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Resilience Enhancement for Transmission Lines under Decision-dependent Uncertainty

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Abstract: Reinforcement of transmission lines before natural disasters such as typhoons is an effective measure to ensure that the power system can operate safely in face of extreme weather. To enhance the grid resilience, the uncertain problem is formulated as a two-stage robust optimization (TRO) problem for the resilient unit commitment. The exogenous uncertain polyhedral model does not address the coupling problem of typhoon hazard, reinforcement decision and transmission lines state, for which an decision-dependent uncertainty (DDU) set is constructed in this paper. Because the two-stage robust optimization problem based on decision-dependent uncertainty sets cannot be solved by the traditional column and constraint generation (C&CG) algorithm, a novel iterative algorithm based on the C&CG is invoked in this paper, in which advanced optimality cuts and feasibility cuts are designed to combine the uncertainty decision coupling. Lastly, the IEEE-5 bus test system is simulated under the influence of a typhoon to verify the effectiveness of the proposed method.

Key Words: Resilience enhancement, Typhoon, Decision-dependent uncertainty, Novel C&CG iterative algorithm

1 Introduction

With global climate change, the frequency of typhoons making landfall in coastal areas has increased in recent years. Transmission lines, towers and other equipment in the power system are exposed to the atmosphere for a long time and are vulnerable to typhoon disasters, causing substantial economic losses. Under typhoon disasters, the probability of system component failure increases dramatically, making it easy for the power grid to produce mass disconnections and thus evolve into large-scale power outages, seriously threatening energy and social security. In this context, some scholars have introduced "resilience" to describe the ability of the grid to reduce fault losses and restore regular power supply under extreme disasters [1].

Currently, scholars at home and abroad have conducted research on the resilience of power grids under typhoon disasters [2]. According to the existing concept and connotation of grid resilience, grid resilience enhancement measures have two primary purposes. One is to reduce the direct impact caused by extreme weather hazards [3], and the other is to restore the normal function of the grid as soon as possible after extreme weather hazards [4]. Due to the influence of extreme weather, the uncertainty of power system gradually increases, and the difficulty of decision making in power system dispatching operations is further enhanced. However, robust optimization has excellent advantages in solving such problems. In [5], in order to enhance the resilience of the transmission network of typhoons, resilient unit commitment (UC) programming is formulated as a TRO problem, where thermal units are optimized in the first stage and pump hydro energy storage systems (PHESSs) are dispatched as an emergency resource that efficiently reduces the worst-case load shedding. In [6], a polyhedral model is constructed for the impact of typhoons on transmission lines, considering the time-varying damage, repair, and operation status. This model is incorporated into a two-stage distribution robust and robust optimization (DR&RO) approach that minimizes operating costs and maximizes system robustness, aiming to enhance the grid resilience against typhoons. In [7], a resilience-oriented TRO optimization model is proposed to enhance resilience by incorporating UC schemes and planning-operating recovery measures into the prevention and emergency response framework.

In many real-world problems, uncertainty is usually endogenous, i.e., the decision dynamically influences the uncertainty set. Reference [8] presents a pre-disaster investment problem in which the probability of failure of a transportation network is changed by pre-disaster investment decisions that strengthen the road. Its endogenous uncertainty set is incorporated into a two-stage stochastic process for optimal scheduling. The decision-dependent uncertainty set is incorporated into a multi-stage robust optimal scheduling framework in [9]. The uncertainty set in [10] is fixed. However, the decisions in two-stage and multi-stage robust optimization can observe some uncertain parameters, which is also a class of endogenous uncertainty. Multi-stage situations with continuous and binary variables and decision-dependent uncertainty set where any stage may be affected by the decision are considered in [11]. Because the decision-dependent uncertainty set is variable, this significantly increases the computational complexity compared to robust optimization with static exogenous uncertainty. Traditional

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algorithms for solving exogenous uncertainty sets, such as the column and constraint generation algorithm (C&CG) [12]-[14], the Benders dual algorithm [15]-[16] and the sample average approximation (SAA) algorithm [17]-[18], cannot solve them. So the algorithm needs to be further optimized.

