Resilient Transmission Network Hardening Planning Coordinated with Distribution Network Defensive Strategies against Typhoons

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Abstract*—With the development of active distribution networks, transmission system (TS) and distribution system (DS) can be coordinated to operate in an efficient and secure manner. However, the high-impact and low-probability natural disasters like typhoons can inflict severe damage on the critical infrastructures of power sector such as transmission lines and distribution lines, putting the whole transmission and distribution network under the threat of paralysis. In order to enhance the prevention ability of the integrated transmission and distribution network (ITDN) for typhoons, a resilient transmission network hardening planning (TNHP) model and a distribution network defensive planning (DNDP) model against typhoons are established in this paper, which consider unit commitment in TNHP and the strategies of reconfiguration, islanding, distributed generators (DGs) dispatch in DNDP. To realize the coordination of ITDN's planning, a distributed optimization framework based on alternating direction method of multipliers (ADMM) algorithm is formulated to implement the resilient integrated planning of TNHP and DNDP by updating their boundary variables. Finally, the effectiveness of the proposed method is validated by numerical results of the modified IEEE-14 test system integrated with modified IEEE-33 test system.

Keywords—transmission network hardening planning, distribution network defensive planning, ITDN resilience, distributed optimization

I. Introduction

With the intensification of ecological pollution, natural disasters have occurred more frequently such as typhoons, floods, ice storm, etc. As one of the major natural disasters, the strike of typhoons can lead to a huge loss of power system once it arises owing to its high-impact characteristic. This poses a great challenge for power system resilience to guarantee the power delivery during typhoons on the level of power transmission [1] and distribution [2]. In terms of exploiting the resilience enhancement strategies, line hardening can significantly boost the resilience of transmission network and distribution network by mitigating the physical impact of typhoons and preventing the line or tower from tripping out and collapse by the storm, thus hamper the further incapacitation of larger areas in power grid [3]. Therefore, it is imperative to make effective line hardening decisions with other resilience enhancement strategies for transmission network and distribution network in defensive of the severe typhoons.

For enhancing the prevention ability of transmission network against catastrophic events, many researchers have focused on improving the resilience by preventive planning or scheduling. Ref [4] studied the resilience enhancement strategy with high renewable energy penetrated and proposed a two-stage stochastic TNHP model considering multiple random disruptions and renewable energy uncertainty. Ref [5] presented a transmission grid investment planning model for hardening transmission lines, generators and substations. A resilience-oriented transmission planning model integrated with optimal transmission switch was developed in [6] under typhoon weather. In [7], a coordinated preventive scheduling method of conventional generators and wind power was proposed to satisfy priority-based load in resistance of typhoons. Most studies are committed to promote the TS resilience by planning or operation, but the resilient planning with hourly operation constraints is less considered.

For the advance in DS resilience, the deployment of DGs [8], remote-controlled switches [9] and provisional microgrids [10] was considered respectively on the basis of resilient distribution hardening planning problem. Ref [11] developed a resilient distribution network hardening planning model with the placement of multiple DGs to manage system risk against stochastic failures. A co-optimization mathematical model of distribution network reconfiguration and repair sequence was developed in [12] to maximize recovery agility.

Nowadays, the interaction between TS and DS becomes more frequent and the coordination of them has provided higher efficiency and security for their operation. In [13], a decentralized hierarchical optimization framework of transmission and distribution networks was designed based on analytical target cascading (ATC) method. In [14], the ADMM algorithm was employed to solve the distributed ITDN restoration problem. In view of the privacy of DS data, the coordination and collaboration of TS and DS can provide economic and safety benefits for their planners. However, when implementing transmission and distribution decision-making with their interaction considered, the post-planning and post-

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scheduling schemes will also confront typhoons and suffer the detriment from them if not taking precautionary measures. The TS and DS are both under the potential risks of destruction by typhoons.

