Optimal Restoration Strategy Based on Resilience Improvement for Power Transmission Systems Under Extreme Weather Events

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Abstract. In the past few years, extreme weather events have threatened operations of power systems. The improvement of resilience for power system becomes crucial. This paper proposes an optimal restoration strategy, considering the resilience index of power transmission systems in restoration processes. Firstly, a typhoon is taken as an example to establish an extreme weather event impact model to obtain the failure probability of lines. Then Monte Carlo method is used to generate fault sets. For each restoration time point, the optimal restoration model is used to acquire the maximum recovery loads. The resilience index of system can be obtained by the resilience assessment methodology during restoration. Finally, the proposed strategy is compared with distance-based strategy in IEEE 6-bus system, which demonstrates the superiority of the proposed strategy.

1. Introduction

In recent years, extreme weather events occurred more frequently, which addressed the importance of rapid restoration in power transmission systems. But most power systems are designed and maintained for normal weather conditions with low impact and high probability, which cannot withstand damages caused by extreme weather events [1]. For example, in the 2012 Hurricane Sandy resulted in outages that affected over 8.5 million customers [2]. Tropical storm Irene hit the State of Connecticut (CT) in 2011, causing sustained interruptions of electric service up to 11 days and a total damage of about $200 million in CT [3]. One way to address this issue is to improve the resilience of power transmission systems that can withstand the extreme weather events with high impact and low probability.

Generally, resilience has been widely used in many disciplines as a judgment of system's ability to resist disasters and recover from disasters [4]. The traditional reliability analysis is mainly aimed at the typical failures with low impact and high probability, which mainly focuses on the influence of disturbance on the power failure of users. While resilience is aimed at extreme weather events with high impact and low probability [5].

When it comes to the resilience improvement strategy, there are two kinds of measure, i.e., pre-disaster hardening measures and post-disaster restoration measures [6]. The pre-disaster hardening measure which covers transmission lines, upgrading poles and structures with stronger materials is efficient but costly [7]. The post-disaster restoration strategy is convenient but inefficient. Reference [8] proposed a resilience-oriented design (ROD) technique to improve the resilience of system. The problem is formulated as a two-stage problem, and its first stage is to harden the existing distribution lines and then deploy ROD resource. Reference [2] put forward three kinds of resilience improvement strategies...
and analysed which one should be adopted in different situations. Three measures to improve the resilience of system were proposed in [5]. It can be seen that increasing resilience is very important for system to resist disasters and restoration after disasters.

Research has been conducted to study repair and restoration measures. Arab et al. [9] developed a framework for proactive recovery of electric power assets with the primary objective of resiliency enhancement. A two-stage co-optimization approach for the repair and restoration of distribution networks was proposed in [10], which grouped the damaged components and corresponding depots in the first stage, and co-optimized the repair, reconfiguration, and distributed generation dispatch in the second stage. But none of them used an appropriate resilience index to indicate the resilience of the system after restoration.

In this paper, an optimal restoration strategy is proposed to take load shedding and repair crews into consideration. We consider the impact of extreme weather events on transmission lines. The resilience index of system is obtained by developing a resilience assessment methodology during restoration. The proposed strategy effectively improves the resilience of the system and can provide a reference for power company to perform post-disaster restoration.

The remainder of this paper is organized as follows. Section 2 presents the framework of the proposed strategy. The model and methodology are discussed in Section 3. In Section 4, the numerical results and technical discussion are provided. Conclusions of this paper are given in Section 5.

2. Framework of the proposed strategy

As mentioned above, the framework of the proposed strategy is illustrated in Figure 1. The framework includes three parts, i.e., an extreme weather event impact model, an optimal restoration model, and a resilience assessment methodology. The framework contains the following steps.

- The data of extreme weather events and power transmission systems are input, and component failure probability are calculated by the extreme weather event impact model.
3. Model and methodology analysis

3.1. Extreme weather event impact model
The impact of extreme weather events on power transmission systems in many dimensions. This research takes the typhoon which is the most frequent extreme weather event as an example. Since the transmission lines located outdoors are most vulnerable to a typhoon, the relation between wind speed and fault probability of transmission line is considered. The transmission line fragility curve associated with the wind speed is shown in Figure 2 [12]. The horizontal axis represents the wind speed of the typhoon and the vertical axis denotes the failure probability of the transmission line, $V$ is the designed wind speed of the transmission line, and $\beta$ stands for the designed value.

$$
P_l = \begin{cases} 
0, & v < V \\
\exp \left[ \frac{0.6931(v-V)}{V} \right] - 1, & V < v < 2V \\
1, & v > 2V
\end{cases}
$$

where $P_l$ is the failure probability of the transmission line. $V$ is the designed wind speed of the transmission line.