Taking inspiration from the previously described, in order to enhance the resilience of the power system against typhoons, precise reinforcement of possible faulty transmission lines is an effective measure before the arrival of typhoons. The impact of typhoons on the lines can be described in the probabilistic form. The previous problem is formulated as a TRO problem to balance the optimal operating cost and the best robustness of the system. The damage and operational status of the lines are used as time-varying parameters to construct a polyhedral model, and pre-disaster reinforcement actions can change this polyhedron to form a decision-dependent uncertainty set. Besides, the C&CG algorithm is modified to effectively solve the formulated model. The system operation framework is shown in Fig. 1.

The rest of the paper is organized as follows. The models of the TRO problem with decision-dependent uncertainty sets are presented in Section II. The improved C&CG algorithm is described in Section III. The experimental details and results of the case study are presented in Section IV. The paper is concluded in Section V.

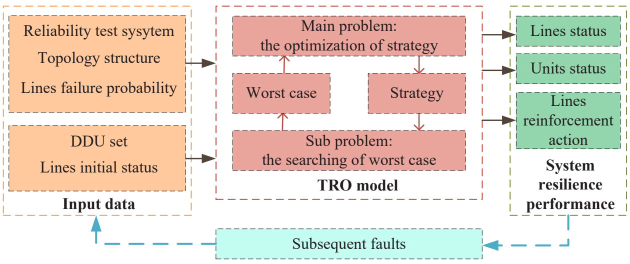


Fig. 1: The framework of system operation.

2 Problem Formulation

This section adopts the TRO framework of day-ahead resilient enhanced dispatch for units. By pre-dispatching the generation-side and demand-side resources, the impact of typhoons on transmission lines with uncertain failures is effectively reduced. The balance between system operation economy and grid resilience is further achieved.

2.1 TRO with DDU

For subsequent analysis, the following detailed models are uniformly described as a general mathematical framework of the uncertainty set restricted by the right-hand side (RHS) decision dependence.

$$\min_{x \in X}\left\{f(x)+\max_{w \in W(x)} \min_{y \in Y(x, w)} c^T y\right\} \tag{1}$$

$$\text{s.t. } X=\left\{x \in \mathbb{R}^{n_x} \times \mathbb{Z}^{m_x} \mid A x \leq b\right\}$$
$$Y(x)=\left\{y \in \mathbb{R}^{n_y} \mid B x+C y+D w \leq d, y \geq \mathbf{0}\right\}$$
$$W(x)=\left\{w \in \mathbb{Z}^{n_w} \mid G w \leq g+h(x)\right\}$$

where x is the vector of decision variables in the first stage. X is the set of constraints to be satisfied by x. c is the coefficient vector of decision variables in the second stage. y is the vector of decision variables in the second stage. w is the uncertain variable vector. $W(X)$ is the set of RHS constraints to be satisfied by the uncertain parameters w of DDU. $Y(x)$ is the set of constraints to be satisfied for the second stage of the recourse problem given x and w.

2.2 The first stage optimization model

The first stage objective function includes two components, aiming at minimizing the operating cost of the generators and the reinforcement cost of the transmission lines.

$$\begin{aligned} f(x)= & \sum_{t \in \mathrm{T}} \sum_{g \in G}\left(c_{\text{start},g} \alpha_{g, t}+c_{\text{shut},g} \beta_{g, t}+a_g u_{g, t}\right. \\ & \left.+b_g P_{g, t}\right) \Delta t+\sum_{l \in L} c_{\text{harden}} r_{i j} \end{aligned} \tag{2}$$

where $c_{\text{start},g}$ and $c_{\text{shut},g}$ are the start-up and shut-down costs of the generating units, respectively. a_g and b_g are the costs of the fuel consumption of the generating unit g in relation to the operating status and output, respectively. c_{harden} is the reinforcement cost of the transmission lines in advance of the typhoon. $\alpha_{g,t}$, $\beta_{g,t}$ and $u_{g,t}$ are the binary variables indicating the start-up, shutdown command and operation state of unit g at the moment t, respectively. $P_{g,t}$ is a continuous variable indicating the active output of unit g at the moment t. r_l is a binary variable that indicates whether line l is reinforced before the arrival of the typhoon. Specifically, $r_l = 1$ means reinforced, otherwise $r_l = 0$.

In the first stage of the constraints, i.e., $X = \{x \in \mathbb{R}^{n_x} \mid Ax \leq b\}$, the following restraints need to be satisfied regarding the resilient unit commitment, etc.

