Service restoration strategy of AC/DC hybrid distribution networks

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Abstract: This study proposes a service restoration strategy for an AC/DC hybrid distribution system. A mathematical model for voltage source converter with different control strategies in service restoration is developed. Power storage system scheduling based, expert systems [9], heuristic techniques [10], fuzzy logic [11], and optimal routing algorithm [12]. As power electronic technology develops, DC power system has been applied widely around the world, because of its advantages of high-cost performance quick adjustment and controllability. Zhao et al. [13] deal with the service restoration problem in renewable-powered microgrids that are driven islanded by an unscheduled breakdown from the main grid. Ou et al. [14] present a hybrid programming technique to solve the DC microgrid reconfiguration problem for loss reduction and service restoration. Little research has been conducted on the service restoration strategy of AC/DC distribution networks. There are two main challenges on service restoration strategies for AC/DC hybrid systems. (i) Service restoration strategies become more complex in AC/DC hybrid distribution systems, which have different types of controllable devices and loads, such as converters, circuit breakers, DC and AC loads. How to combinatorial control voltage source converters (VSCs) of different nodes for reliable power supply for de-energised areas after fault isolation need to be researched. (ii) Service restoration in AC/DC hybrid distribution system is difficult to solve, which is a mixed-binary non-linear optimisation problem with binary variables (switches) and continuous variables (e.g. VSC outputs). VSCs and energy storages (ESs) devices need to cooperate with conventional control devices, such as tie switches, to achieve the service restoration in a hybrid AC/DC distribution network with high penetration of renewable energy. The main contributions of this paper are as follows:

i. The influence of different types of faults on AC/DC hybrid networks at distribution levels are surveyed. Decision matrix method is used for establishment of an appropriate optimisation objective function, which includes minimum weight of lost load, minimum DG curtailments, and minimum network loss. Modelling method of power electronic devices is studied, especially, VSCs and the interaction different types of DGs (e.g. renewable energy generators (REGs) and ESs) during service restoration.

ii. For an AC/DC hybrid distribution system, its service restoration can be achieved by optimising the topology and the outputs of VSCs and DGs simultaneously. However, such an integrated optimisation is a mixed integer non-convex programming problem, which is mathematically hard to be solved as it consists of not only continuous variables but also discrete variables. To address this issue, this letter proposes a mixed-integer quadratic programming (MIQP) model, to simplify the solving process through transforming the original model. To formulate the convex MIQP model, the main idea is to convert the non-convex models of branch currents and the constraints express can make sure the distribution network operates in a radial manner. With the conditions of power balance in islands as the constraints, the islands are then divided. It adopts minimum loss in the object makes it not only stable but also economically acceptable. Simulation results show that the proposed strategy is feasible and effective to reduce lost load, distribution generation curtailments, and network loss.

1 Introduction

Nowadays, large-scale renewable energy source integration brings a significant challenge to the dispatch of power networks. In contrast to the AC distribution network, DC distribution networks provide a workable approach for the power grid to accommodate more renewable energy sources [1].

Medium voltage DC (MVDC) has attracted more and more attention with a bright prospect for enhancing transfer capacity and distribution generation (DG) accommodation. DC distribution networks have been proposed to connect DGs, electrical vehicles, and stored energy, have higher power supply capability, lower line losses, better power quality, freedom from reactive compensation, and reduce environmental pollution. The development of power electronic technologies offers great possibilities for DC distribution networks. Such areas currently include the following: control strategies of MVDC systems (e.g. real-time control [2], link strategy [3–5], protection strategy [6, 7], and energy management [8]).

Service restoration is an important issue in case of occurrence of distribution system outages, whose main objective is to minimise load curtailment. Various methods have been proposed for solving service restoration problems, for instance: knowledge-based, expert systems [9], heuristic techniques [10], fuzzy logic [11], and optimal routing algorithm [12]. As power electronic technology develops, DC power system has been applied widely around the world, because of its advantages of high-cost performance quick adjustment and controllability. Zhao et al. [13] deal with the service restoration problem in renewable-powered microgrids that are driven islanded by an unscheduled breakdown from the main grid. Ou et al. [14] present a hybrid programming technique to solve the DC microgrid reconfiguration problem for loss reduction and service restoration. Little research has been conducted on the service restoration strategy of AC/DC distribution networks.

