Resilience Enhancement for Transmission Lines with Circuit Breakers under Exogenous Uncertainties

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***Abstract*—To improve the resilience of the power system against typhoon events, a two-stage robust optimization (TRO) model considering the line failure stochasticity is proposed. The generator status and output are pre-scheduled in the first stage to minimize operation costs. In the second stage, a recourse method is applied to identify the worst-case failure scenario of the transmission line within a polyhedral uncertainty set. This uncertainty set considers line repair and non-repair strategies, and the impact of typhoons on transmission lines is quantified as the failure probability. The objective function of the second stage is to minimize the load shedding and generator curtailment costs of power system due to circuit breaker (CB) operation. The column-and-constraint generation (C&CG) algorithm is used to solve this TRO model. The proposed model is tested on the IEEE 24-reliability test system (RTS) under a typhoon to verify its effectiveness.**

***Index Terms*—Resilience, two-stage robust optimization, circuit breaker, typhoon.**

I. Introduction

The power system faces various risks and challenges, such as human damage, grid load fluctuations, and natural disasters [1]. Among them, extreme weather events have caused substantial economic losses to power systems worldwide. For example, typhoon Sandy in 2012 caused widespread damage in New York, resulting in power outages for 85% of the population [2]-[3]. The frequent occurrence of extreme weather and climate events brings great challenges to the power system, and how to deal with these challenges has become an essential issue in the operation of the power system.

During the operation of transmission lines, weather changes, natural disasters, and other external factors may lead to failures of transmission lines, seriously affecting the safe operation of the power system [4]. To ensure the safe and stable operation of the power grid, protection devices are required to respond to these extreme events on the transmission lines. Presently, many scholars and engineers have studied a lot of transmission line protection problems. Reference [5] predicts line failures before the arrival of typhoons and defends and reinforces lines that may fail, for which the grid resilience is greatly improved. The resilience of the power system is ensured as a precondition to maintain its regular operation after a natural disaster. Reference [6] assessed the damage probability of transmission line-tower systems under typhoon disasters based on model-driven and data-driven. Analysis and prediction of the failure probability are significant for disaster prevention and as a protection method. The previous studies are all about some optimal scheduling and forecasting methods. In contrast, the circuit breaker protection methods [7] on the transmission lines can also protect the transmission lines from damage.

The resilient unit commitment (UC) strategy is one of the primary ways to improve the operational resilience of the power system, and a resilience-based generation resource dispatch model has been established. Reference [8] proposed a three-stage resilient UC model that considers uncertain typhoon paths and line outages to improve the resilience of the power system against a typhoon. The proposed solution coordinates resources to cope with the worst-case scenario for each possible typhoon path. In [9], a resilience constrained day-ahead UC framework is proposed to improve the resilience of power systems exposed to extreme weather events. A resilient constrained unit commitment (RCUC) framework is proposed in [10], in which the system operational constraints, the heterogeneity of the tidal distribution, and the line forced outages are addressed simultaneously.

Currently, there are two major types of research methods for UC problems with uncertainty: stochastic optimization (SO) [11]-[12] and robust optimization (RO) [13]-[14]. SO methods are applied to generate many discrete samples by analyzing the

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probability distribution of historical data and transforming the uncertain optimization problem into a deterministic optimization problem with multiple scenarios to be solved. However, the SO method has the following drawbacks [15]. Firstly, the computational amount increases exponentially as the scenario set increases. Secondly, it is difficult to obtain the exact probability distribution information of random variables in practical situations, leading to a significant decrease for the reliability in the SO method. Therefore, RO methods are emerging [16]. The RO approach aims to design an optimization model with robustness by considering uncertainty, enabling the model in the face of unknown or difficult to accurately model factors, but still providing acceptable optimization results. Compared with the SO, the RO focuses more on the stability and robustness of the solution and has lower computational complexity.

