Distributionally Robust Optimal Strategy for Resilience Enhancement of Power Distribution Networks under Uncertain Earthquake Failures

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Abstract—**Earthquakes have posed a significant threat to the power system, and it is imperative to enhance the earthquake resilience of power distribution networks (PDN). However, the uncertainty of line failure due to earthquakes presents a formidable challenge in decision-making. In this article, the strategies for resilience enhancement are carried out from the perspectives of pre-earthquake and post-earthquake. In the pre-earthquake stage, three kinds of strategies are considered: line hardening, distributed generator (DG) configuration, and line setting; in the post-earthquake stage, emergency teams are dispatched to repair failed lines, the distributed generators are started, and the contact lines are switched, according to the strategy taken before the disaster and the post-earthquake failure scenario. The moment-based ambiguity set of line failure is established, and a two-stage distributionally robust optimization model is put forth to find the optimal decision. The column-and-constraint generation algorithm is used to solve the two-stage problem. The results show that it is essential to install the tie line with a line switch to enhance the resilience of PDNs.**

Keywords—resilience, power distribution network, restoration, column-and-constraint generation algorithm

I. INTRODUCTION

In the contemporary landscape of critical infrastructure systems, the uninterrupted supply of electrical power is paramount for sustaining societal operations and economic activities [1], [2]. However, the inherent vulnerability of power networks to earthquakes poses a formidable challenge to the dependability of electrical supply chains. Power distribution networks (PDN), serving as the indispensable nexus between power generation and end-users, are intrinsically predisposed to the deleterious impacts of earthquake disturbances. On September 5, 2022, a devastating earthquake with a magnitude of 6.8 struck Luding County, Sichuan Province, China. This earthquake resulted in the shutdown of five 110kV substations and four 35kV substations, causing 46 power lines with a voltage of 10kV and above to trip. Consequently, this led to power outages affecting 724 distribution areas and impacting 34,718 households. The earthquake disruption highlighted the critical importance of reducing the damage sustained by PDNs during earthquakes and expediting their post-earthquake recovery and reconstruction efforts. These efforts are pivotal in facilitating emergency response and relief operations, ensuring the resettlement of affected residents, and expediting the restoration of electrical power supply in disaster-stricken areas [3].

Resilience, as a theoretical construct, encapsulates the capacity of a system to preserve its fundamental functionality and to provide mission-critical services in the face of perturbations and adversity [4], [5]. Importantly, in the context of PDNs, resilience transcends the mere fortification of earthquake resistance; further, it extends to encompass the strategic measures to expedite the post-seismic restoration of normal operational states [6]. In terms of improving resistance performance before earthquakes, Jiang et al. [7] studied the optimal configuration of fixed ESS and mobile ESS in the power grid, proposed a two-step optimization model, and introduced a mixed allocation strategy based on subjective and objective weight analysis, ultimately providing the final allocation models of the two ESS. In terms of research on rapid recovery and power guarantee after an earthquake, Poudel et al. [8] proposed an elastic recovery method for the rapid recovery of critical loads using distributed energy, rational allocation of system resources, and feeder scheduling optimization to maximize the system's recovery ability after failure. It is imperative to develop a two-stage method to enhance the resilience of PDNs.

Research on enhancing the resilience of PDNs has a certain depth and breadth [9], but due to the unpredictability of earthquake disasters, a method for making decisions under unknown earthquake scenarios is necessary. The distributionally robust optimization (DRO) approach is an effective optimization method for dealing with uncertain scenarios [10]. It can overcome the dependence on specific scenarios and the requirement for accurate predictions while optimizing problems under the worst-case scenario distribution. This method aligns with the need to ensure the stable operation of power systems in the face of highly destructive events such as earthquakes. Babaei et al. [11] presented a DRO model to optimize network topology in the face of random contingencies, integrating distributed generation and minimizing load shedding under uncertainty. Li et al. [12] developed a DRO model to enhance the resilience of distribution networks by considering decision-dependent uncertainty and distributional ambiguity in extreme weather events.