A. Logical constraints for units

The logical constraints show the relation between the unit state $u_{g,t}$ and the start-up/shut-down $(\alpha_{g,t}, \beta_{g,t})$ state. If a unit starts up at the moment t, then $u_{g,t} = 1$ and $\alpha_{g,t-1} = 0$, which leads to $\alpha_{g,t} = 1$, otherwise, $\alpha_{g,t} = 0$. The a unit receives the shut-down command at time t with a similar process. The unit status should return to the initial status at the end of a dispatch cycle. The previous logical expression is expressed as

$$\alpha_{g,t} - \beta_{g,t} = u_{g,t} - u_{g,t-1}, \forall t, g \tag{3}$$

$$\alpha_{g,t} + \beta_{g,t} \leq 1, \forall t, g \tag{4}$$

$$u_{g,t} = u_{g,0} \quad \forall t \in \{1, 2, \cdots, t_{\mathrm{UR},g} + t_{\mathrm{DR},g}\} \tag{5}$$

where $t_{\mathrm{UR},g}$ and $t_{\mathrm{DR},g}$ are the remaining on/off time of the unit g, respectively.

B. Start-up/Shut-down time constraints for units

Due to the physical restrictions of the generators themselves, each unit requires a minimum up/down time to start up and shut down, which is described as

$$\sum_{q=t-t_{\mathrm{U},g}}^{t} \alpha_{g,q} \leqslant u_{g,t} \quad \forall t \in \{t_{U,g}, \cdots, T\} \tag{6}$$

$$\sum_{q=t-t_{\mathrm{D},g}}^{t} \beta_{g,q} \leqslant 1-u_{g,t} \quad \forall t \in \{t_{\mathrm{D},g},\cdots,T\} \tag{7}$$

where $t_{\mathrm{U},g}$ and $t_{\mathrm{D},g}$ are the minimum time for start-up and shut-down of unit g, respectively.

C. Output constraint for units

Each generator is limited by its own characteristics, and the power output must be specified within a certain range, which is expressed as

$$u_{g,t}P_{g,\min} \leq P_{g,t} \leq u_{g,t}P_{g,\max}, \forall t, g \tag{8}$$

where $P_{g,t}$ is the output power of unit g at moment t. $P_{g,\max}$ and $P_{g,\min}$ are the maximum and minimum output power of unit g, respectively.

D. Ramping rate constraints for units

Due to their physical characteristics, the units cannot change their output levels significantly during neighbouring periods. Therefore, the change of the output of each generating is constrained by the climbing rate. The specific mathematical formulations are expressed as

$$P_g^{t+1} - P_g^t \leq \mathrm{SU}_g u_{g,t} + P_{g,\min}\alpha_{g,t+1}, \forall t, g \tag{9}$$

$$P_g^t - P_g^{t+1} \leq \mathrm{SD}_g u_{g,t} + P_{g,\min}\beta_{g,t+1}, \forall t, g \tag{10}$$

$$-P_{g,\min}\beta_{g,t+1} \leq P_g^{t+1} - P_g^t \leq P_{g,\min}\alpha_{g,t+1}, \forall t, g \tag{11}$$

where SU_g and SD_g are the allowable upward and downward rates of unit g, respectively.

2.3 The second stage optimization model

The second stage objective function includes two components and aims to minimize the penalty cost of load shedding and generator curtailment for the power system under the worst-case scenario when the system is the most robust.

$$\mathbf{c}^{\mathrm{T}}\mathbf{y} = \sum_{t\in\mathcal{T}} \left(c_{\mathrm{VOLL}} \sum_{d\in\mathcal{D}} p_d^t + c_{\mathrm{VOGC}} \sum_{g\in\mathcal{G}} p_{\mathrm{cur},g}^t \right) \Delta t \tag{12}$$

where c_{VOLL} and c_{VOGC} are the load shedding and generator curtailment cost coefficient, respectively; p_d^t and $p_{\mathrm{cur},g}^t$ are the load shedding volumes and over generation capacities, respectively.

In the second stage of the constraints, i.e. $Y(x) = \{y \in \mathbb{R}^{n_y} \mid Bx + Cy + Dw \leq b, y \geq \mathbf{0}\}$, the following constraints on the transmission system and other aspects need to be satisfied.

