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Optimal Branch Upgrade to Enhance Distribution Network Resilience

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ABSTRACT

The growing frequency of natural disasters, such as hurricanes and flooding, have brought new challenges including higher uncertainty of power supplies to the reliability of modern distribution networks. Resilience is introduced in the electrical engineering field to quantify the ability of a system to withstand and recover from external disturbances. This paper proposes a novel algorithm to optimize strategies for enhancing distribution network resilience by branch upgrade. According to the Extreme Value Theory, the method determines the failure probability of branches based on their physical strength under hurricanes during a designed lifetime. The method of Monte Carlo simulation is applied in the optimization model to maximize resilience. The result shows the optimal solution converges and compared with traditional methods that enhance main branches or upgrade as many branches as possible, the proposed method has a significant advantage in seeking the globally optimal solution.

Keywords: resilience, distribution network, planning, hurricane, Monte Carlo simulation

1. INTRODUCTION

The global climate change results in the increasing frequency of natural disasters, which threaten the stability and reliability of electricity systems. The number of reported disasters worldwide increased from 130 in 1980 to nearly 400 in 2010 [1]. For example, in August 2019, the typhoon Lekima severely impacted Eastern China, causing 45 deaths and 7.59 million families were influenced by the power cut due to the typhoon. In 2012, Hurricane Sandy caused a power outage affecting 8.5 million customers in the US [2]. The concept of resilience was introduced into the electricity system field as an important index to make power networks more reliable under external impacts [3]. Resilience describes the ability of an entity to anticipate, resist, absorb, respond to, adapt to and recover from a disturbance. It means a resilient system should be able to withstand natural disasters and artificial attacks, or recover rapidly even if the performance has decreased when an external impact is too huge [4].

The key point of resilience analysis is the quantification of itself and external disturbances. The load shedding and its recovery are the most important factors [5]. The dispatching of repair crews in distribution networks is modelled as a mixed integer linear programming for operational analysis based on Monte Carlo method in [6]. Different weather scenarios are assessed based on a Brazilian distribution network and the resilience loss is proved to be not linear to the size of the network [7]. However, there are few studies on the planning of distribution networks with economic constraints.

This paper focuses on the planning stage, aiming to quantify the resilience enhancement by changing branches of a distribution network from overhead lines into underground cables, filling the gap of infrastructural resilience analysis in distribution networks. Firstly, by using Extreme Value Theory (EVT), the threshold of hurricane strength during a given network lifetime is determined. Secondly, failure probabilities of branches can be calculated by referring fragility curves of components according to the expectation value of wind speed. Finally, based on the theorem of Monte Carlo simulation, the expectation resilience is the average value of abundant random scenarios, and the result is proved to converge within the proposed number of simulations.

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2. METHODOLOGY

2.1. Extreme Value Theory

The EVT is an effective method for assessing the distribution of extreme values in a system. In most cases, natural disasters are associated with abnormal values of some types of data in climate records. Thus, the EVT method is suitable for setting threshold for preventing natural disasters like hurricanes in distribution network planning.

Assuming a given sample set $\{X_n\}$ follows a cumulative distribution function F , which can be expressed as

$$\Pr(x \leq z) = F(z). \tag{1}$$

Letting $M_n = max(X_1, \ldots , X_n)$, the distribution of M_n is

$$\Pr(M_n \leq z) = (F(z))^n. \tag{2}$$

None of X_n exceeds z [8]. However, (2) is not suitable for analyzing a sample with a massive number of data. According to the Central Limit Theorem, the EVT proves that if appropriate arrays of a_n and b_n exist, the distribution of extreme values can be transferred into another form as the Generalized Extreme Value (GEV) with an expression as

$$\lim_{n\to\infty} \Pr\left(\frac{M_n - b_n}{a_n} \leq z\right) = \exp\left\{-\left[1 + \xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\} \tag{3}$$

where ξ , μ and σ are shape parameter, location parameter and scale parameter respectively.

The return level z_p and period T implicate that an event with a level exceeding z_p appears for every period of T. According to EVT, the return level

$$z_p = \begin{cases} \mu - \dfrac{\sigma}{\xi}[1 - {y_p}^{-\xi}],\ \xi \neq 0 \\ \mu - \sigma log y_p,\ \xi = 0 \end{cases} \tag{4}$$

where

$$y_p = -\log(1-p). \tag{5}$$

It means it is possible to set proper thresholds according to the specific requirements if a GEV model of extreme values has been built [9]. Thus, based on historical data of local wind speed, the return level and period can be calculated by the method.

2.2. Failure Probability

Historical records indicate that the correlation between the failure probability of an overhead line and wind speed is a sigmoid function, expressed as

$$P_{wind} = \frac{\exp\{\sigma(\omega-\mu)\}}{\exp\{\sigma(\omega-\mu)\}+1}. \tag{6}$$

where ω is the wind speed in m/s, μ and σ are shape parameters and can be determined by the physical characteristics of transmission lines [10].