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TABLE I. NOTATIONS OF PARAMETERS

Parameters	Descriptions
$\mathcal{N}$	Set of nodes in PDN
$\mathcal{N}_s$	Set of substations in PDN
$\mathcal{N}_d$	Set of installable DGs in PDN
$\mathcal{L}$	Set of transmission lines in PDN
$\mathcal{L}_h$	Set of lines that can be hardened in PDN
$\mathcal{L}_s$	Set of installable lines in PDN
$\mathcal{K}$	Set of emergency teams
$\mathcal{T}$	Set of time in the second stage
cx_{ij}	Cost of hardening line (i,j)
cd_n	Cost of installing DG in nth node
cs_{ij}	Cost of installing tie line (i,j) and the switch
B_p	Budget in the first stage
T	Maximum time in the second stage
$\xi_{ij}^{\max}$	Upper limits of the failure probability line (i,j)
p_i^{demand}	Maximum active power demand of node i
p_{it}^{generate}	Maximum active power in node i
$\underline{v}_i$	Lower limit of voltage magnitude of node i
$\overline{v}_i$	Upper limit of voltage magnitude of node i
φ_i	Power factor of node i
r_{ij}	Resistance of line (i,j)
x_{ij}	Reactance of line (i,j)
$tr_{(i,j)\to(p,q)}$	Time for a emergency team to travel from from line (i,j) to line (p,q)
h_{ij}	The total time to restore line (i,j)
α_i	Weight of node i

TABLE II. NOTATIONS OF VARIABLES

Parameters	Descriptions
Variables in the first stage	
x_{ij}	1, if the line (i,j) is hardened, and 0, otherwise
d_n	1, if a DG is installed in node n, and 0, otherwise
s_{ij}	1, if a tie line (i,j) is installed, and 0, otherwise
Variables in the second stage	
p_{it}	Active load shedding of node i in time t
q_{it}	Reactive load shedding of node i in time t
p_t^{ij}	Active power flow on line (i,j) in time t
q_t^{ij}	Reactive power flow on line (i,j) in time t
p_{jt}^G	Active power supply of node j in time t
q_{jt}^G	Reactive power supply of node j in time t
v_t^i	Voltage magnitude of node i in time t
α_t^{ij}	1, if the line (i,j) is working in time t, and 0, otherwise
z_{ijt}	1, if the line (i,j) can work in time t, and 0, otherwise
m_{ijt}^k	1, if the kth emergency team is restoring the line (i,j) in time t, and 0, otherwise

This article focuses on the unknown damage caused by earthquakes to PDNs and proposes a two-stage method to enhance the resilience of PDNs. The innovations are listed as follows:

- We establish a novel moment-based ambiguity set of line failure. A two-stage DRO model for the earthquake resilience of PDNs is constructed.
- The model is reformulated through the primal-dual relationship. The column-and-constraint generation algorithm is used to solve the two-stage problem.
- We provide some empirical evidence that the proposed method can effectively enhance the resilience of PDNs. This is done by applying the approach in the IEEE 33 distribution system.

The remainder of this article is organized as follows. Section II provides the proposed two-stage DRO model. The solution methodology is presented in Section III. A case study of the IEEE 33 distribution system is shown in Section IV, respectively.

II. MODEL FRAMEWORK

This Section focuses on the formulation of strategies in the pre-earthquake and post-earthquake stages, considering the uncertainty of line failure due to the earthquake. A two-stage distributionally robust optimization model is constructed to enhance the earthquake resilience of PDNs. In the pre-earthquake stage, various strategies, such as line hardening, distributed generator (DG) configuration, and line setting, are considered. And the line-setting strategy refers to simultaneously installing the tie lines and the line switches in the tie lines. A comprehensive set of pre-earthquake resistance strategies is adopted. In the post-earthquake stage, multiple rapid recovery strategies, including network reconfiguration and repair of the failure lines, are implemented to ensure the stable operation of electricity after disasters. Tables I and II list the notations of parameters and variables in the model, respectively.