Inspired by the previous analysis, this paper proposes a transmission line protection strategy with CB protection to protect transmission lines from extreme weather. It reduces the potential impacts by formulating a resilient UC scheme for a TRO problem. The first stage minimizes operating costs and responds to worst-case load forecasts and line failures by pre-scheduling the status and output of the generating units. In the second stage, the time-varying operating state of the transmission line is considered, and the recourse problem is formulated while considering load shedding and generator curtailment. This paper uses the popular C&CG algorithm to solve this TRO model. The main contributions of this paper are as follows:

1) To enhance the power system resilience, the resilient UC model is constructed as a TRO model. The corresponding scheduling plan of the units is formulated by forecasting the load changes during disasters to prevent the system from disintegration or collapsing due to power imbalance.
2) To address the uncertainty brought by typhoons to the power system, a polyhedral uncertainty set for time-varying transmission line faults is constructed and incorporated into a TRO model.

The rest of this paper is organized as follows. The circuit breaker protection consid-ering the impact of typhoons is introduced in Section II. The two-stage UC problem is formulated in Section III, with the polyhedral uncertainty set under line failure probability. The solution method is presented in Section IV. Case studies are conducted in Section V, and conclusions are drawn in Section VI.

II. Circuit Breaker Protection Considering Impact of Typhoons

In this section, we construct a transmission system that includes circuit breaker protection. The CBs are designed to quickly disconnect faulty components to prevent cascading failures and improve the system's resilience during extreme weather events, such as typhoons. Using a TRO model, we also describe an optimization process for the CB strategy.

A power transmission system that utilizes CBs as a protection mechanism is efficient and reliable. This system consists of generators, transformers, transmission lines, loads, and circuit breakers on each transmission line, as illustrated in Fig. 1. Due to their lower strength, transmission lines are vulnerable to damage caused by extreme weather conditions. As a result, these events can result in power supply interruptions to the loads, which poses a significant threat to the entire system. In order to ensure the reliable operation of the transmission system, a circuit breaker protection scheme is installed. This scheme is designed to detect the location of a fault on the transmission lines and quickly cut off the fault circuit. This prevents the fault from spreading and ensures the safety of the system.

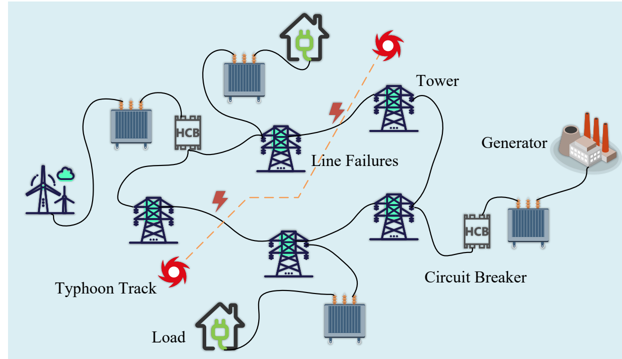


Fig. 1: Illustration of circuit breaker protection.

III. Resilient Unit Commitment with Line Failures Probability

This section adopts the TR0 framework for the day-ahead dispatch of generator units. It considers the impact of transmission line faults on loads and units in the power system to achieve a balance between the system operating economy and the grid resilience.

A. Objective Function

The objective function is to minimize the total system operating cost, including the generators' start-up, shut-down, and operating costs in the first stage, and the load shed-ding and cutting costs in the second stage when the typhoon affects the power system. The robustness of the system is taken care of by the second stage of TRO, as follows.

$$\min_{x \in \mathbf{X}} f(x) + \max_{\xi \in \zeta} Q(x) \tag{1}$$

$$\begin{aligned} f(x) &= \mathbf{c}^{\mathrm{T}} \mathbf{x} \\ &= \sum_{t \in T} \sum_{g \in G} \left\{ \left(c_g u_{g,t} + c_g^{\mathrm{UP}} \kappa_{g,t} + c_g^{\mathrm{DN}} \chi_{g,t} + a_g p_{g,t} \right) \Delta t \right\} \\ Q(x) &= \min_{y \in \mathrm{Y}} \mathbf{d}^{\mathrm{T}} \mathbf{y} \\ &= \sum_{t \in T} \sum_{d \in D} c_{\mathrm{VOLL}}\, p_{d.t} \Delta t + \sum_{t \in T} \sum_{g \in G} c_{VOGC} p_{g,t}^{\mathrm{cur}} \Delta t \end{aligned}$$

