shows the flowchart of the proposed optimisation strategy for network reconfiguration with the support of a centralised EV charging station. The major steps are as follows:

(1) Input the initial data including the size of the particle swarm population M_p, learning factors c_1 and c_2, inertia weight w, the reproduction generations M_c, the times of Monte Carlo simulation M_s and the confidence level β.
(2) Randomly generate an initial population which includes M particles.
(3) For each particle, carry out the Monte Carlo simulation for M_s times to obtain the available battery capacity in the EV charging station.
(4) The available generation capacity of the power system can be determined by the bi-level optimisation-based model according to the simulation results in step 3.
(5) Check the chance constraints and compute the objective function of each particle.

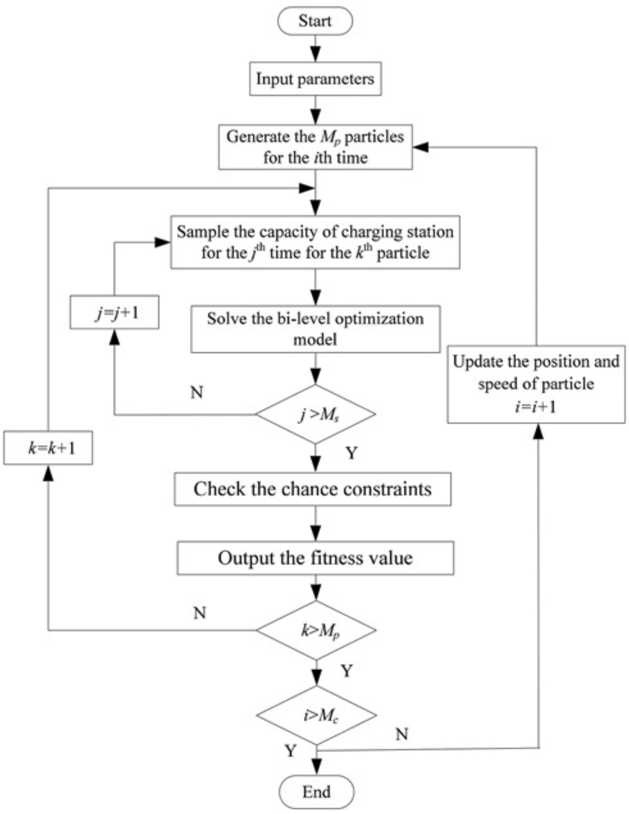

Fig. 3 *Flowchart of the network reconfiguration optimisation strategy with the support of centralised EV charging stations*

(6) Calculate the fitness value of each particle according to its objective function.
(7) Update the location and speed of each particle and then generate the new population.
(8) Once the reproduction generations M_c is reached, stop the programme and output the optimal particle; otherwise, repeat the steps from 3 to 7. The result of the upper-level model corresponds to the optimal start-up time of generators, whereas the result of the lower-level model denotes the optimal restoration paths.

4 Case studies

4.1 *Case 1: the modified New England 10-unit 39-bus power system*

A modified New England 10-unit 39-bus power system is employed to demonstrate the proposed model and methodology. It is assumed that there is a centralised EV charging station located at the node 33, and the generators are located at nodes 30, 31, 32, 34, 35, 36, 37, 38 and 39. Fig. 4 shows the topology of the power system. The parameters of the lines and the generators are given in Tables 1 and 2, respectively. The time interval considered in the restoration model is specified to be 1 min.

The daily mileage of family cars conforms to the lognormal distribution, and the average and standard deviation of the distribution are set to 3.2 and 0.88, respectively. The distribution function of hourly mileage in the daily mileage, donated as $f_s(t)$, is acquired from [13]. The initial capacity of battery is sampled from the uniform distribution $U(0.6C, C)$. Additionally, there will be 2000 EVs in this studied area and the number of batteries that has been fully charged in the EV charging station at the initial time is set to 1500, whereas the number in the EV swapping stations is set to 800 accordingly. Table 3 shows the settings of some crucial