The main reason for damage in distribution networks is line failure due to earthquakes. Assuming that only lines are susceptible to damage, each failure scenario can be represented by an L-dimensional vector $\tilde{\xi}$, where the ith parameter defines the operational status of the ith line (1 represents the line is undamaged, and 0, otherwise). Therefore, the set of feasible damage scenarios can be expressed as follows:

$$\mathcal{A}=\left\{\tilde{\xi}\left|\begin{matrix}\tilde{\xi}\in\{0,1\}^L, \|\tilde{\xi}\|_1\geq L-K,\\ \tilde{\xi}_{ij}\geq x_{ij}, \forall(i,j)\in\mathcal{L}_h\end{matrix}\right.\right\}, \tag{1}$$

where K represents the number of failed lines in the PDN. The larger K is, the more failure scenarios can be included in set $\mathcal{A}$, indicating that there are more potential damage scenarios in the second stage.

Assume that distribution $\mathbb{P}$ can be selected from the family of distributions defined by the ambiguity set $\mathcal{M}$, and this set is determined by the vulnerability of lines in the distribution network to earthquake disasters. Based on this, the ambiguity set $\mathcal{M}$ is constructed as follows:

$$\mathcal{M}=\left\{\mathbb{P}\in\mathcal{P}(\mathcal{A}):0\le\mathbb{E}_{\mathbb{P}}\left[1-\tilde{\boldsymbol{\xi}}\right]\le\boldsymbol{\xi}^{\max}\right\}, \tag{2}$$

where $\mathcal{P}(\mathcal{A})$ represents the set of all probability distributions of $\mathcal{A}$, and $\boldsymbol{\xi}^{\max}$ is a vector containing the upper bound of the failure probability of all lines.

The two-stage distributionally robust optimization model for earthquake resilience of distribution networks is as follows:

$$\min_{\boldsymbol{x},\boldsymbol{d},\boldsymbol{s}}\max_{\mathbb{P}\in\mathcal{M}}\mathbb{E}_{\mathbb{P}}\left[\mathcal{Q}\left(\boldsymbol{d},\boldsymbol{s},\tilde{\boldsymbol{\xi}}\right)\right]. \tag{3}$$

s.t.

$$\sum_{(i,j)\in\mathcal{L}_h}cx_{ij}x_{ij}+\sum_{j\in\mathcal{N}_d}cd_jd_j+\sum_{(i,j)\in\mathcal{L}_s}cs_{ij}s_{ij}\le B_P, \tag{4}$$

$$\begin{aligned}&x_{ij}\in\{0,1\},\forall(i,j)\in\mathcal{L}_h\\&d_j\in\{0,1\},\forall j\in\mathcal{N}_d\\&s_{ij}\in\{0,1\},\forall(i,j)\in\mathcal{L}_s\end{aligned}, \tag{5}$$

where Eq.(3) represents the objective function in the first stage, aiming to minimize the expected value of resilience loss under the worst distribution of failure scenarios. $\mathcal{Q}\left(\boldsymbol{d},\boldsymbol{s},\tilde{\boldsymbol{\xi}}\right)$ represents the objective function in the second stage. Constraint (4) describes that the total cost of line hardening decisions, installation of DG, and line setting strategy in the first stage must not exceed budget B_P. Constraint (5) represents the binary constraint in the first stage.

The recourse function $\mathcal{Q}\left(\boldsymbol{d},\boldsymbol{s},\tilde{\boldsymbol{\xi}}\right)$ is as follows:

$$\mathcal{Q}\left(\boldsymbol{d},\boldsymbol{s},\tilde{\boldsymbol{\xi}}\right)=\min\left(1-\frac{\sum_{t\in\mathcal{T}}\sum_{j\in\mathcal{N}}\alpha_jp_{jt}}{T\sum_{j\in\mathcal{N}}\alpha_jp_j^{\text{demand}}}\right). \tag{6}$$

s.t.