2.3. Optimization Model

The objective of this model is to conclude an optimal strategy to change overhead lines into underground cables to enhance the resilience of a distribution network under hurricanes. The optimization model is shown as follows

$$\min\left(-\mathfrak{R} = -\sum_{i=0}^{n_b}\int_{t_0}^{t_e}\frac{P_{L,i} - P_{L,i,t}}{P_{L,i}}dt\right) \tag{7}$$

$$s.t. \quad \underline{V_i} \leq V_i \leq \overline{V_i} \tag{8}$$

$$0 \leq P_i \leq \overline{P_i} \tag{9}$$

$$\underline{\varphi_i} \leq \varphi_i \leq \overline{\varphi_i} \tag{10}$$

$$0 \leq P_{i,j} \leq \overline{P_{i,j}} \tag{11}$$

$$0 \leq P_{G,i} \leq \overline{P_{G,i}} \tag{12}$$

$$0 \leq Q_{G,i} \leq \overline{Q_{G,i}} \tag{13}$$

$$\underline{V_{G,i}} \leq V_{G,i} \leq \overline{V_{G,i}} \tag{14}$$

$$S_G = S_{loss} + S_{bus} \tag{15}$$

$$S_{bus} = [\boldsymbol{V}]\boldsymbol{Y}^*\boldsymbol{V}^* \tag{16}$$

$$0 \leq C \leq C_{inv} \tag{17}$$

$$C = \boldsymbol{x}^{\boldsymbol{T}}\boldsymbol{c} \tag{18}$$

$$\Pr\{Y_{ij} = 0\} = \frac{\exp\{\sigma_i(\omega-\mu_i)\}}{\exp\{\sigma_i(\omega-\mu_i)\}+1} \tag{19}$$

where (7) is the objective function of the model, whose meaning is to maximize the resilience of the system according to the Resilience Trapezoid model. Equations (8)-(14) are constraints of electricity system operation, indicating the basic physical structure- nodal admittance matrix $\boldsymbol{Y}$; and values of voltage V, active power P, reactive power Q and phase angle φ of all components should locate within their limits. Equations (15) and (16) mean that the input apparent power is equal to the summation of total load and power loss. Equations (17) and (18) are the constraints of investment, where $\boldsymbol{x}$ is a binary-variable vector whose length is equal to the number of branches in the network and $\boldsymbol{c}$ is the vector of upgrading cost of branches in the distribution network. The total cost must be less than the investment budget C. Equation (19) contains chance-constrained terms. Thus proper The Monte Carlo method is a feasible way to transfer stochastic constraints into linear forms [11].

2.4. Proposed Algorithm

The flow chart of methodology for making the strategy is shown as Fig. 1, whose function is outputting the total active loads of the system after a hurricane when the structure of the electricity system and local historical wind speed data are input. Then the quantified resilience can be calculated according to (7).

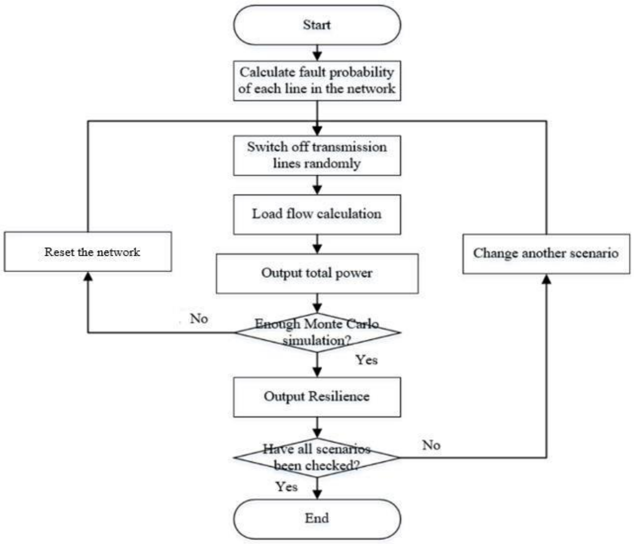

Fig. 1.Flow chart of the proposed algorithm.

The first step is to build the mathematical model for the study. These parameters and their connection relationship build the model of the network together. Meanwhile, the expected wind speed with its return period can be calculated according to historical data based on the EVT. Since the scale of distribution network is usually small compared to transmission systems, the maximum wind speed can be modelled the same for every branch within the network [12]. Then the failure probability of each branch can be calculated according to the infrastructure physical strength and the chosen wind speed by (19). Finally, assuming the Monte Carlo simulation has N loops, the expectation system resilience

$$\Re = \frac{\sum_i^N \Re_n}{N} \tag{21}$$

3. CASE STUDY

Since hurricanes can harm overhead lines while nearly have no effect on underground cables, it is a feasible way to enhance the resilience of a distribution network by upgrading branches from transmission lines to cables. However, the cost of the project is high so optimized strategies should be conducted to maximize investment efficiency. In this section, a modified IEEE 33bus distribution network shown in Fig. 2 is used as a case study to test the effectiveness of the proposed methodology. There are 33 buses and 32 branches in the network, where the bus 1 is linked to the grid as the only power supplier of the system.