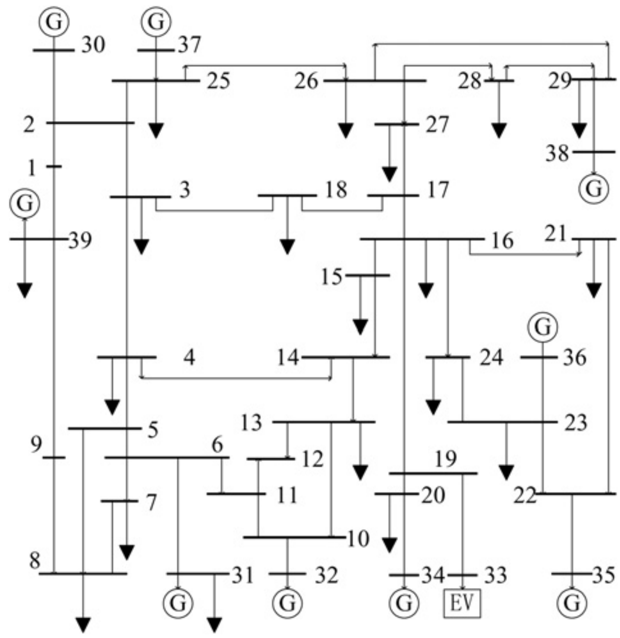

Fig. 4 *Modified New England 10-unit 39-bus power system*

Table 1 Line parameters of the New England 10-unit 39-bus power system

The sending node of the line	The receiving node of the line	Charging capacitance, pu	The restoration operation time of the line, min	The number of switching actions
2	1	0.6987	4	3
39	1	0.75	4	4
3	2	0.2572	3	2
25	2	0.146	4	2
4	3	0.2214	3	3
18	3	0.2138	4	4
5	4	0.1342	4	2
14	4	0.1382	3	4
6	5	0.0434	4	2
8	5	0.1476	4	2
7	6	0.113	3	3
11	6	0.1389	3	2
8	7	0.078	4	2
9	8	0.3804	4	2
39	9	1.2	5	2
11	10	0.0729	5	2
13	10	0.0729	4	4
14	13	0.1723	4	3
15	14	0.366	3	3
16	15	0.171	3	4
17	16	0.1342	3	2
19	16	0.304	5	3
21	16	0.2548	5	1
24	16	0.068	5	3
18	17	0.1319	4	3
27	17	0.3216	4	2
22	21	0.2565	5	2
23	22	0.1846	4	2
24	23	0.361	4	3
26	25	0.513	5	2
27	26	0.2396	3	2
28	26	0.7802	4	3
29	26	1.029	5	2
29	28	0.249	4	3
12	11	0.249	4	3
12	13	0.249	4	3
6	31	0.1319	4	2
10	32	0.3216	4	2
19	33	0.2565	3	2
20	34	0.1846	2	2
22	35	0.361	3	2
23	36	0.249	4	2
25	37	0.249	3	2
2	30	0.249	4	2
29	38	0.249	3	2
19	20	0.249	3	3

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Table 2 Parameters of generating units of the New England 10-unit 39-bus power system

Generating units	Active power capacity, MW	Ramping rate, MW/h	Start-up power required, MW	Start-up time required, min
30	350	108	12	25
31	1145.55	186	45	60
32	750	144	30	50
33	—	—	—	—
34	660	132	24	30
35	750	150	30	50
36	660	132	26	40
37	640	138	25	40
38	930	156	37	55
39	1100	168	44	60

Table 3 Parameter settings in the capacity model of the centralised EV charging station

Parameters	Value
C	30 kWh
W_f	6 kWh
s	0.25
β	0.95
W_{100}	15 kWh
T	1 h
S	0.85
η_{inv}	0.93

parameters in the capacity model of centralised EV charging stations. Since the final result of the proportions of the battery swapping requirement might be influenced by the setting of the initial state, we perform the simulations for 50 days. The simulation data from the 21st day to the 50th day is employed to obtain the distribution of the number of EVs that need to replace the batteries within one day, which is illustrated in Table 4. Furthermore, Table 5 shows the distribution of the available battery energy in the EV charging station in hours within one day could be easily acquired.