$$\sum_{i\in\mathcal{N}:(i,j)\in\mathcal{L}}p_t^{ij}+p_{jt}^Gd_j=\sum_{k\in\mathcal{N}::(j,k)\in\mathcal{L}}p_t^{jk}+p_{jt},\quad\forall j\in\mathcal{N},t\in\mathcal{T}, \tag{7}$$

$$\sum_{i\in\boldsymbol{N}:(i,j)\in\boldsymbol{L}}q_t^{ij}+q_{jt}^Gd_j=\sum_{k\in\boldsymbol{N}:(j,k)\in\boldsymbol{L}}q_{jkt}+q_{jt},\quad\forall j\in\mathcal{N},t\in\mathcal{T}, \tag{8}$$

$$p_{jt}^G\le p_{jt}^{\text{generate}},\forall j\in\mathcal{N}_d,t\in\mathcal{T}, \tag{9}$$

$$p_{jt}\le p_j^{\text{demand}},\forall j\in\mathcal{N},t\in\mathcal{T}, \tag{10}$$

$$\left(\underline{v}_i\right)^2\le\left(v_t^i\right)^2\le\left(\overline{v}_i\right)^2,\forall j\in\mathcal{N},t\in\mathcal{T}, \tag{11}$$

$$q_{jt}=p_{jt}\tan\left(\cos^{-1}\varphi_i\right),\forall j\in\mathcal{N},t\in\mathcal{T}, \tag{12}$$

$$q_t^{ij}\le\overline{q}_t^{ij}\alpha_t^{ij},\forall(i,j)\in\mathcal{L},t\in\mathcal{T}, \tag{13}$$

$$p_t^{ij}\le\overline{p}_t^{ij}\alpha_t^{ij},\forall(i,j)\in\mathcal{L},t\in\mathcal{T}, \tag{14}$$

$$\left(v_t^i\right)^2-\left(v_t^j\right)^2\le2\left(r_{ij}p_t^{ij}+x_{ij}q_t^{ij}\right)+M\left(1-\alpha_t^{ij}\right),\quad\forall(i,j)\in\mathcal{N},t\in\mathcal{T}, \tag{15}$$

$$\left(v_t^i\right)^2-\left(v_t^j\right)^2\ge2\left(r_{ij}p_t^{ij}+x_{ij}q_t^{ij}\right)+M\left(\alpha_t^{ij}-1\right),\quad\forall(i,j)\in\mathcal{L},t\in\mathcal{T}, \tag{16}$$

$$z_t^{ij}=\alpha_t^{ij}+\alpha_t^{ij},\forall(i,j)\in\mathcal{L}\setminus\mathcal{L}_s,t\in\mathcal{T}, \tag{17}$$

$$s_{ij}\ge\alpha_t^{ij}+\alpha_t^{ij},\forall(i,j)\in\mathcal{L}_s,t\in\mathcal{T}, \tag{18}$$

$$\sum_{(i,j)\in L}\alpha_t^{ij}\le1,\forall(i,j)\in\mathcal{N}\setminus\mathcal{N}_s,t\in\mathcal{T}, \tag{19}$$

$$\sum_{(i,j)\in L}\alpha_t^{ij}=0,\forall j\in\mathcal{N}_s,t\in\mathcal{T}, \tag{20}$$

$$z_t^{ij}\le\frac{\sum_{k=1}^K\sum_{\tau=1}^tm_{ij\tau}^k}{h_{ij}}+\tilde{u}_{ij}\forall(i,j)\in\mathcal{L},t\in\mathcal{T}, \tag{21}$$

$$z_t^{ij}\le z_{t+1}^{ij},\forall(i,j)\in\mathcal{L},t\in\mathcal{T}\setminus\{T\}, \tag{22}$$

$$\sum_{(i,j)\in\boldsymbol{L}}m_{ijt}^k\le1,\forall t\in\mathcal{T},k\in\mathcal{K}, \tag{23}$$

$$\sum_{\tau=t}^{\min\left(t+tr_{(i,j)\to(p,q)},T\right)}m_{pq\tau}^k\le\left(1-m_{ijt}^k\right)\cdot\min\left(tr_{(i,j)\to(p,q)},T\right),\quad\forall t\in\mathcal{T},k\in\mathcal{K},(i,j)\in\mathcal{L},(p,q)\in\mathcal{L} \tag{24}$$