To the author's best knowledge, there still lacks the research of coordinated execution of transmission and distribution network planning aimed at raising system resilience in the existing work. The integrated resilience-oriented planning may render possible solution to reduce the total post-disaster load curtailment and total planning cost in TS and DS. Thus the overlook of resilient ITDN planning discards the feasible alternatives to improve the overall resilience in an economical way. Within the context of the above problems, the main contributions of this paper can be summarized as follows:

1) A resilient TNHP model and a resilient DNDP model are proposed in this work. The hourly generation operation is modeled in TNHP which captures the variation of load and wind power and guarantees the security of power balance. Distribution network hardening and reconfiguration, bus islanding and DGs' dispatch are employed as defensive strategies against typhoons in DNDP model.

2) A distributed optimization framework of resilient TNHP coordinated with defensive strategies in DNDP based on ADMM algorithm is developed in this work. The overall resilience of transmission and distribution network can be enhanced by distributed preventive hardening planning in which the boundary information between TS and DS is exchanged and updated in the iterative procedure.

II. Resilient Transmission and Distribution Network Hardening Planning Model

A. Transmission Network Hardening Planning model

To hedge against severe impact of typhoons on power transmission, the resilient TNHP is constructed in this paper to enhance the TS resilience. The objective function of hardening planning model is formulated as follows.

$$\begin{aligned}\min \sum_{(i,j)\in\Gamma_T} C_{ij}^{trans} x_{ij}^{trans} + \sum_{t\in\Psi}\Big(\sum_{j\in\Omega_T} C^{LS} P_{j,t}^{TS,c} + \sum_{w\in\Theta} C^{cur} P_{w,t}^{c} + \\ \sum_{g\in\Xi}(C_g P_{g,t} + C_g^U SU_{g,t} + C_g^D SD_{g,t})\Big)\end{aligned} \tag{1}$$

where x_{ij}^{trans} represents the hardening decision variable of transmission lines. C_{ij}^{trans} represents the hardening cost of line (i,j). $P_{j,t}^{TS,c}$ represents the load shedding amount in TS at bus j. C^{LS} represents the cost of load shedding per MW. $P_{w,t}^{c}$ represents the wind power curtailment amount at wind farm w. C^{cur} represents the wind power curtailment cost per MW. $P_{g,t}$, $SU_{g,t}$, $SD_{g,t}$ denote the generated power, start-up and shutdown binary variables of conventional generating unit (CGU) g. C_g, C_g^U, C_g^D denote the cost of power generating per MW, start-up and shutdown per CGU g. Γ_T, Ω_T, Θ, Ξ denote the sets of lines, buses, wind farms and CGUs in TS. Ψ denotes the timeslots.

Power balance and transmission network constraints based on big-M method are shown as (2)-(4). $P_{j,t}^{TS}$ represents the load power at each bus. $P_{TD,j,t}$ indicates the boundary exchange power between TS and DS at the boundary bus. M signifies a large enough number. ζ_{ij} represents line status after the occurrence of typhoons. When a line is out of operation because of the typhoons' impact, it is set to 0. $x_{ij}^{trans}+\zeta_{ij}-\zeta_{ij}x_{ij}^{trans}$ denotes the line status considering the mutual impact of line hardening and typhoons. Constraint (4) restricts the power flow passing through each line will not surpass the rated capacity considering the mutual impact of line hardening and typhoons' damage.

$$\sum_{\forall g\in\Xi_j} P_{g,t} + \sum_{\forall w\in\Theta_j} P_{w,t} - \sum_{\forall(i,j)\in\Gamma_{Tj}} P_{ij,t} = P_{j,t}^{TS} - P_{j,t}^{TS,c} - P_{TD,j,t} \quad \forall j\in\Omega_T,\ \forall t \tag{2}$$

$$\begin{cases} P_{ij,t} - B_{ij}(\theta_{i,t}-\theta_{j,t}) \ge -(1-(x_{ij}^{trans}+\xi_{ij}-\xi_{ij}x_{ij}^{trans}))M \\ P_{ij,t} - B_{ij}(\theta_{i,t}-\theta_{j,t}) \le (1-(x_{ij}^{trans}+\xi_{ij}-\xi_{ij}x_{ij}^{trans}))M \end{cases} \quad \forall(i,j)\in\Gamma_T,\ \forall t \tag{3}$$

$$\begin{cases} P_{ij,t} \ge -(x_{ij}^{trans}+\xi_{ij}-\xi_{ij}x_{ij}^{trans})F_{ij}^{\min} \\ P_{ij,t} \le (x_{ij}^{trans}+\xi_{ij}-\xi_{ij}x_{ij}^{trans})F_{ij}^{\max} \end{cases} \quad \forall(i,j)\in\Gamma_T,\ \forall t \tag{4}$$