where $f(x)$ is the first stage objective function in the TRO model. $Q(x)$ is the second stage inner layer objective function in the TRO model. $\mathbf{x} := \{u_{g,t}, \kappa_{g,t}, \chi_{g,t}, p_{g,t}\}$ is the decision variable in the first stage. $f(\mathbf{x})$ is the decision variable in the second stage. $\mathbf{y} := \left\{p_d^t, p_{g,t}^{cur}, \gamma_{i,t}, p_{ij,t}\right\}$ is the second-stage decision variable vector. $\zeta := \{m_{ij,t}, n_{ij,t}, r_{ij,t}\}$ is the uncertain variable. c_g, c_g^{UP}, c_g^{DN}, a_g, c_{VOLL} and c_{VOGC} are the cost coefficients of the respective variables, which are constants.

B. Exogenous Uncertainty Set under Typhoons

Considering the impact of typhoons on transmission lines, specific transmission lines failures, circuit breaker actions and lines operation are treated as uncertainty factors. The uncertainty set, i.e., $\zeta := \{\mathbf{C}\xi \leq \mathbf{f}\}$ is described as the following polyhedral model.

$$r_{ij,t} = r_{ij,t-1} + m_{ij,t} - n_{ij,t}, \forall t, ij \tag{2}$$

$$\sum_{t \in T} n_{ij,t} \leq 1, \forall ij \tag{3}$$

$$n_{ij,t}\left(\pi_{ij,t} - \Pi\right) \geq 0, \forall t, ij \tag{4}$$

$$\sum_{ij \in \Omega} I_{ij}^t \geq |\mathcal{E}| - K, \forall t, ij \tag{5}$$

where $m_{ij,t}$, $n_{ij,t}$, and $r_{ij,t}$ are binary variables representing the repair of the faulted lines, the operation of the circuit breakers, and the operation states of the transmission lines, respectively. $\pi_{ij,t}$ is the failure probability of line ij at time t. Π is the threshold value for determining line faults by fault probability. K is the number of maximum lines failures. $\mathcal{E}$ is a tiny constant.

Constraint (2) describes the relationship between circuit breaker response, line repair, and line operating status in case of a line fault. When repair is not considered, the line can only fault once in a dispatch cycle, i.e., the circuit breaker operates only once, as shown in Eq. (3). The constraint for determining whether a line is faulted by the probability of failure is shown in Eq. (4). During the preparation of a typhoon, it is considered that at most lines are failed, as shown in Eq. (5).

C. Constraint Set of First Stage

The constraint of the first stage in the TRO model, i.e., $\mathbf{Ax} \leq \mathbf{b}$, describes the constraint of the generator operation. These constraints are depicted as follows.

$$u_{g,t} - u_{g,t-1} = \kappa_{g,t} - \chi_{g,t}, \kappa_{g,t} + \chi_{g,t} \leq 1, \forall t, g \tag{6}$$

$$u_{g,t} = u_{g,0}, \forall t \in \left\{\Delta t, \ldots, t_{\mathrm{UR},g} + t_{\mathrm{DR},g}\right\}, g \tag{7}$$

$$\sum_{q=t-t_{\mathrm{UT},g}+1}^{t} \kappa_{g,q} \leq u_{g,t}, \forall t \in \left\{t_{\mathrm{UT},g}, \ldots, T\right\}, g \tag{8}$$

$$\sum_{q=t-t_{\mathrm{DT},g}+1}^{t} \chi_{g,q} \leq 1 - u_{g,t}, \forall t \in \left\{t_{\mathrm{DT},g}, \ldots, T\right\}, g \tag{9}$$

$$P_{g,t} - P_{g,t-1} \leq \mathrm{R}_g^{60+} u_{g,t-1} \Delta t + \kappa_{g,t} \mathrm{SU}_g, \forall t, g \tag{10}$$

$$P_{g,t-1} - P_{g,t} \leq \mathrm{R}_g^{60-} u_{g,t} \Delta t + \chi_{g,t} \mathrm{SD}_g, \forall t, g \tag{11}$$

where $\kappa_{g,t}, \chi_{g,t}, u_{g,t}$ are binary variables that represent the start-up, shut-down and running commands of the generator g, respectively. $t_{\mathrm{UT},g}$ and $t_{\mathrm{DT},g}$ are the minimum up and down time of generator g, respectively. $t_{\mathrm{UR},g}$ and $t_{\mathrm{DR},g}$ are the remaining up and down duration of generator g, respectively. R_g^{t+} and R_g^{t-} are the maximum ramp up and ramp down rate of generator g.