$$\begin{aligned}&p_{it},q_{it},p_{it}^G,q_{it}^G,v_t^i\ge0,\forall i\in\mathcal{N},t\in\mathcal{T}\\&p_t^{ij},q_t^{ij}\ge0,\forall(i,j)\in\mathcal{L},t\in\mathcal{T}\end{aligned}, \tag{25}$$

$$\begin{aligned}&\alpha_t^{ij},z_t^{ij}\in\{0,1\},\forall(i,j)\in\mathcal{L},t\in\mathcal{T}\\&m_{ij\tau}^k\in\{0,1\},\forall(i,j)\in\mathcal{L},t\in\mathcal{T},k\in\mathcal{K}\end{aligned}, \tag{26}$$

where Eq.(6) represents the objective function in the second stage, aiming to minimize post-earthquake resilience loss. Constraints (7) and (8) represent the active power and reactive power flow balance in the PDN. $p_{jt}^Gd_j$ and $q_{jt}^Gd_j$ represent the reactive power and active power generated at node j, respectively. For the substations and the nodes equipped with DG, $d_j=1$ while $d_j=0$ for nodes without DG preparedness. Constraint (9) represents that the output of the DG should not exceed its maximum power capacity. Constraint (10) represents that the load consumed at each node should not exceed its maximum demand. Constraint (11) describes that the voltage at each node needs to be within a certain voltage range. Constraint (12) defines the power factor constraint for the active power and reactive power consumed at a certain node. Constraints (13) and (14) represent that the power transmitted through each transmission line should not exceed its maximum transmission capacity. The DC power flow model is defined by constraints (15) and (16). These constraints are inactive if $\alpha_t^{ij}=0$. Constraints (17) to (20) represent the radial topology constraints of the PDN. Constraint (21) represents that a transmission line can only resume operation after being restored by the emergency team for a sufficient amount of time. Constraint (22) represents that once a transmission line is restored, it will continue to operate for all the following time. Constraint (23) represents that the emergency team can only reach one location at a time. Constraint (24) represents that it takes at least $tr_{(i,j)\to(p,q)}$ for the emergency team to travel from the line (i,j) to the line (p,q). The nonnegative and binary constraints of the variables are shown as constraints (25) and (26).

III. Solution Methodology

In order to deal with the expected part contained in the optimization model, the model is transformed into a three-layer mixed integer programming model. The reconstructed model is a two-stage robust optimization model and the model in the second stage contains binary variables. The nested column-and-constraint generation (NC&CG) algorithm is usually used to solve this problem. The key idea of the NC&CG algorithm is to extend the max-min subproblem into a max-min-min problem, which is further solved by the C&CG algorithm [13]. Therefore, the whole algorithm is represented as the mutual iteration between the inner and outer layer C&CG algorithm to solve the model.

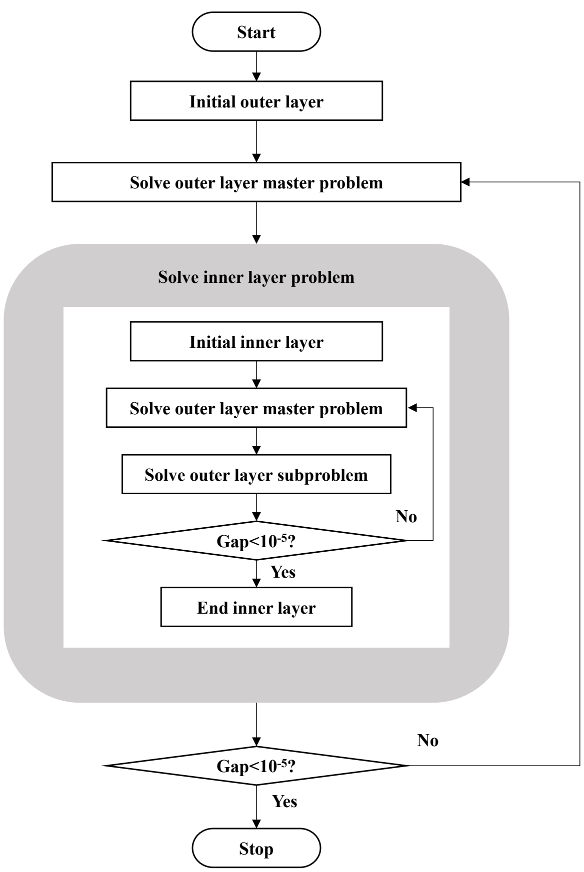

Fig. 1. Flowchart of the Nested Column-and-Constraint Generation algorithm.