Remark 1 *The second stage problem, i.e., $\mathbf{c}^{\mathrm{T}}\mathbf{y}$ is a complete recourse problem. It can be verified that all loads can be shedded and generators can be curtailed.*

A. Transmission system constraints

Due to the transmission line's physical characteristics, the energy transmitted on each line should be specified within a specific range. Considering the relationship between the line power transmission and the power angle gap after the line operation state, the transmission lines delivery constraints are expressed as

$$p_{ij}^t - B_{ij}\left(\gamma_i^t - \gamma_j^t\right) \geq \left(I_{ij}^t - 1\right) P_{ij}^{\max}, \forall t, ij \tag{13}$$

$$p_{ij}^t - B_{ij}\left(\gamma_i^t - \gamma_j^t\right) \leq \left(1 - I_{ij}^t\right) P_{ij}^{\max}, \forall t, ij \tag{14}$$

$$-I_{ij}P_{ij}^{\max} \leq p_{ij}^t \leq I_{ij}P_{ij}^{\max}, \forall t, ij \tag{15}$$

where p_{ij} is the actual power transmitted on line ij. $P_{ij}^{\max}$ is the maximum energy that can be transmitted on line ij. B_{ij} is the conductance of line ij. γ_i^t and γ_j^t are the power angles at bus i and j, respectively. I_{ij}^t is the 0-1 variable indicating the operating status of line ij. $I_{ij}^t = 1$ means the line ij is online, otherwise $I_{ij}^t = 0$.

B. Cut load/generator capacity constraints

During the typhoon, generation unit dispatched can be adjusted and the load demand may be curtailed. However, there is a relationship between the amount of load shedding and the forecasted load demand as well as the actual load. The unit curtailment capacity also cannot exceed the generation capacity. These expressions are expressed as the following constraints.

$$P_d^t + \Delta p_d^t \geq p_d^t \geq 0, \forall t, d \tag{16}$$

$$p_g^t \geq p_{\text{cur},g}^t \geq 0, \forall t, g \tag{17}$$

where P_d^t and p_d^t are the power demand and shedding of load d, respectively. Δp_d^t is the variation of load d.

C. Power balance constraint

When the power system is running, the power system must be kept in balance, i.e., the power generated by the unit is equal to the power consumed by the load. Otherwise, there will be frequency shifts and other phenomena that are detrimental to the regular operation of the system. The power balance constraint is expressed as

$$\begin{aligned} &\sum_{g\in\mathcal{G}_j}\left(p_g^t - p_{\text{cur},g}^t\right) + \sum_{ij} p_{ij}^t - \sum_{ji} p_{ji}^t \\ &= \sum_{d\in\mathcal{D}_j}\left(P_d^t + \Delta p_d^t - p_d^t\right), \forall t, j \end{aligned} \tag{18}$$

Since there is a double circuit in the system, p_{ij}^t and p_{ji}^t indicate the power flowing through the line from bus i to j and from j to i lines, respectively.

3 Main Results

In this section, a polyhedral model of DDU is constructed and applied to the operational aspects of transmission lines. The primary purpose is to couple the reinforcement actions on transmission lines before typhoons with the time-varying variables of transmission line operation and faults, making the model more practical for engineering purposes. The DDU set changes in the result of each decision iteration, instead of the uncertainty set is fixed when solved by classical C&CG. Therefore, the algorithm is improved as described in Section 3.2.

3.1 Construction of DDU set

The relationship between the operational state of the transmission lines, the fault state and the pre-disaster reinforcement action are shown in Fig.2. The current operating state of the line depends on its previous operating state and the fault state at this time, as shown in Eq. (19). Equation (20) describes the relationship between the reinforcement action and the fault state, i.e., the decision action is associated with the uncertain polyhedral model, which constitutes the DDU. Considering that the line failure probability is higher than Π, as shown in Eq. (21). During each time slot, at most K transmission lines are allowed to be destroyed simultaneously in Eq. (22).