To improve the flexibility of TS in prevention for load shedding and renewable energy curtailment, the specific operation constraints of CGUs are considered, which are formulated below. Constraint (5) expresses the range of CGUs' output. $u_{g,t}$ is the binary variable representing if CGU is online. Constraint (8) illustrates the minimum start-up/shutdown time of CGUs. Constraint (7) expresses the logic relationship between the state variables.

$$\begin{cases} u_{g,t}P_g^{\min} \le P_{g,t} \le u_{g,t}P_g^{\max} \\ P_{g,t} - P_{g,t-1} \le u_{g,t-1}RU_g^{\max} + (1-u_{g,t-1})P_g^{\max} \\ P_{g,t-1} - P_{g,t} \le u_{g,t}RD_g^{\max} + (1-u_{g,t})P_g^{\max} \end{cases} \quad \forall g\in\Xi,\ \forall t \tag{5}$$

$$\begin{cases} -u_{g,t-1} + u_{g,t} - u_{g,\tau} \le 0 \quad \forall\tau\in\{t,\ldots,T_g^{SU}+t-1\} \\ u_{g,t-1} - u_{g,t} + u_{g,\tau} \le 1 \quad \forall\tau\in\{t,\ldots,T_g^{SD}+t-1\} \end{cases} \forall g\in\Xi \tag{6}$$

$$\begin{cases} u_{g,t} - u_{g,t-1} = SU_{g,t} - SD_{g,t} \\ SU_{g,t} + SD_{g,t} \le 1 \end{cases} \quad \forall g\in\Xi,\ \forall t \tag{7}$$

In (8), the amount of load curtailment is bounded. Constraints (9)-(10) express the operation of wind farms where $P_{w,t}^{fore}$ represents the forecast power output at wind farm w.

$$0 \le P_{j,t}^{TS,c} \le P_{j,t}^{TS} \quad \forall j\in\Omega_T,\ \forall t \tag{8}$$

$$0 \le P_{w,t} \le P_{w,t}^{fore} \quad \forall w\in\Theta,\ \forall t \tag{9}$$

$$P_{w,t}^{fore} = P_{w,t} + P_{w,t}^{c} \quad \forall w\in\Theta,\ \forall t \tag{10}$$

B. Distribution Network Defensive Planning Model

To confront the advent of typhoons, DS also needs to reinforce its defensive ability against the impact of typhoons. The DNDP model is established to enhance its resilience. The objective function of the model is to minimize the total cost including planning cost, load curtailment cost and operation cost in reaction to the predicted impact of typhoons which is formulated as follows.

$$\begin{aligned}\min &\sum_{(i,j)\in\Gamma_D} C_{ij}^{distri} x_{ij}^{distri} + \sum_{t\in\Psi}\Big(\sum_{j\in\Omega_D} C^{LS} P_{j,t}^{DS,c} + \\ &\sum_{j\in\Omega_D} C^{LS}(1-\gamma_j) P_{j,t}^{DS} + \sum_{j\in\Omega_{D(DG)}} C_{DG,j} P_{DG,j,t} + \\ &\sum_{j\in\Omega_{D(sub)}} C^{EX} P_{DT,j,t}\Big)\end{aligned} \tag{11}$$

where x_{ij}^{distri} represents the hardening decision variable of distribution lines. C_{ij}^{distri} represents the hardening cost per line. $P_{j,t}^{DS}$ and $P_{j,t}^{DS,c}$ represent the load demand power and load shedding amount in DS at bus j. γ_j represents islanding status of bus j, if γ_j=0, the bus is totally cut off from the system, otherwise, the bus is on normal operation and its load demand can be curtailed partially. Ω_D denotes the set of buses in DS. $P_{DG,j,t}$ indicates the active power output of DGs. $C_{DG,j}$ represents the dispatch cost of DG per MW. $P_{DT,j,t}$ represents the boundary exchange power between DS and TS. C^{EX} represents the purchase/sell cost of exchange power per MW.