After obtaining the failure probability, the Monte Carlo method is used to compare it with a random number $m$ from a uniform distribution $U(0,1)$. If the failure probability of transmission line is greater than $m$, the line is considered as offline.

3.2. Extreme weather event impact model
Under extreme weather events, power transmission systems may be divided into several subsystems due to multiple failures, and generators must be rescheduled or even load shedding is performed to meet the stability requirement of systems. In the process of calculation, an optimization model based on the DC power flow is often used to simplify the calculation. If there exists an island in the system, generator scheduling or load shedding is carried out in the subsystem. If there are no generators in the subsystem, all loads are considered to be removed. The objective and constraints of the optimization model is given as follows [10].
The objective of (2) is to maximize the recover loads at each time, where $w_i$ represents the weight of bus $i$, $a_{i,t}$ is a binary variable indicates whether the load of bus $i$ at time $t$ is restored, i.e., $a_{i,t}=1$ means the load of bus $i$ at time $t$ is restored, $PD_{i,t}$ is the active demand at bus $i$ and time $t$.

The operation constraints of power transmission systems are represented by (3)-(7). Constraint (3) is the load balance of power transmission systems, where $P_{G_i}$ is the active power of generator at bus $i$ and time $t$, $LS_{i,t}$ is the load shedding at bus $i$ and time $t$. Constraint (4) defines the active power output limits for generator at bus $i$ and time $t$, where $P_{G_i}^\text{min}$ and $P_{G_i}^\text{max}$ are the maximum and minimum active power in the generator at bus $i$ respectively. Constraint (5) indicates that the power flow through a damaged line should be zero, which is achieved by multiplying the line limits by a binary variable $L_{kt}$, i.e., $L_{kt}=0$ means the line $k$ is damaged at time $t$. $P_{kt}$ is the power flows on line $k$ at time $t$, $P_{k}^\text{max}$ is the maximum capacity of the line $k$. Constraint (6) denotes the voltage limits, where $V_{i,t}$ is the voltage at bus $i$ and time $t$, $V_{i}^\text{min}$ and $V_{i}^\text{max}$ are the maximum and minimum voltage at bus $i$ respectively. Constraints (7) represents the load shedding limit.

The restoration constraints of power transmission systems are represented by (8)-(16). Constraint (8) ensures that a repair crew arriving at a damaged component leaves it after finishing the repair, where $E$ is the damaged component sets, $x_{m,n}$ is a binary variable indicating whether a repair crew moves from a damaged component $m$ to $n$. Constraint (9) ensures that the repair crews start from depots, where $x_{0,m}$ is a binary variable indicates whether a repair crew moves from depots to the damaged components $m$. Constraint (10) indicates that all repair crews return to the depots after repairing, where $n$ is the number of repair crews. If a repair crew visits a damaged component $m$, then $y_{m}$ equals 1. Constraint (11) means that a damaged component is repaired by only one repair crew to ensure that no repair crew visits a repaired component. Constraint (12) couples the binary variables $x_{m,n}$ and $y_{m}$, i.e., if a repair crew takes the traveling path $x_{m,n}$ then $y_{m}=1$. Constraint (13) indicates that depots contain all the resources for repair, where $R_k$ is the resource that damaged component $k$ needs, $R$ is the resource that depots can provide.
Constraint (14) shows that the restoration time of a damaged component $k$ is the sum of repair time and waiting time, where $t_k$ is the restoration time of the damaged component $k$, $t_{re}^k$ and $t_{wa}^k$ are the repair time and waiting time of damaged component $k$, respectively. Constraint (15) illustrated that the waiting time of the damaged component $k$ is the sum of repair time and waiting time of the previous damaged component $k-1$. Constraint (16) represents the restoration time of the first damaged component, which is composed of repair time and travel time, where $d_{0,1}$ is the distance between the depot to the first damaged component and $v_r$ is the travel speed of a repair crew.

### 3.3. Resilience assessment methodology

When a power transmission system is affected by an extreme weather event, it is likely that the components fail, resulting in a large-scale blackout. The whole process of an extreme event affecting power transmission system is usually divided into three stages: a pre-disaster stage, a during-disaster stage, and a post-disaster stage. The system performance under an extreme event is shown in Figure 3 [10].

In Figure 3, time $t_1$ is the start of an extreme event. The system performance reaches its minimum $F(t_2)$ at time $t_2$. The restoration process starts at time $t_3$ and ends at time $t_4$. $F(0)$ is a curve, which represents the system performance if there is no extreme event. $F(0) - F(t_2)$ represents the maximum performance loss, when an extreme event happens. $F(t) - F(t_2)$ represents the performance which is restored at time $t$. We define $RI(t)$ as the resilience index of system at time $t$ [7]. $RI(t)$ denotes the ratio of restored load, which equals to the ratio of $A_1$ to $A_1 + A_2$ as shown in Figure 4. The calculation formula of $RI(t)$ is given as follows.

$$\text{RI}(t) = \frac{A_1}{A_1 + A_2} = \int_{t_2}^{t} \frac{F(t) - F(t_2)}{F(0) - F(t_2)} dt$$

$$\text{(17)}$$

Figure 3 System performance curve of resilience.