Equations (6)-(7) indicates the logical constraint between the unit start-up, shut-down command and operation status. Equations (8)-(9) are the minimal start-up and shut-down times of the generator, respectively. Equations (10)-(11) are the ramping rate constraints of the generator.

D. Constraint Set of Second Stage

The constraint of the second stage of the TRO model, i.e., $\mathbf{Y} := \{\mathbf{Gx} + \mathbf{Ey} + \mathbf{Mu} \geq \mathbf{h}\}$, describes the impact of the typhoon on the transmission lines and the power system, and quantifies this impact as load shedding and generator curtailment in the second stage. The constraints include transmission system, load shedding capacity, generator curtail-ment capacity and the system balance restrictions, which are shown as follows.

$$u_{g,t} P_g^{min} \leq p_{g,t} \leq u_{g,t} P_g^{max}, \forall t, g \tag{12}$$

$$p_{ij,t} - B_{ij}\left(\gamma_{i,t} - \gamma_{j,t}\right) \geq \left(r_{ij,t} - 1\right) P_{ij}^{\max}, \forall t, ij \tag{13}$$

$$p_{ij,t} - B_{ij}\left(\gamma_{i,t} - \gamma_{j,t}\right) \leq \left(1 - r_{ij,t}\right) P_{ij}^{\max}, \forall t, ij \tag{14}$$

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

$$P_{d,t} + \Delta p_{d,t} \geq p_{d,t} \geq 0, p_{g,t} \geq p_{g,t}^{\mathrm{cur}} \geq 0, \forall t, d, g \tag{16}$$

$$\begin{aligned} \sum_{g \in \mathcal{G}_j} \left(p_{g,t} - p_{g,t}^{\mathrm{cur}}\right) + \sum_{ij} p_{ij,t} - \sum_{ji} p_{ji,t} \\ = \sum_{d \in \mathcal{D}_j} \left(P_{d,t} + \Delta p_{d,t} - p_{d,t}\right), \forall t, j \end{aligned} \tag{17}$$

where $P_{g,t}$ and $p_{g,t}$ are the energy set-point and active power output of generator g, respectively. $P_{d,t}$ and $p_{d,t}$ are the power demand and shedding of load d, respectively. $B_{i,j}$ is the susceptance of line ij. $P_{ij}^{\max}$ is the maximal power transfered on line ij. $p_{g,t}^{\mathrm{cur}}$ is the curtailment of generator g. $\Delta p_{d,t}$ is the variation of load d.

Equation (12) shows the second-stage generator output constraints. Considering the operating state of the line, the transmission capacity of the line is limited by Eqs. (13)-(15). For a given bus, the load shedding and generation curtailment constraint during the hurricane is shown in Eq. (16). Equation (17) is the power balance constraint for the second stage.

IV. Solution Methods

The TRO scheduling model proposed in this paper is a three-level optimization model with a min-max-min structure. In this paper, it is firstly decoupled into a master problem (MP) and a sub-problem (SP), and the first stage is regarded as the MP. The second stage is regarded as the SP after being transformed into a single-layer problem by a dual approach. The results of the decision variables solved in the MP are used as known quantities in the SP, and the optimal solution of the SP adds new constraint parameters to the model of the MP. The column and constraint generation (C&CG) algorithm solves the problem iteratively until the upper and lower bounds converge and the optimal value is found. After converting the MP and SP into mixed-integer linear programming (MILP) problem, the solution is solved in the MATLAB R2019b environment using the CPLEX12.10 commercial solver.

In the above solution process, the C&CG algorithm mainly solves the MP and SP objective functions, which are formulated in detail as follows. The algorithm process is shown in Algorithm 1.