There are two main challenges on service restoration strategies for AC/DC hybrid systems. (i) Service restoration strategies become more complex in AC/DC hybrid distribution systems, which have different types of controllable devices and loads, such as converters, circuit breakers, DC and AC loads. How to combinatorial control voltage source converters (VSCs) of different nodes for reliable power supply for de-energised areas after fault isolation need to be researched. (ii) Service restoration in AC/DC hybrid distribution system is difficult to solve, which is a mixed-binary non-linear optimisation problem with binary variables (switches) and continuous variables (e.g. VSC outputs). VSCs and energy storages (ESs) devices need to cooperate with conventional control devices, such as tie switches, to achieve the service restoration in a hybrid AC/DC distribution network with high penetration of renewable energy. The main contributions of this paper are as follows:

i. The influence of different types of faults on AC/DC hybrid networks at distribution levels are surveyed. Decision matrix method is used for establishment of an appropriate optimisation objective function, which includes minimum weight of lost load, minimum DG curtailments, and minimum network loss. Modelling method of power electronic devices is studied, especially, VSCs and the interaction different types of DGs (e.g. renewable energy generators (REGs) and ESs) during service restoration.

ii. For an AC/DC hybrid distribution system, its service restoration can be achieved by optimising the topology and the outputs of VSCs and DGs simultaneously. However, such an integrated optimisation is a mixed integer non-convex programming problem, which is mathematically hard to be solved as it consists of not only continuous variables but also discrete variables. To address this issue, this letter proposes a mixed-integer quadratic programming (MIQP) model, to simplify the solving process through transforming the original model. To formulate the convex MIQP model, the main idea is to convert the non-convex models of branch currents and the currents of VSCs, DGs, and loads into the linear models, since the objective is quadratic and convex, and other constraints are linear.

The remainder of this paper is organised as follows. Section 2 discusses different control models of VSCs in hybrid AC/DC distribution networks. Section 3 describes the service restoration strategy of MVDC distribution network. The algorithm for solving the proposed model is given in Section 4. Simulation results on an improved IEEE 33 nodes distribution network under different types of fault are illustrated in Section 5. Conclusions are outlined in Section 6.

2 Control models of VSC

A hybrid AC/DC distribution network is shown in Fig. 1. VSC1 is configured at the 10 kV bus station, which is operating at control
model $V \text{DC} - Q$ in order to control the voltage of the DC line. VSC2 is connected 10 kV distribution lines. The control model of VSC2, which are adjusted to fit different system conditions, are discussed next.

In condition 1, the fault happens in position 1 as shown in Fig. 1, the outage loads in the dashed line square cannot connect to VSC1. In condition 2, the fault happens in position 2 in Fig. 1, the outage loads in the dashed line square cannot connect to VSC1.

2.1 Control models of VSC2 in normal system

In a normal system, VSC2 is operating at control model $P - Q$ in order to optimise the power flow of two lines.

2.2 Control models of VSC2 in service restoration

i. Power outage areas can be connected to the superior network through the circuit breaker (fault type 1).

If a fault occurs in position 1, the circuit breaker can connect the power outage area to the main system after fault isolation, and the VSC2 is operating at $P - Q$ model when shutdown and restart process is finished.

ii. Power outage areas cannot be connected to the superior network through the circuit breaker (fault type 2).

When a serious fault occurs in the distribution network, there are power outage areas cannot be reconnected by the circuit breaker.

This paper classifies power outage areas as the power outage subnet (such as fault position 2 in Fig. 1, power outage areas are in the dashed line square). The VSC2, which is operating at control model, in order to control the voltage of the power outage subnet. The service restoration can be achieved by the VSC2, REGs, and ESs.

3 Service restoration strategy of MVDC distribution network

3.1 Objective function

In the service restoration, the objective function consists of a total minimum weight of lost load, minimum DG curtailments, and minimum network loss. The optimisation variables include the VSC power and circuit breakers states of the power outage subnet.

$$f_1 = \min \sum_{k=1}^{N} a_k P_k$$

$$f_2 = \min \sum_{i}^{M} P_{\text{DG}}$$

$$f_3 = \min \sum_{i}^{T} R_i f_i' + \sum_{i}^{M} R_{i j} f_{ij}$$

where $P_k$ is lost load of node $k$; $a_k$ is important degree of node $k$, loads are divided into three levels; $N$ is a set of power loss load; $M$ is a set of lost disconnected REGs; $B^{AC}$ is a set of nodes in the AC distribution network, $B^{DC}$ is a set of nodes in the AC distribution network, $P_{i j}$ denote the real and reactive power of branch $i$ at time $t$; $R_{i j}$ denote the resistance of branch $i$; $U_{i j}$ is voltage of the node $j$.