$$I_{ij}^{t} = I_{ij}^{t-1} - \gamma_{ij}^{t}, \forall t, ij \tag{19}$$

$$\gamma_{ij}^{t,0} - r_{ij} \leq \gamma_{ij}^{t} \leq \gamma_{ij}^{t,0} \tag{20}$$

$$\gamma_{ij}^{t}\left(\pi_{ij}^{t} - \Pi\right) \geq 0, \forall t, ij \tag{21}$$

$$\sum_{ij\in\mathcal{E}} I_{ij}^{t} \geq |\mathcal{E}| - K, \forall t \tag{22}$$

where both I_{ij}^{t} and γ_{ij}^{t} are binary variables, which are the operating and fault states of the line ij at moment t, respectively. r_{ij} is a time-independent binary variable that indicates the reinforcement action of the transmission line ij before the arrival of the typhoon, $r_{ij} = 1$ means reinforcement, otherwise $r_{ij} = 0$. π_{ij}^{t} is the fault probability of the line, which is modeled with reference to [19]. Π is the threshold value to detect the impacts of typhoons on transmission lines.

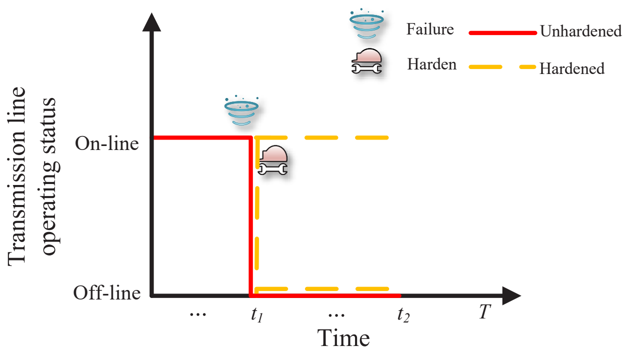


Fig. 2: A conceptual description of failure, reinforcement and operation of one transmission line.

3.2 Modified C&CG Algorithm for TRO-DDU

Problem (1) is a classic two-stage robust optimization model whose second-stage max-min bi-level optimization can be equivalently transformed into the following bi-linear maximization problem by the duality of the inner-level problem. The subproblem (SP) is shown as follows.

$$S(x) = \max_{w,u} u^{T}(d - Bx - Dw) \tag{23a}$$

$$\text{s.t.} \quad w \in W(x), u \in U \triangleq \left\{u \mid C^{T}u \leq c, u \leq \mathbf{0}\right\} \tag{23b}$$

The above subproblem is a non-linear optimization problem. Some articles use McCormick's inequalities to address [20]. we linearize the non-linear term $u^{T}Dw$ by the Big-M method [21].

By the method of equation relaxation and equivalence transformation, problem (1) is further expressed in the following form, i.e., as the master problem (MP).

$$\min_{x,\eta} f(x) + \eta \tag{24a}$$

$$\text{s.t.} \quad x \in X, \eta \geq S(X) \tag{24b}$$

$$\eta \geq u_j^{*T}(d - Bx - Dw), \quad \forall w \in W(x) \tag{24c}$$

$$0 \geq u_j^{*T}(d - Bx - Dw), \quad \forall w \in W(x) \tag{24d}$$

Note that in the master problem, constraint (24c) and constraint (24d) are the optimal cut and feasible cut, respectively, which come from the existence of two cases corresponding to extreme points and extreme rays when solving the subproblem, so they do not exist at the same time.

Algorithm 1 Modified C&CG Algorithm for TRO-DDU Problem (1)

Input: $X, Y(x,w), W(x)$, c and the convergence tolerance ε
Output: x, w
1: Initialize $k = 0$, $LB^{0} = -inf$, $Gap = inf$ and $UB^{0} = inf$
2: **while** $k \leq k_{max}$ **do**
3: Solve the MP (24a) and let (x^{k}, η^{k}) be the optimum;
4: Update the lower bound of the optimal objective by $LB^{k} = f(x^{k}) + \alpha^{k}$;
5: Solve the SP (23a) and denote by $(w^{k}, u^{k}) = \arg S(x^{k})$;
6: Update the upper bound of the optimal objective by $UB^{k} = f(x^{k}) + S(x^{k})$;
7: Update $k = k + 1$;
8: **if** $\left(UB^{k} - LB^{k}\right) / \max\left(UB^{k}, LB^{k}\right) \leq \varepsilon$ **then**
9: **Break**;
10: **else**
11: Return to step 2 and continue to cycle for solutions;
12: **end if**
13: **end while**

Remark 2 *Solving the subproblem (23a) requires a given x, so the first iteration of the algorithm to solve it needs to be solved for x in advance. This step of the algorithm is processed by taking the inverse of the reinforcement cost, after using Algorithm 1 to solve TRO-DDU.*

4 Case Study

In this section, to verify the feasibility of the proposed model and algorithm, we present a numerical simulation of the IEEE-5 bus system. These studies are carried out on a laptop with Inter i9-12900H CPU and 16GB of RAM. The simulation platform is MATLAB 2019B, and the commercial solver CPLEX is used to solve the master problems and subproblems of the algorithm.