Algorithm 1: C&CG Algorithm for TRO Problem (1)

Input: $\mathbf{X}$, $\mathbf{Y}$, ζ, $\mathbf{c}$, $\mathbf{d}$, ε
Output: $\mathbf{x}$, $\mathbf{y}$, ξ
Set $LB^0 = -\inf$, $UB^0 = \inf$ and k=1
while $k \leq k_{max}$ **do**
  Solve the master problem (18)
  if *MP (18) is infeasible* **then**
    Terminate
  else
    Derive an optimal solution $\mathbf{x}^k$ and update $LB^k = \max\left\{LB^{k-1}, \text{objective value of MP}\right\}$
    Derive $\xi^{k,*}$, $\mathcal{Q}\left(\mathbf{x}^k\right)$ by solving (19) and update $UB^k = \min\left\{\mathbf{c^T}\mathbf{x}^k + \mathcal{Q}\left(\mathbf{x}^k\right), UB^{k-1}\right\}$
    if $\left(UB^k - LB^k\right) / \max\left(UB^k, LB^k\right) \leq \varepsilon$ **then**
      Return $\mathbf{x}^k$, $\xi^{k,*}$ and terminate
    else
      Create variables $\mathbf{y}^{k+1}$, and add the following constraints to MP $\eta \geq \mathbf{d}^{\mathrm{T}}\mathbf{y}^{k+1}$
      $\mathbf{Gx} + \mathbf{Ey}^{k+1} + \mathbf{M}\xi^{k,*} \geq \mathbf{h}$
    end
    Update $k = k + 1$
  end
end

A. Master problem (MP)

The main problem objective function and its constraints are as follows.

$$\begin{aligned} \text{MP:}\ & \min_{\mathbf{x},\eta,\mathbf{y}^k} \mathbf{c}^{\mathrm{T}}\mathbf{x} + \eta \\ \text{s.t.}\ & \eta \geq \mathbf{d}^{\mathrm{T}}\mathbf{y}^k, \eta \in \mathbb{R} \\ & \mathbf{Ey}^k \geq \mathbf{h} - \mathbf{Gx} - \mathbf{M}\zeta^{k-1,*}, x \in \mathbf{X} \end{aligned} \tag{18}$$

B. Sub-problem (SP)

The second stage of the TRO is a max-min problem, where the inner minimization problem, i.e., $Q(x)$, is transformed into a maximum problem by a dual approach with the outer layer merged into a maximization problem. The specific mathematical description is as follows.

$$\begin{aligned} S(x) = & \max_{\zeta,\pi} (\mathbf{h} - \mathbf{Gx} - \mathbf{M}\xi)^{\mathrm{T}}\pi \\ \text{s.t.}\quad & \mathbf{E}^{\mathrm{T}}\pi \leq \mathbf{d}, \pi \geq \mathbf{0} \end{aligned} \tag{19}$$

where π is the dual variable of $\mathbf{y}$. It is worth noting that the optimization problem obtained from Eq. (19) can be classified as a bilinear problem. Since ξ is a binary vector, the nonconvex quadratic term $\xi^{\mathbf{T}}\mathbf{M}^{\mathbf{T}}\pi$ can be precisely redefined by using its McCormick envelope, as proposed in [17].

Note that since the recourse problem $Q(x)$ is always feasible, only the optimal cut needs to be introduced when solving problem (19) by C&CG algorithm decoupling. Also, the problem (19) is a two-stage robust optimization problem with complete recourse, converging in a finite number of times when solved using the C&CG algorithm.

V. Case Study

We used an IEEE 24-reliability test system (RTS) under one typhoon to verify the effectiveness of the proposed model. The proposed model was carried out using MATLAB 2019b on a laptop with an Intel i9-12900H CPU and 16.0 GB of RAM.

A. Case Description

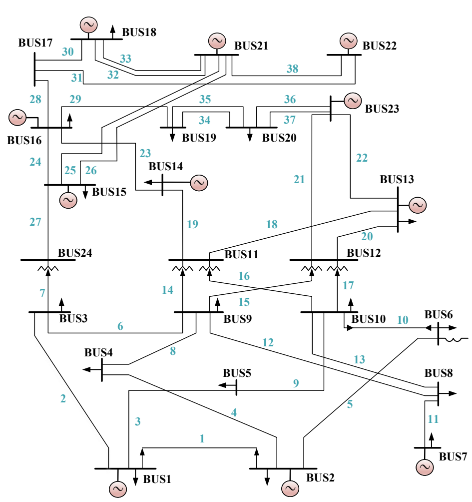


Fig. 2: IEEE 24-Reliability Test System under the typhoon.