It is assumed that a blackout occurs with an equal probability in every hour within one day. Moreover, the EV charging station will stop to provide cranking power to the NBS generators if the available battery capacity in the EV charging station is <5% of the total battery capacities. The Monte Carlo simulation is performed for 1000 times for each particle in the particle swarm optimisation algorithm.

Table 6 shows the final optimisation results of the restoration time for the generating units in the modified New England 10-unit 39-bus power system, and the final optimisation results of the restoration paths for the generating units are presented in Fig. 5.

Comparative studies are carried out between the method developed in this paper and the method in [21], so as to demonstrate the effectiveness of the proposed methodology. Table 7 shows the final optimal start-up time of generators attained by the method in [21]. The solid curve and the dotted curve in Fig. 6 represent the generating output power curve obtained by the method proposed in this paper and [21], respectively.

It can be seen from Fig. 6 that the generators start to output power at the 55th minute based on the proposed method. Although the generators 34 and 30 are supplied with the cranking power at the 8th minute and the 29th minute, respectively, they start to output power at the 55th minute due to the long restoration time of auxiliary equipment and the small ramping rate. The sum of the output power of the generators 34 and 30 is not greater than their auxiliary equipment consumption until at the 55th minute. Furthermore, the battery capacity provided by the EV charging station to the power system is 4.5067 MWh from the 29th minute to the 55th minute. From the 55th minute, the restoration capacity supplied by the EV charging station is only 0.0233 MWh, and the generators 30 and 34 start to output power to the power system. Therefore, the EV charging station will not act as the power supplier to supply power to other NBS generators. Moreover, the generator output power obtained by the proposed method in this paper and that in [21] at the 180th minute is 1033.6 and 1012.1 MW, respectively, whereas the power energy is 523.8 and 507.64 MWh, respectively. The generator 39 is restarted at the 109th minute and is the last restarted generator. It takes almost 9 h for all the generators to reach their rated power.

The main difference between the proposed method and the method in [21] lies in the optimisation of the restoration paths. The restoration paths are optimised for minimising the number of switching operation in [21]; however, the selected restoration path in [21] might not be optimal because the time for delivering the cranking power to the NBS generators might be delayed. Take the start-up of generator 30 as an example, the optimal restoration path 33-19-16-17-27-26-25-2-30 is selected to supply the cranking power to generator 30 by the method in [21] and the generator 30 receives the cranking power in the 31st minute. However, the generator 30 could receive the cranking power in the 29th minute by the optimal path optimised by the proposed method. It is concluded that the restarting process of generator 30 in [21] is delayed, and then will delay the restarting of the other generators. Therefore, the restoration strategy optimised by the proposed method is more effective for the restoration of the power system after the blackout than the method in [21].

Table 4 Means and variances of the proportions of the battery swapping requirement in each hour

Time, h	1	2	3	4	5	6	7	8	9	10	11	12
means	0.0123	0.0046	0.0020	0.0011	0.0006	0.0021	0.0083	0.0258	0.0613	0.0772	0.0565	0.0652
variances	0.0020	0.0012	0.0006	0.0006	0.0005	0.0008	0.0016	0.0026	0.0039	0.0047	0.0042	0.0041
Time, h	13	14	15	16	17	18	19	20	21	22	23	24
means	0.0649	0.0657	0.0690	0.0701	0.0728	0.0864	0.0895	0.0523	0.0441	0.0277	0.0206	0.0197
variances	0.0038	0.0040	0.0043	0.0038	0.0040	0.0042	0.0050	0.0037	0.0034	0.0025	0.0027	0.0024

Table 5 Means and variances of available energy in the centralised EV charging station in each hour

Time, h	1	2	3	4	5	6	7	8	9	10	11	12
Means, MWh	39.2	40.8	42.1	42.9	43.5	43.8	43.5	42.1	38.6	34.3	31.9	30.1
variances, $(MWh)^2$	7.15	6.25	5.15	4.08	3.12	2.69	3.73	6.00	8.39	9.16	8.33	6.79
Time, h	13	14	15	16	17	18	19	20	21	22	23	24
Means, MWh	29.0	28.5	28.3	28.1	27.8	26.8	25.5	26.8	28.9	31.8	34.7	37.1
variances, $(MWh)^2$	5.93	6.30	5.87	5.58	5.80	6.05	5.93	6.11	6.02	5.96	6.15	7.14