In this paper, the decision matrix method is used to transform the multi-objective function into a single objective function. The objective function of the original multi-objective problem can be transformed into

$$f = \min (a_1 f_1' + a_2 f_2' + a_3 f_3')$$

where $f_1', f_2', f_3'$ are normalised to $f_1, f_2, f_3$ (i.e. the conversion to the interval $J = [\frac{1}{7} \frac{1}{3} \frac{1}{3}]$ to eliminate the effect on the optimisation results due to the difference in the magnitude of each target function's value.

The core of the judgment matrix method is to determine the judgment matrix according to the hierarchical relationship between the targets. In view of the problem of this paper, each target can be graded according to its importance. The total loss of power load weight directly reflects the effect of power supply recovery as the first-grade target. The connected REG number directly reflects the effect of the restored power supply, as the second-level target. The active network loss directly reflects the economic operation of the system as the third-level target. According to the above analysis, the judgment matrix is formed.

$$J = \begin{bmatrix} 1 & 5 & 7 \\ 1 & 3 & 1 \\ 1 & 7 & 3 \end{bmatrix}$$

After matrix processing, the weight vectors of each target are obtained as follow.

$$[a_1, a_2, a_3] = [0.7655, 0.1600, 0.0745]$$

3.2 Restrictions

3.2.1 Constraint of network topology: After reconfiguration, the network is still connected radially without the presence of the islanding.

3.2.2 VSC power limit: Active and reactive power outputs of VSCs should meet VSC capacity restrictions.

$$\begin{cases} P_{i j}^{\text{VSC}} + P_{i j}^{\text{VSC}} = 0 \\ (P_{i j}^{\text{VSC}})^2 + (Q_{i j}^{\text{VSC}})^2 \leq (S_{i j}^{\text{VSC}})^2 \end{cases}$$

where $P_{i j}^{\text{VSC}}$, $Q_{i j}^{\text{VSC}}$ are active powers of VSC at time $t$, VSC connects node $i$ and node $j$; $Q_{i j}^{\text{VSC}}$ is reactive power of VSC at time $t$; $S_{i j}^{\text{VSC}}$ is the capacity of VSC.

3.2.3 Constraints of load shedding: The loads consist of interruptible loads and normal loads. During the recovery, priority is given to adjusting the interruptible load. On this basis, the necessary load-shedding actions are performed. Finally, the normal operation of the network after the fault recovery is realised.

$$P_{\text{LOAD}} = \{P_{\text{INTERRUPTIBLE LOAD}}, P_{\text{NORMAL LOAD}}\}$$
where $P_{\text{INTERRUPTIBLE LOAD}}^t$ is interruptible load; $P_{\text{NORMAL LOAD}}^t$ is normal load.

1. Interruptible loads

$$P_{\text{INTERRUPTIBLE LOAD}}^t = P_{\text{INTERRUPTIBLE LOAD}}^t \max \phi_t^i \quad 0 \leq \phi_t^i \leq 1$$

where $P_{\text{INTERRUPTIBLE LOAD}}^t \max$ is the maximum interruptible load of node $i$ at time $t$; $\phi_t^i$ is interruptible load regulation factor; $B_{\text{INTERRUPTIBLE LOAD}}$ is a set of interruptible load nodes.

2. Normal loads

$$P_{\text{NORMAL LOAD}}^t = P_{\text{NORMAL LOAD}}^t \partial_t^i \quad i \in B_{\text{NORMAL LOAD}}$$

where $P_{\text{NORMAL LOAD}}^t$ is active power of node $i$ at time $t$; $\partial_t^i$ is the state of load access; $B_{\text{NORMAL LOAD}}$ is a set of normal load nodes.