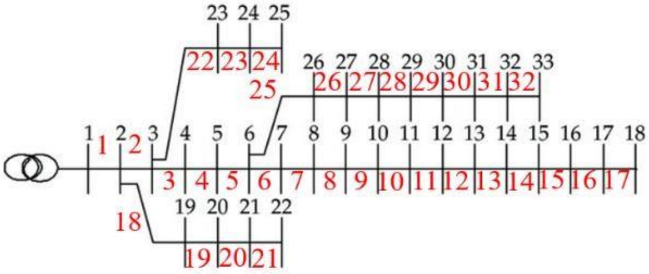

Fig. 2. The modified IEEE 33-bus system.

The duration of responsiveness and recovering are assumed to be 1 hour and 3 hours respectively l for each branch. In this case, a lower load shedding means a higher value of resilience, thus the total satisfied load of the network is an important indicator for determining the resilience. It is assumed that the cost of changing overhead lines into underground cables is $142,560 per mile and the total investment budget is $1,500,000.

4. RESULTS

These results are obtained by executing the algorithm for the case study.

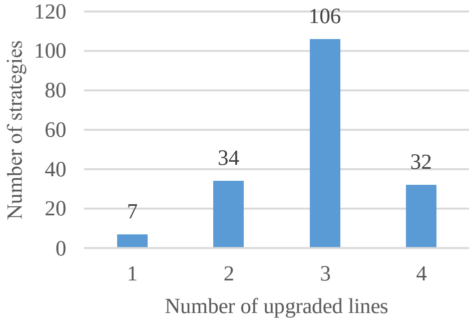

Fig. 3. The histogram of numbers of upgraded branches

Constrained by the investment budget, there are 179 strategies for upgrading branches, where the number of upgraded branches varies from 1 to 4. Figure 6 shows the number of strategies that upgrade different numbers of branches. There are only 7 feasible strategies for upgrading one line because costs of these lines are too high to be upgraded with any other branches, including strategy 157.

Fig. 3 lists average total active power values under cases where different numbers of branches are upgraded. The tendency implies the resilience enhancement is higher when fewer branches are changed into underground cables. Because upgrading fewer branches means the enhanced branches themselves have higher priorities, performances of this case are commonly better, implying the traditional method that upgrades more important branch is reasonable. However, though the average enhancement of upgrading only one branch is the highest shown in Fig. 4, the best strategy which changes one branch has a relatively lower efficiency than other best strategies. This highlights the ability of the proposed algorithm to seek optimal solution.

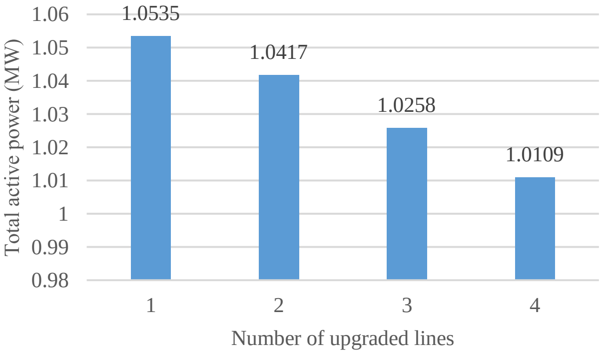

Fig. 4. Average power to numbers of upgraded branches

The results prove that changing overhead lines into underground cable is a feasible way to enhance the resilience of a distribution network. The qualitative analysis suggests upgrading those lines that are nearer to the main substation should have high efficiency. For example, branch 14 is closer to the main substation than branch 15, thus strategy 167 has a higher value of total power than strategy 168 that upgrades branch 15 and 23. Besides, the original failure probability of branches to be upgraded is also an important factor. For example, branch 1 has a much lower failure probability because its physical strength was designed to be reliable. In this case, changing branch 2 from overhead line to underground cable has a higher efficiency than branch 1, thus this is the best strategy which only upgrades one branch.

5. CONCLUSION

This paper indicates that neither the importance nor the number of branches to be upgraded is the only term to be concerned in the planning stage. Limited by the investment, strategies that upgrade important branches can lead to a poor improvement if the number of branches is not enough; while upgrading more branches may also result in an inefficient strategy if the priority of these branches is lower. To balance these cases, the proposed algorithm is an efficient tool for strategy makers to maximize the resilience of a distribution network under threats of natural disasters.

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