Table 6 Final optimisation results of restoration time for the generating units in the modified New England 10-unit 39-bus power system

Generating units	Starting time, min	Consumed energy of the charging station, MWh
34	8	14.1817
30	29	4.5067
37	61	0
36	67	0
35	75	0
32	82	0
38	92	0
31	102	0
39	109	0

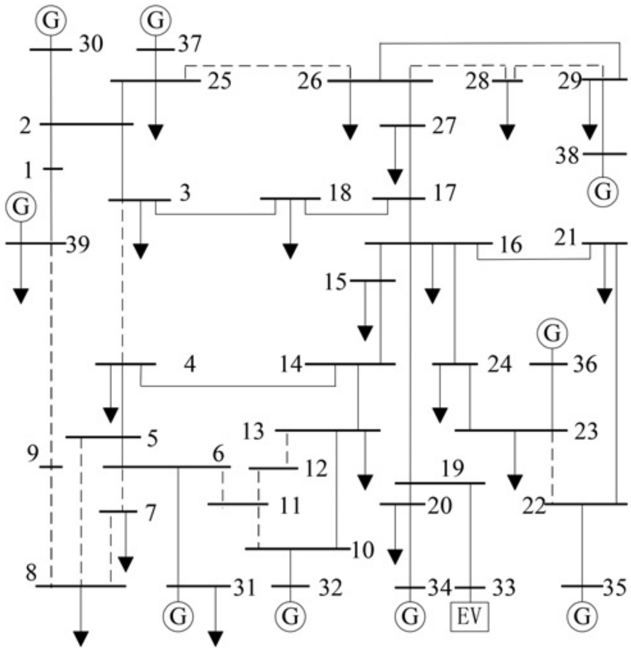

Fig. 5 *Final optimisation results of the restoration paths for the generating units in the modified New England 10-unit 39-bus power system*

4.2 Case 2: a part of the Guangdong power grid in China

A part of the Guangdong power grid in China as shown in Fig. 7 is employed to demonstrate the effectiveness of the developed model and method. There are 22 generators, 68 buses and 97 transmission lines. The centralised EV charging station is located at Xu Neng Plant. Table 8 shows the final optimisation results of the restoration time for the generating units. The restoration paths of this actual power systems are optimised by the proposed method and shown in Fig. 8.

Table 7 Final restoration time of the generating units optimised by the method in [21] for Case 1

Generating units	Starting time, min	Consumed energy of the charging station, MWh
34	8	14.1817
30	31	4.1217
37	62	0
36	68	0
35	76	0
32	83	0
38	93	0
31	103	0
39	110	0