### 3.2.4 Constraints of energy storage:

$$\begin{align*}
\dot{P}_{\text{ES}}^t &\leq P_{\text{ES}}^t \leq E_{\text{ES}}^t \max \\
E_t^j &= E_{t-1}^j + P_{\text{ES}}^t \\
E_{\text{ES}}^t \cdot \text{SOC}_{\text{min}} &\leq E_t^j \leq E_{\text{ES}}^t \cdot \text{SOC}_{\text{max}}
\end{align*}$$

where $P_{\text{ES}}^t$ is the charge power or discharge power; $E_{\text{ES}}^t$ and are the charging power limit or discharge power limit at time $t$; $E_t^j$ is the state ES present state; $E_{\text{ES}}^t$ is the ES capacity; SOC$_{\text{min}}$ and SOC$_{\text{max}}$ the state of charge.

### 3.2.5 Constraints of AC part system:

i. Constraints of AC power flow.

$$\begin{align*}
\sum_{k \in \Phi^i} P_{\text{ij}}^t &= \sum_{j \in \Phi^i} (P_{\text{ij}}^t - R_j (I_{\text{ij}})^2) + P_{\text{ij}}^t \\
\sum_{k \in \Phi^i} Q_{\text{ij}}^t &= \sum_{j \in \Phi^i} (Q_{\text{ij}}^t - X_j (I_{\text{ij}})^2) + Q_{\text{ij}}^t \\
\end{align*}$$

$$i, j, k \in B_{\text{DC}}$$

$$\begin{align*}
I_{\text{ij}}^2 &= P_{\text{ij}}^t - P_{\text{ij}}^t \text{REG} - P_{\text{ij}}^t \text{NSC} - P_{\text{ij}}^t \text{LOAD} \\
Q_{\text{ij}}^t &= Q_{\text{ij}}^t \text{REG} + Q_{\text{ij}}^t \text{NSC} + Q_{\text{ij}}^t \text{LOAD} \\
\end{align*}$$

$$i, j \in B_{\text{DC}}$$

$$\begin{align*}
(U_{\text{ij}}^t)^2 &= (U_{\text{ij}}^t)^2 - 2(R_j P_{\text{ij}}^t + X_j Q_{\text{ij}}^t) + (R_j^2 + X_j^2) \\
\end{align*}$$

where $\Phi_{\text{DC}}$ is the set of the head nodes from the AC system whose terminal node is $i$; $\Psi_{\text{DC}}$ is the set of the terminal nodes from the AC system whose head node is $j$; $R_j$ and $X_j$ are the resistance and reactance of branch $ij$; $P_{\text{ij}}^t$ and $Q_{\text{ij}}^t$ are the active and reactive power injection from node $j$ to node $i$; $P_{\text{ij}}^t$ and $Q_{\text{ij}}^t$ are active and reactive power injection of node $i$; $Q_{\text{ij}}^t$ is the reactive power of ES; $I_{\text{ij}}^t$ is the current amplitude from node $j$ to node $i$.

ii. Constraint of REG output

$$\begin{align*}
0 \leq P_{\text{REG}}^t \leq P_{\text{MAX}}^t \\
0 \leq Q_{\text{REG}}^t \leq Q_{\text{MAX}}^t \\
\end{align*}$$

where $P_{\text{MAX}}^t$ and $Q_{\text{MAX}}^t$ are the maximum active and maximum reactive powers of REG of node $i$ at time $t$.

iii. The voltage constraint

$$U_{\text{ij}} < U_{\text{ij}}^t < U_{\text{ij}} \max \quad i \in B_{\text{DC}}$$

where $U_{\text{ij}}$ and $U_{\text{ij}} \max$ are lower and upper voltage limits of node $i$.

iv. The current constraints

$$I_{\text{ij}} \leq I_{\text{ij}} \max \quad i \in B_{\text{DC}}$$

where are upper current limits of node $i$.

### 3.2.6 Constraint of DC power flow:

$$\begin{align*}
\sum_{j \in \Phi^k} (P_{\text{ij}}^t - R_j P_{\text{ij}}^t) &= \sum_{k \in \Phi^i} P_k \\
P_{\text{ij}}^t &= P_{\text{ij}}^t \text{REG} + P_{\text{ij}}^t \text{NSC} + P_{\text{ij}}^t \text{LOAD} \\
(U_{\text{ij}}^t)^2 &= (U_{\text{ij}}^t)^2 - 2(R_j P_{\text{ij}}^t + X_j Q_{\text{ij}}^t) + (R_j^2 + X_j^2) \\
\end{align*}$$

where $\Phi_{\text{DC}}$ is the set of the head nodes from the DC system whose terminal node is $i$; $\Psi_{\text{DC}}$ is the set of the terminal nodes from the DC system whose head node is $i$.