The flowchart of the NC&CG algorithm is shown in Fig. 1.

IV. Case Study

This study chooses the IEEE 33 distribution system as the research subject [14]. The system reference voltage is 12.66kV, with a nominal voltage of 1.05Un at the primary source point. The active power of the network is 3.715MW, and the reactive power is 2.3Mvar. The lower and upper voltage limits for each load node are set at 0.95 times and 1.05 times the nominal voltage, respectively.

The triangles marked in Fig. 2 indicate the lines that can be strengthened, and the reinforcement cost is related to the length of the line. The cost of reinforcement per kilometer of the lines is $\$1.0\times10^5$ [15] as shown in Table III.

Fig. 2 lists the locations where 4 DGs can be installed, namely at nodes 15, 21, 23, and 28. Table IV presents the types of DGs, active power, power factor, and installation cost [16]. The dotted lines in Fig. 2 represent the tie lines that can be used for installation locations. Installed tie lines will not fail during an earthquake. The installation cost of a tie line is \$5 million.

This article considers three types of node loads, as shown in Table V. The type A load has a high daily load rate and belongs to the first-level load, which is given limited consideration for power restoration during the post-earthquake stage. The type B load has the highest number of nodes and belongs to the second-level load. The type C load, located at the end of the distribution network, has relatively low importance and is typically considered for restoration last during the recovery phase.

TABLE III. Line Hardening Parameters in PDN

Line	First Node	Terminal Node	Line Length/km	Hardening Cost /million (\$)
1	1	2	20	2
18	2	19	10	1
5	5	6	10	1
10	10	11	20	2
16	16	17	10	1
31	31	32	20	2

TABLE IV. Parameters of DG

Node	Type of DG	Active Power/kW	Power Factor	Installation Cost/million (\$)
15, 21	Wind power	250	0.9	10
23, 28	Photoelectricity	200	0.9	8

TABLE V. Node Load Type

Type	Node	Weight
Type A load	7,9,11,18,26	1
Type B load	2,3,4,5,6,8,10,13,15,19,20,21,22,23,24,25,27,28,30	0.5
Type C load	12,14,16,17,29,31,32	0.1

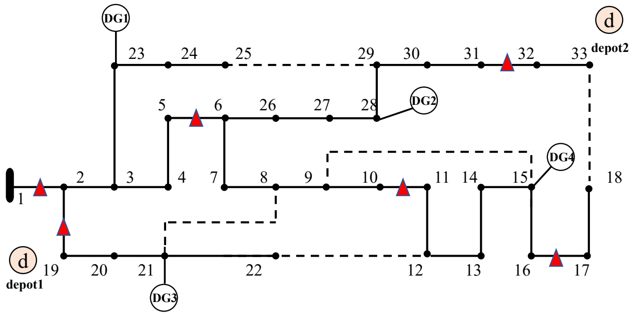

Fig. 2. The diagram of IEEE 33 distribution network system.

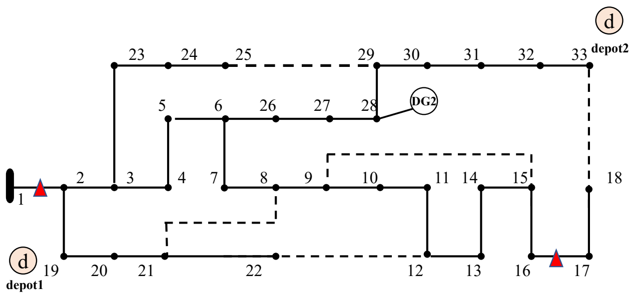

Fig. 3. Optimal strategy when $K = 2$, $Bp = \$4\times10^7$.