![System performance curve of resilience.](image)

Figure 4 Resilience index at different periods.

(a) Resilience index at time $t$

(b) Resilience index of the whole restoration process
4. Numerical analysis

4.1. Test system and data

In this research, typhoon is employed as an extreme event. To simplify the calculation, only the impact of typhoon on transmission lines which are in open air are considered. The design wind speed of component $V$ in (1) is assumed to be 25 m/s, and the wind speed of typhoon is set as a normal distribution with an average of 20 m/s.

The proposed method is tested on IEEE 6-bus network [12], as shown in Figure 5. The importance weight assumption of each bus is shown in Table 1. The distance between buses of the system is given in Table 2, which represents the distance travelled by a repair crew. Assume that only one repair crew is located at bus 1, and the repair capability of each repair crew corresponds to one line. The normal average travel speed of the repair crew is 80 km/h, and the average repair time of each line is 1 h.

![Figure 5 The IEEE 6-bus system.](image)

| Bus | 1   | 2    | 3    | 4    | 5    | 6    |
|-----|-----|------|------|------|------|------|
| Weight | 0  | 5    | 4    | 3    | 2    | 1    |

Table 2. The distance between buses of IEEE 6-bus system.

| Bus | 1    | 2    | 3    | 4    | 5    | 6    |
|-----|-----|-----|-----|-----|-----|-----|
| 1   | 0km | 80km| 30km| 50km| 50km| 70km|
| 2   | 80km| 0km | 110km| 100km| 120km| 140km|
| 3   | 30km| 110km| 0km | 20km| 20km| 50km|
| 4   | 50km| 100km| 20km| 0km | 20km| 40km|
| 5   | 50km| 120km| 20km| 20km| 0km | 20km|
| 6   | 70km| 140km| 40km| 40km| 20km| 0km |

4.2. Simulation results and technical discussion

Two typical failure scenarios are investigated by using (1) and the Monte Carlo method, as shown in Table 3. To illustrate the effectiveness of the proposed strategy, two measures are studied as below.

- **Measure 1**: According to the optimal restoration strategy proposed in this paper for post-disaster repair.
- **Measure 2**: Perform post-disaster repair in accordance with the distance-based strategy, giving the priority to repairing the nearest damaged line.

Using the proposed strategy, the load recovery of power transmission systems in the two scenarios are obtained, as shown in Figure 6. It can be seen that the repair time of measure 1 is always smaller than measure 2. In scenario 1, the system restores all the load at 5.125 h, while in measure 2 it takes 9.75 h to restore the full load. Measure 1 takes only 52.6% time of measure 2, because measure 1 gives the priority to repairing important lines so that the buses with higher weights restore first. Similarly, in scenario 2, measure 1 restores the full load at 4.5 h, which is 15.4% of the 29.125 h in measure 2.
Table 3. Fault scenarios of lines.

| Faulty line | Scenario 1 | Scenario 1 |
|-------------|------------|------------|
| L1 L3 L4 L5 L8 L9 | L1 L2 L3 L5 L6 L7 L8 L9 |

The resilience index of each scenario under different measures are calculated according to (17), as shown in Table 4.

The resilience index of measure 1 in scenarios 1 and 2 is 29% and 16% higher than those of measure 2, respectively. The load restoration efficiency of measure 1 is better than that of measure 2.

From the analysis of the results, the strategy proposed in this research can improve the resilience of power transmission systems, and realize rapid load restoration of the systems under extreme weather events. It can provide a reference for the post-disaster restoration for power companies.

![Figure 6 Load recovery under two measures of two scenario.](image)

Table 4. Resilience index of different scenarios under two measures.

| Scenario | Measure | Scenario 1 | Measure 1 | Measure 2 |
|----------|---------|------------|-----------|-----------|
| Resilience index | Measure 1 | 0.8336 | 0.6448 | 0.7230 | 0.6232 |

5. Conclusions
In this paper, an optimal restoration strategy based on resilience improvement has been proposed for power transmission systems under extreme weather events. The paper develops an optimal restoration model to maximize the recovery loads. To reduce the computational complexity, fault sets are generated by a simplified typhoon model and the Monte Carlo method. The proposed optimization strategy is compared with the distance-based strategy in the IEEE 6-bus system. The results confirm the superiority of the proposed strategy in improving resilience of power transmission systems under extreme weather events.

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