Other constraints are similar to the ones in (15)-(17).

### 4 Optimisation algorithm

#### 4.1 Second-order cone transforming of objectives

The standard form of second-order cone programming model can be formulated as follows:

$$\begin{align*}
\min \ c^T x \\
\text{s.t.} \quad Ax = b \\
x \in K
\end{align*}$$

$$K = \left\{ x \in R^n : 2x_i x_j \geq \sum_{j=0}^{m} x_i x_j, x_i \geq 0 \right\}$$

With $(U_{\text{ij}}^t)^2$ and $(U_{\text{ij}}^t)^2$ replaced by $I_{\text{ij}}$ and $U_{\text{ij}}$ in the object can be expressed as follows:

$$f_3 = \min \left( \sum_{i,j \in \Psi} R_j I_{\text{ij}} + \sum_{i,j \in \Psi} R_j I_{\text{ij}} \right)$$

$$I_{\text{ij}} = \frac{(P_{\text{ij}}^t)^2 + (Q_{\text{ij}}^t)^2}{U_{\text{ij}}^2}$$

Equations (22) and (23) can be further loosened and transformed into the form of SOCP:

$$\begin{align*}
\|2P_{\text{ij}} - 2Q_{\text{ij}} - I_{\text{ij}} - U_{\text{ij}}\|^2_2 &\leq I_{\text{ij}} + U_{\text{ij}} \\
\|2R_{\text{ij}} - I_{\text{ij}} - U_{\text{ij}}\|^2_2 &\leq I_{\text{ij}} + U_{\text{ij}}
\end{align*}$$

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4.2 Second-order cone transforming of constraints

The constraint of network reconfiguration in the second-order cone programming model is formulated as follows: (see (26)) where $a_{ij}$ is a Boolean variable, referring to the switch status between node $i$ and node $j$, $n_i$ is the number of head nodes; $\beta_{ij}$ is an auxiliary Boolean variable, and if node $i$ is the parent node of node $j$, $\beta_{ij}$ is equal to 1, and if not, $\beta_{ij}$ is equal to 0; $N_i$ is the node set; $N_i$ is the head node.

With $(I_i^j)$ and $(U_i^j)$ replaced by $I_{1,i,j}$ and $U_{1,i,b}$, the AC and DC constraints of power flow and node voltage can be transformed and expressed as (24)–(27). Especially, a big $M$ method is adopted to reflect the impact of network reconfiguration during the transforming.

\[
\sum_{k \in \Psi^i} P_{i,k} = \sum_{j \in \Phi^i} (P_{j,i} - R_{j,i,j} + P_{t,i}) \\
\sum_{k \in \Psi^i} Q_{i,k} = \sum_{j \in \Phi^i} (Q_{j,i} - X_{j,i,j} + Q_{t,i})
\]

\[
\sum_{k \in \Psi^i} P_{i,k} = \sum_{j \in \Phi^i} (P_{j,i} - R_{j,i,j} + P_{t,i}) + P_{t,i} \quad i,j,k \in B^{AC}
\]

\[
-(1 - a_{ij})M \leq U_{1,i,j} - (U_{2,i,t} - 2R_{j,i,j} + X_{j,i,j}Q_{j,i}) \quad i,j \in B^{DC}
\]

\[
-(1 - a_{ij})M \leq U_{1,i,j} - (U_{2,i,t} - 2R_{j,i,j} + X_{j,i,j}Q_{j,i}) - (1 - a_{ij})M
\]

The operation constraints of VSCs can be transformed into rotation cone constraints.

\[
(P_{i}^{VSC})^2 + (Q_{i}^{VSC})^2 \leq \frac{S_{ij}^{VSC} S_{ij}^{VSC}}{\sqrt{2}}
\]

The service restoration strategies are as follows:

i. Judge the fault type and adjust VSC control model according to the fault type.
ii. Set the balance node according to the control model fault network control mode VSC.
iii. Relax convex constraints, build a mixed integer linear model and using the CPLEX unified solving.