In this paper, the IEEE RTS is analyzed under the influence of a typhoon, as shown in Fig. 2. The system is modeled to cover an area of approximately 150×200 km, with geographical coordinates ranging from 30.52°N to 32.32°N and 87.68°W to 89.25°W. The typhoon is assumed to originate within the area of 29.31°N to 30.21°N and 86.64°W to 90.29°W, and is considered to start posing a threat to the power system at 02:00 am on the operating day. The typhoon is assumed to have no impact on the power system once it reaches the northern region of 33.22°N at 2:00 am on the same day.

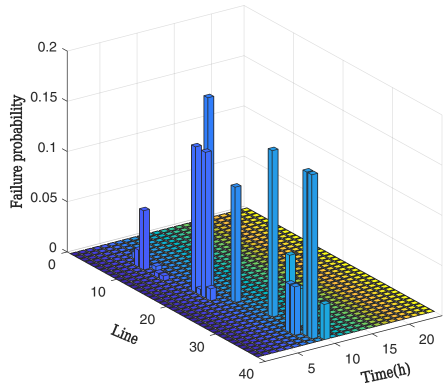


Fig. 3: Failure probability of transmission lines during the typhoon.

The parameters in the case are set as K = 2, c_{VOLL} = 4000\$/MWh, c_{VOGC} = 1000\$/MWh, Π = 0.01. Δt is set to 1 hour and T = 24. The parameters for generators, loads, and transmission lines are provided in [18]. The reference power in the power sys-tem is set to be 100MVA. During the typhoon, the failure probability of the transmission lines within 24 hours when using the IEEE 24-RTS is shown in Fig. 3.

To demonstrate the effectiveness of the proposed resilience enhancement scheme involving the circuit breaker, we will compare and analyze the operation of the circuit breaker when the repair is considered and not considered.

B. Simulation Results and Discussions

If the measure of post-disaster lines repair is considered, the operation of the circuit breaker under the worst-case scenario according to the second stage of recourse uncertainty set in two-stage robust optimization is shown in Fig. 4(a). Meanwhile, the post-disaster repair action will repair some faults, making the line on-line again as soon as possible, and the line operation results are shown in Fig. 4(b). However, it can be noted that there are lines that are not repaired, which is due to the fact that the line is a double circuit in the two buses where it is located. It makes practical engineering sense to repair one of the lines first, to meet the load demand.

The TRO model can be efficiently solved using the C&CG algorithm, which incorporates the transmission lines' operation as uncertain variables to establish a polyhedral set. The algorithm's convergence behavior is presented in Fig. 6, where the optimal solution is obtained after the second iteration with a value of 7.11×10^7 , demonstrating the strong performance of Algorithm 1 in achieving the optimal solution. Therefore, considering transmission lines with circuit breaker protection and post-disaster lines restoration strategies can effectively enhance the resilience of the power system and reduce losses as low as possible.

If the measure of post-disaster lines repair is not considered, the operation of the circuit breaker under the worst-case