The topology of the power system is shown in Fig. 3. Table 1 and Table 2 provide the parameters of the generators and transmission lines, respectively. All parameters are given as p.u. and a nominal power of 100 MVA. The probability of failure for each line in the IEEE-5 bus system is shown in Fig. 4. As shown in Fig. 4, typhoons mainly occur between 8 to 10 o'clock. The parameters in the case are set as K = 2, $VOLL$ = 4000\$/MWh, $VOGC$ = 1000\$/MWh, Δt = 1 h, T = 24, Π = 0.001. The cost of hardening each line c_{harden} is 6000\$.

The proposed model and algorithm are verified by the above test system. According to the strategy proposed in this

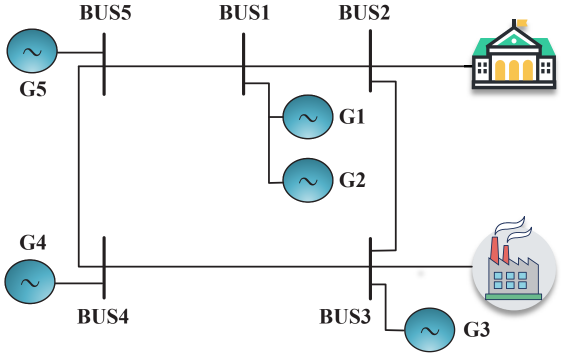


Fig. 3: The topology of IEEE 5-bus system.

Table 1: GENERATOR DATA

Unit Name	Physical Parameter		Cost Parameter		
	P_g^u/P_g^l	R_g^u/R_g^l	a_g	b_g	c_g
G1	12/2.4	0.95/0.6	0.02533	25.5472	24.3891
G2	10/2.4	0.95/0.6	0.02649	25.6753	24.4110
G3	12/2.4	0.95/0.6	0.02801	25.8027	24.6382
G4	10/2.4	0.95/0.6	0.02842	25.9318	24.7605
G5	12/2.4	0.95/0.6	0.02855	26.0611	24.8882

Table 2: TRANSMISSION LINES DATA

Line Number	From Node	To Node	Line Reactance	Transmission Limit F_{ij}
1	1	5	0.0139	175
2	1	2	0.2112	175
3	2	3	0.0845	175
4	3	4	0.1267	175
5	4	5	0.192	175

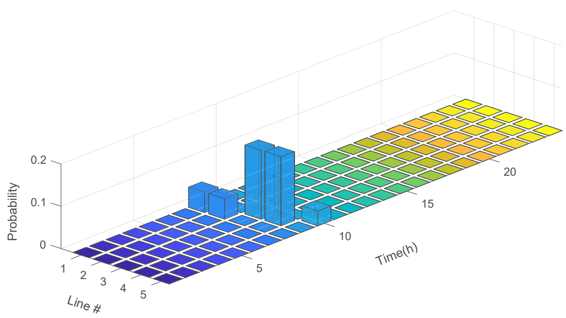


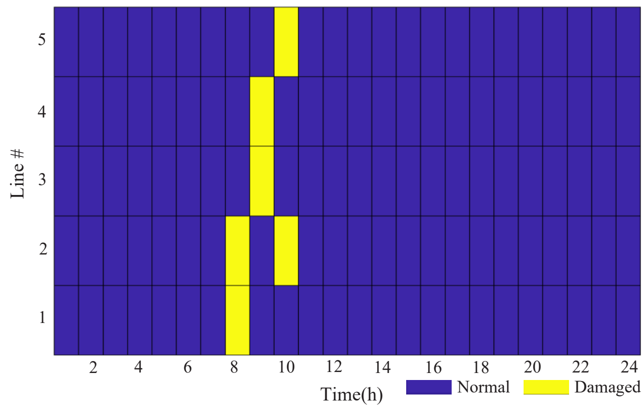
Fig. 4: Transmission lines failure probability in one day.

paper for precise reinforcement of transmission lines before the arrival of typhoons, the reinforcement results as shown in Table 3. The damage states of transmission lines in the worst-case scenario are given in Fig. 5. In which, Fig. 5(a) presents the worst damage states obtained according to the failure probability of the lines before reinforcement and Fig. 5(b) presents the damage states of the transmission lines after reinforcement. By comparing Fig. 5(a) and Fig. 5(b), it can be noticed that the number of off-lines after transmission lines reinforcement is significantly less than that before reinforcement.