5 Case study

In this paper, the hybrid AC/DC distribution network with VSCs shown as Fig. 2 is used as a test system to analyse and verify the proposed model and algorithm. The AC/DC system is an improved two IEEE 33 node systems with VSCs. The DC lines are transformed from AC lines and reconnected with the AC system by VSC1 and VSC2. The capacities of VSC1 and VSC2 are 5000 and 10000 kVA. The DGs parameters are indicated in Table 1. The initial state of charge of ES is 0.5. Priorities and controlling types of the loads are indicated in Table 2. In AC system, REGs' power factor is 0.9. The outage is to be prolonged for 4 h. The REG outputs and loads during the service restoration are indicated in Table 3. The optimisation method proposed in this paper is implemented by MATLAB R2016a, and the operating environment is Intel i5-5200 2.2 GHz CPU, 8 GB RAM.

There are three cases designed to verify the benefits for coordination optimisation of ESs, VSC2 and network reconfiguration.

Case 1: the system is optimised by network reconfiguration, with VSC2 and ESs.
Case 2: the system is optimised by network reconfiguration and VSC2, without ESs.
Case 3: the system is optimised by ESs and VSC2, without network reconfiguration.

5.1 Case of fault type 1

Table 4 shows the result of service restoration of fault type 1. Without ESs, total restoration power supply of case 2 would decrease to some degree compared with case 1. Without network reconfiguration, total losses of case 3 decrease significantly compared with case 1.

Fig. 3 shows a new topology during the service restoration. Fig. 4 shows that after isolating the fault, VSC1 takes major responsibility to support power outage areas’ active power. It is apparent that it changed to follow the load’s demand. Moreover, VSC2 mainly deliver reactive power to the AC line and transfer a part of active power from the AC line to DC line for reducing loss.

Table 5 shows the interruption loads’ regulation factor during service restoration. Fig. 5 shows that ESs from AC lines were in the charge state at time 1 and 2 and turn to the discharge state at time 3 and 4. In contrast, ESs from DC lines output their energy at the beginning. The reason for this phenomenon are as follows: according to a DC system which can adjust itself to adopt the new running condition though increasing VSC2’s output and control interruptible load, ESs from AC lines need to dispatch energy to overcome AC loads peak issue at time 3. Evidenced by the same token, why ESs from DC lines need to output their energy at first.

5.2 Case of fault type 2

Table 6 shows the result of service restoration of fault type 2. Without ESs, total restoration power supply of case 2 and case 3 would significantly decrease compared with case 1. It is worth noting that power outage area cannot be islanded operation in case 2 since there are no ESs in the system. Without network reconfiguration, total losses of case 3 decrease significantly compared with case 1.

Fig. 6 shows a new topology during the service restoration. Fig. 7 shows that after isolating the fault, without VSC1, VSC2 takes major responsibility to support power outage areas’ active power. It is apparent that it changed to follow the load’s demand. In addition, as VSC2 does not have enough capacity to support whole power outage area, the islands are then divided.

Table 7 shows the interruptible loads’ regulation factor during service restoration. Fig. 8 shows that ESs from AC lines were in the charge state at time 2 and turn to the discharge state at time 1, 3 and 4. In contrast, ESs from DC lines output their energy at the beginning same as case 1. The reason for this phenomenon are as follows: according to a DC system which cannot adjust itself to adopt the new running condition though increasing VSC2’s output and control interruptible load, ESs from AC lines need to not only dispatch energy for AC loads peak at time 3 but also dispatch energy for AC loads peak at time 1. ESs from DC lines need to output their energy at time 1 same as case 1.

6 Conclusion

Considering integrating high levels of variable renewable energy into the grid, this paper proposes a service restoration strategy for AC/DC hybrid distribution networks and realise the coordination optimisation of VSCs, ESs, and tie switches.

In this paper, separation of fault from fault positions classification is described. Various control models of VSCs are analysed. Matching analysis is performed between fault types and control models of VSCs.

Based on mixed-integer second-order cone programming, AC lines, DC lines, and the control devices with different characteristics are proposed. The algorithm is proved to be effective according to the experimentation.

Through a numerical simulation computational experiment, it can be determined whether ESs scheduling or network
reconfiguration is positive to the service restoration process. ESs can balance between supply and demand. Network reconfiguration can reduce loss though searching a new network. Both are benefited to restore more load.