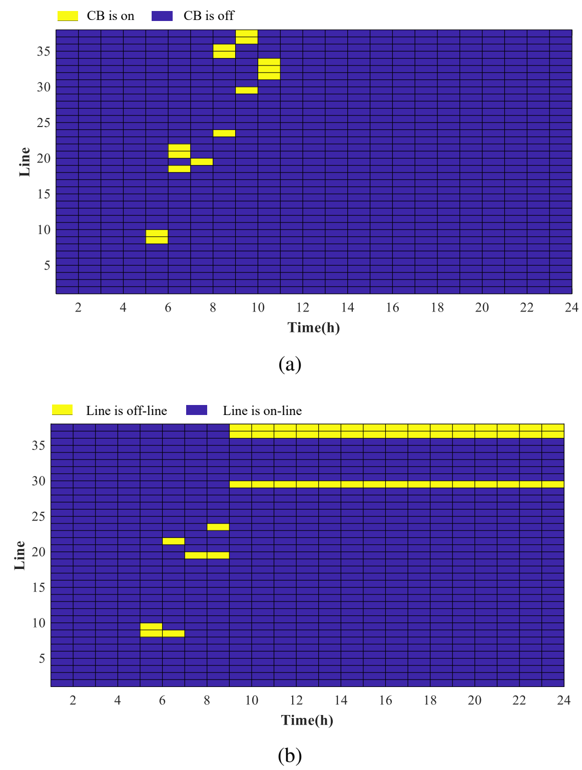


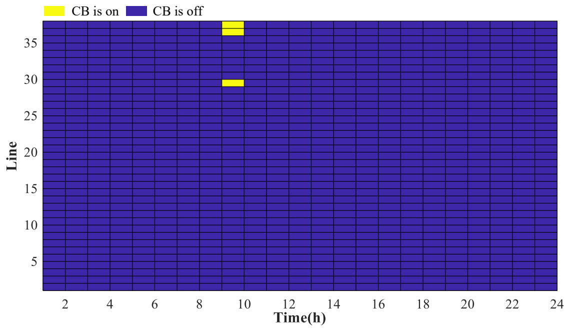
Fig. 4: Worst line failure scenario for the circuit breaker and the line operation status with repair. (a) The circuit breaker operation state. (b) The line operation state.

scenario according to the second stage of recourse uncertainty set in two-stage robust optimization is shown in Fig. 5(a). The worst scenario of the polyhedral uncertainty set finds only three lines that may be faulted, i.e., only the circuit breakers on these three lines are disconnected, as shown in Fig. 5(a). In this case, the operating state of the transmission lines is shown in Fig. 5(b).

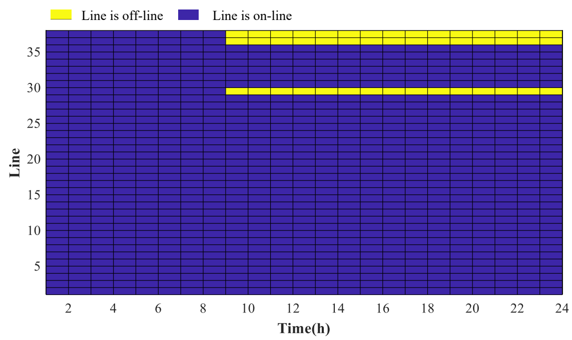
Finally, the C&CG algorithm is used to solve the TRO model without repair strategy. As shown in Fig. 6, the objective function converges to 7.0653×10^7 at the second iteration for the upper and lower bounds, and the minimum operating cost obtained. The results of the two previous strategies show that the circuit breaker protection strategy considering post-disaster line repair is more reliable than that without it. This is because when there is no repair, the number of circuit breaker actions is less, i.e., it is not possible to detect the maximum number of possible failed lines, thus leading to the impossibility of making immediate emergency preparations.

VI. Conclusion

This paper has set up a two-stage robust optimization model considering the stochasticity of line outages. The fault lines were detected by circuit breaker action and removed in time to enhance the resilience of the power system during typhoons. The simulation results on the IEEE 24-RTS demonstrated the effectiveness of the method. Strategies considering line repair



(a)



(b)

Fig. 5: Worst line failure scenario for the circuit breaker and the line operation status without repair. (a) The circuit breaker operation state. (b) The line operation state.

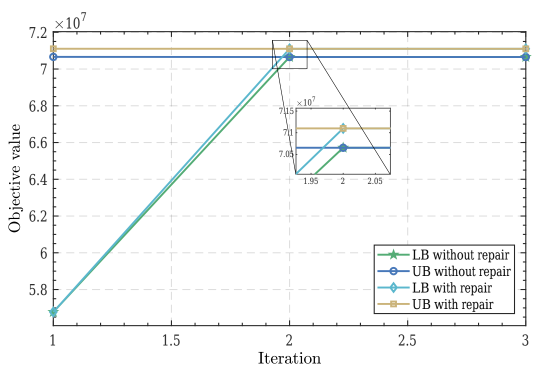


Fig. 6: Evolution of the UB and LB.

and non-repair could be used to find the line fault scenario in the worst-case scenario for the polyhedral uncertainty set through the second stage in the TRO, enabling the circuit breaker to cut off the failed line and then execute the decided emergency plan in time. In addition, the failed line repair strategy has restored power for critical loads as quickly as possible. Future work will incorporate dynamic system simulations into the proposed two-stage robust optimization model.

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