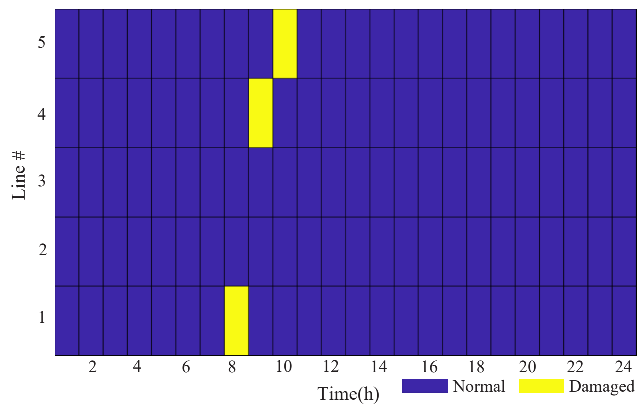
Table 3: RESULTS OF LINE REINFORCEMENT

Reinforced lines $(r_{ij}=1)$	$i \in \{2,3\}$
Unreinforced lines $(r_{ij}=0)$	$i \in \{1,4,5\}$

In addition, Table 3 and Fig. 5(b) show that the two-stage robust optimization problem finds the worst lines fault state in the second stage and then the reinforcement decision in the first stage is not reinforced for lines 1, 4 and 5, but only for lines 2 and 3. This is because reinforcing these two lines will be able to supply the load on bus 2 and bus 3. However, due to the shedding of G4 and G5, the loads still have the amount of attenuation, as shown in Fig. 6.



(a)



(b)

Fig. 5: Transmission lines damage results during the typhoon. (a) Transmission lines damage results before reinforcement. (b) Transmission lines damage results after reinforcement.

Lastly, note that the total operating cost of the system is \$ 2.1199×10^7, and after we harden lines 1, 4 and 5, the system cost at this point grows to \$ 2.1217×10^7, which is \$ 18,000 more than without the reinforcement. However, these three lines also fail after reinforcement, indicating that hardened components are also affected by weather events. Namely, transmission lines may still be damaged by typhoons after strengthening, which has practical significance in engineering applications. The system is not reinforced for these three

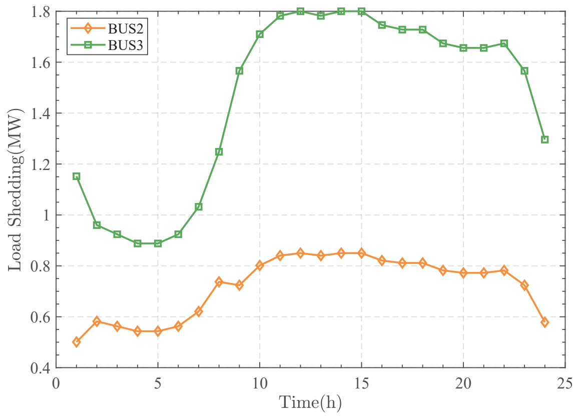


Fig. 6: Load shedding results.

lines in order to meet the goal of cost optimization. Nevertheless, the line reinforcement measures still show a positive effect in preventing outages during extreme weather.

5 Conclusion

In this paper, in response to the problem of extreme weather causing significant damage to the power system, preventive measures for reinforcing transmission lines were proposed to enhance grid resilience before the arrival of typhoons. The effects of typhoons on transmission lines have been constructed as decision-dependent uncertainty sets with time-varying parameters and line fault operations into them. A two-stage robust optimization problem has been formulated to balance economic efficiency and robustness. Simulations have been performed on the IEEE-5 bus system to solve the problem using an improved column constraint generation algorithm, which has verified that the proposed method can effectively improve the grid resilience.

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