In the AC/DC hybrid distribution network, with the comprehensive utilisation of VSCs, ESs, and tie switches, the best result of the service restoration would be achieved.

\[
\sum_{j \in n} \alpha_{ij} = n - n_t \quad i, j \in B^{AC} \text{ or } i, j \in B^{DC}
\]

\[
\beta_{ij} + \beta_{ji} = \alpha_{ij} \quad i, j \in B^{AC} \text{ or } i, j \in B^{DC}
\]

\[
\sum_{j \in N(i)} \beta_{ij} = 1 \quad \forall i \in N \cap N_t \quad i, j \in B^{AC} \text{ or } i, j \in B^{DC}
\]

(26)

**Table 1** Comparisons of optimisation results of four cases

<table>
<thead>
<tr>
<th>Line</th>
<th>The type of DG</th>
<th>Position</th>
<th>Capacity, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>REG</td>
<td>14</td>
<td>600</td>
</tr>
<tr>
<td>1, 2</td>
<td>REG</td>
<td>19</td>
<td>800</td>
</tr>
<tr>
<td>1, 2</td>
<td>REG</td>
<td>26</td>
<td>400</td>
</tr>
<tr>
<td>1, 2</td>
<td>REG</td>
<td>29</td>
<td>400</td>
</tr>
<tr>
<td>1, 2</td>
<td>ES</td>
<td>14</td>
<td>100</td>
</tr>
<tr>
<td>1, 2</td>
<td>ES</td>
<td>19</td>
<td>100</td>
</tr>
<tr>
<td>1, 2</td>
<td>ES</td>
<td>26</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 2** Priorities and controlling types of the loads

<table>
<thead>
<tr>
<th>Line</th>
<th>Primary load</th>
<th>Second grade load</th>
<th>Third-grade load</th>
<th>Interruptible load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>1, 5, 8, 12, 19, 22, 25, 29, 32</td>
<td>the rest</td>
<td>7, 23</td>
<td>9, 15, 16, 30</td>
</tr>
</tbody>
</table>

**Table 3** REG outputs and loads during the service restoration

<table>
<thead>
<tr>
<th>Time</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>load of DC lines, kW</td>
<td>5572.5</td>
<td>5201</td>
<td>3715</td>
<td>3343.5</td>
</tr>
<tr>
<td>load of AC lines, kW</td>
<td>1857.5</td>
<td>2600.5</td>
<td>4829.5</td>
<td>3715</td>
</tr>
<tr>
<td>REG outputs, kW</td>
<td>880</td>
<td>1320</td>
<td>4400</td>
<td>3080</td>
</tr>
</tbody>
</table>

**Table 4** Result of service restoration of fault type 1

<table>
<thead>
<tr>
<th>Restoration power supply from main system, kW</th>
<th>Restoration power supply from islands, kW</th>
<th>Total restoration power supply, Total losses, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>3338.728</td>
<td>0</td>
<td>89.87 3907.91</td>
</tr>
<tr>
<td>3065.076</td>
<td>0</td>
<td>82.51 3034.80</td>
</tr>
<tr>
<td>3331.22</td>
<td>0</td>
<td>89.67 4340.40</td>
</tr>
</tbody>
</table>

reconfiguration is positive to the service restoration process. ESs can balance between supply and demand. Network reconfiguration can reduce loss though searching a new network. Both are benefited to restore more load.

In the AC/DC hybrid distribution network, with the comprehensive utilisation of VSCs, ESs, and tie switches, the best result of the service restoration would be achieved.
Table 5  Regulation factor of interruptible load

<table>
<thead>
<tr>
<th>Interruptible load</th>
<th>9</th>
<th>15</th>
<th>16</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>case 1</td>
<td>3.43%</td>
<td>0.87%</td>
<td>0.78%</td>
<td>0.34%</td>
</tr>
<tr>
<td>case 2</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>case 3</td>
<td>0.59%</td>
<td>0.22%</td>
<td>0.22%</td>
<td>0.11%</td>
</tr>
</tbody>
</table>

Table 6  Result of service restoration of fault type 1

<table>
<thead>
<tr>
<th>Restoration power supply from main system, kW</th>
<th>Restoration power supply from islands, kW</th>
<th>Total restoration power supply, %</th>
<th>Total loss, kW</th>
<th>Disconnected REG power, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>case 1</td>
<td>1195</td>
<td>390</td>
<td>42.66</td>
<td>4506.8</td>
</tr>
<tr>
<td>case 2</td>
<td>1135</td>
<td>0</td>
<td>30.55</td>
<td>3431.5</td>
</tr>
<tr>
<td>case 3</td>
<td>865</td>
<td>390</td>
<td>35.40</td>
<td>5623.0</td>
</tr>
</tbody>
</table>
References