As shown in Fig. 3, the resilience enhancement strategy of the distribution network before an earthquake is presented when the maximum budget is $Bp = \$4\times10^7$. It includes hardening lines 1-2 and 16-17, installing DG at node 28, and installing all five tie lines. The system's resilience value reaches 0.8775. It can be observed that after the installation of the five tie lines, most of the failure scenarios under $K = 2$ can ensure the restoration of the interrupted load power supply by switching the tie lines.

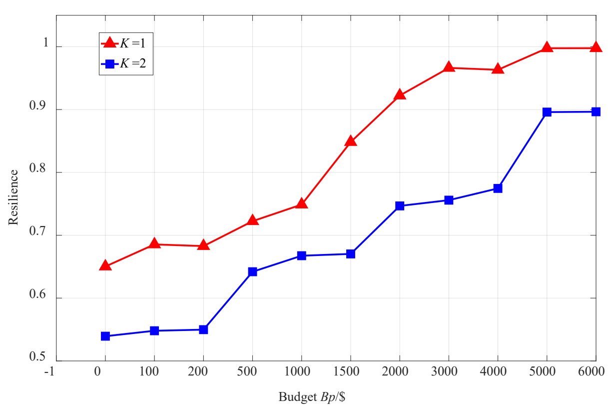

Fig. 4. Resilience value under different budgets.

Fig. 4 shows the resilience values of the PDN under different budgets when $K = 1$ and $K = 2$. Observing the trend of resilience value, overall, the resilience value gradually increases with increasing budget. This means that decision-makers can take more feasible resistance and mitigation strategies to enhance the earthquake performance of the PDN.

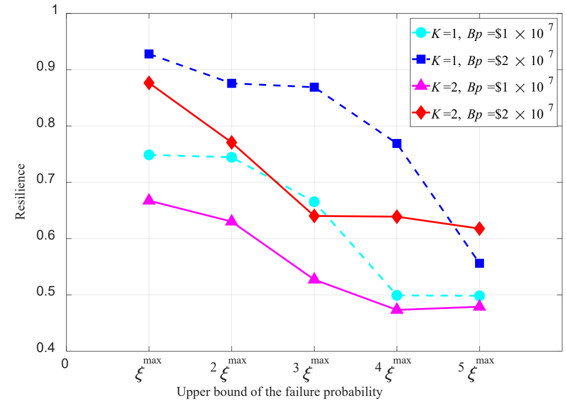

Fig. 5. Resilience value under different upper bounds of failure probability.

Fig. 5 shows the variation of the resilience value of the PDN under different upper bounds of failure probability. With the increase in the failure probability, the resilience value of the PDN as a whole shows a downward trend. The decline trend is the fastest, especially when $K = 1$ and $Bp = \$2\times10^7$.

V. Conclusion

In this article, we constructed a moment-based ambiguity set considering line failures in power distribution networks (PDN). In the pre-earthquake stage, three kinds of strategies, i.e., line hardening, distributed generator (DG) configuration, and line setting, are considered. In the post-earthquake stage, multiple rapid recovery strategies, including network reconfiguration and repair of power lines, are implemented to ensure the stable operation of electricity after disasters. Based on the pre-earthquake and post-earthquake strategies, we put forth a two-stage distributionally robust optimization (DRO) model to enhance the earthquake resilience of the PDNs. The nested column-and-constraint generation (NC&CG) algorithm was used to solve the model. The proposed method in this article was applied to a case study on the IEEE 33 distribution system. It was found that the installation of tie lines with line switches was crucial for improving the resilience of the PDN.

The prospects of this two-stage distributionally robust optimization model are promising. It offers a scalable approach to enhancing the resilience of power distribution networks not just for earthquakes but potentially for other types of natural disasters causing uncertain failures as well. This adaptability ensures the continued stability and reliability of the electrical power supply, which is crucial for critical infrastructure resilience across diverse scenarios.

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