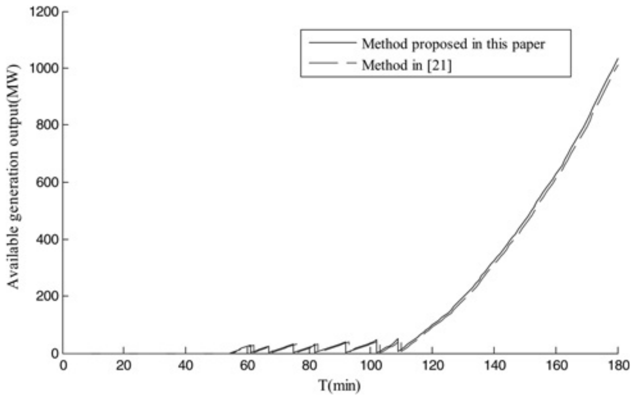

Fig. 6 *Generating outputs obtained by the two methods in Case 1*

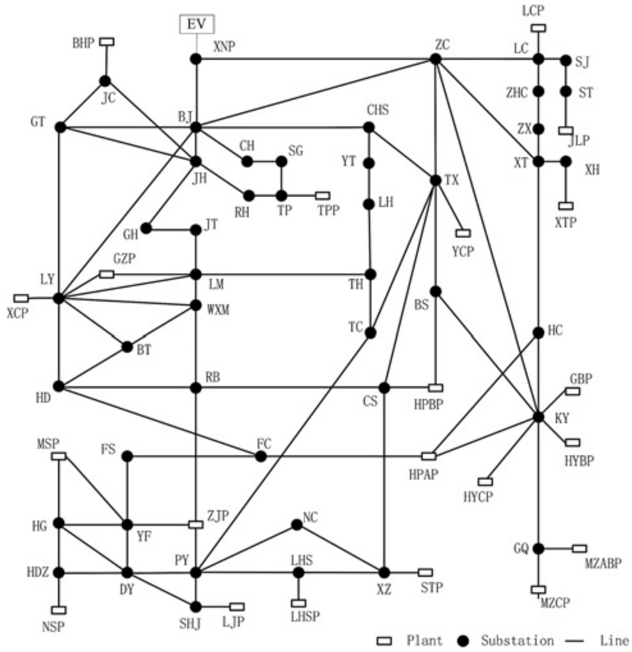

Fig. 7 *Part of the Guangdong power grid in China*

Table 8 Final optimisation results of restoration time for the generating units in a part of the Guangdong power grid in China

Generating units	Starting time, min	Consumed energy of the charging station, MWh
HYCP	10	3.8550
YCP	11	5.8417
MZCP	16	6.2776
HPAP	42	1.9299
HPBP	60	0
HYBP	65	0
GZP	71	0
ZJP	77	0
XCP	82	0
STP	88	0
MZABP	92	0
LHSP	97	0
XTP	101	0
GBP	105	0
JLP	110	0
BHP	112	0
LCP	116	0
NSP	120	0
TPP	125	0
MSP	129	0
LJP	133	0

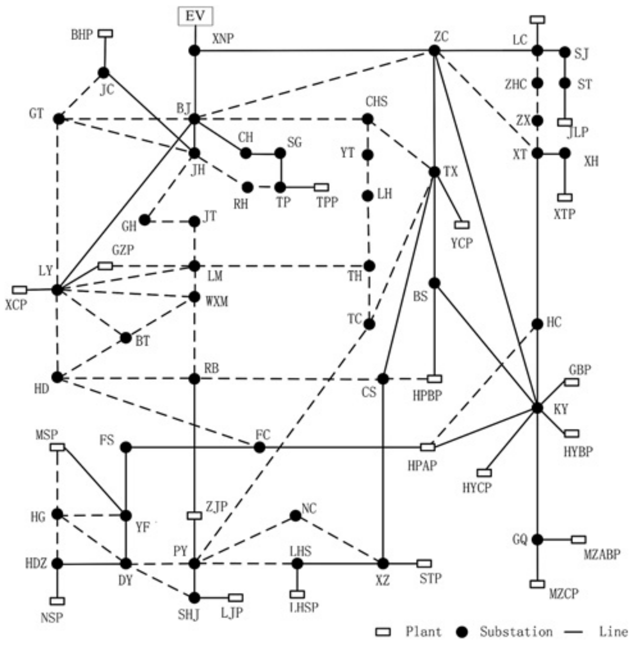

Fig. 8 *Final optimisation results of the restoration paths for the generating units in a part of the Guangdong power grid in China*

5 Conclusions

Centralised EV charging stations provide a new way to restore a power system without BS generators or with insufficient cranking power of BS generators. We analyse the start-up characteristics of restoring a generating unit with the support of an EV charging station. A bi-level optimisation model based on chance constraints programming is developed for network reconfiguration, which could take the uncertainties of EV charging stations into account. In the proposed model, the start-up time of generators and the restoration paths are optimised simultaneously in the bi-level optimisation-based model. The results in case studies illustrate the feasibility and the effectiveness of applying EV charging stations to restore the power system. Furthermore, it is of great importance to analyse the impacts of the distribution of centralised EV charging stations on power system restoration, and to examine the coordination among centralised EV charging stations so as to restore the power system effectively, and these will be our future research focuses.

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