The relaxed distribution network power balance constraints based on second-order cones and big-M method are listed as (12)-(14) and (18), where $p_{ij,t}$ and $q_{ij,t}$ represent the active and reactive power flow passing through branch (i,j). Γ_D denotes the set of distribution network branches. $L_{ij,t}$ and $U_{j,t}$ indicate the square of current magnitude in branch (i,j) and the square of voltage magnitude at bus j. $Q_{DG,j,t}$ indicates the reactive power output of DGs. $Q_{DT,j,t}$ indicates the exchange reactive power at boundary bus which can be calculated as (15). ϕ_j represents the power factor of boundary bus. Constraint (16) limits the amount of load curtailment in DS. Constraint (17) expresses the active and reactive power output of DGs. Constraint (19) indicates the linearized Distflow model which are also restricted by α_{ij}. Constraints (20) and (21) determine the variation range of current and voltage magnitude.

$$\begin{aligned}&\left\| 2p_{ij,t}\ \ 2q_{ij,t}\ \ L_{ij,t}-U_{j,t} \right\|_2 \le L_{ij,t}+U_{j,t} \\ &\qquad \forall (i,j)\in\Gamma_D,\ \forall j\in\Omega_D,\ \forall t\end{aligned} \tag{12}$$

$$\sum_{(i,j)\in\Gamma_D} (p_{ij,t}-L_{ij,t}r_{ij}) + P_{DG,j,t} + P_{DT,j,t} - \gamma_j P_{j,t}^{DS} = 0 \quad \forall j\in\Omega_D,\ \forall t \tag{13}$$

$$\sum_{(i,j)\in\Gamma_D} (q_{ij,t}-L_{ij,t}x_{ij}) + Q_{DG,j,t} + Q_{DT,j,t} - \gamma_j Q_{j,t}^{DS} = 0 \quad \forall j\in\Omega_D,\ \forall t \tag{14}$$

$$Q_{DT,j,t} = P_{DT,j,t}\tan(\arccos\phi_j)\ \ \forall j\in\Omega_{D(sub)},\ \forall t \tag{15}$$

$$0 \le P_{j,t}^{DS,c} \le \gamma_j \cdot P_{j,t}^{DS}\ \ \forall j\in\Omega_D,\ \forall t \tag{16}$$

$$\begin{cases} P_{DG,i}^{\min} \le P_{DG,i,t} \le P_{DG,i}^{\max} \\ Q_{DG,i}^{\min} \le Q_{DG,i,t} \le Q_{DG,i}^{\max}\end{cases} \forall i\in\Phi,\ \forall t \tag{17}$$

$$\begin{cases} -\alpha_{ij}\cdot M \le p_{ij,t} \le \alpha_{ij}\cdot M \\ -\alpha_{ij}\cdot M \le q_{ij,t} \le \alpha_{ij}\cdot M\end{cases} \forall (i,j)\in\Gamma_D,\ \forall t \tag{18}$$

$$\begin{aligned}&\begin{cases} U_{i,t} \ge -(1-\alpha_{ij})\cdot M + U_{j,t} - 2(r_{ij}p_{ij,t}+x_{ij}q_{ij,t}) - (r_{ij}^2+x_{ij}^2)L_{ij,t} \\ U_{i,t} \le (1-\alpha_{ij})\cdot M + U_{j,t} - 2(r_{ij}p_{ij,t}+x_{ij}q_{ij,t}) - (r_{ij}^2+x_{ij}^2)L_{ij,t}\end{cases} \\ &\qquad \forall (i,j)\in\Gamma_D,\ \ \forall t\end{aligned} \tag{19}$$

$$\alpha_{ij}\cdot (I_{ij}^{\min})^2 \le L_{ij,t} \le \alpha_{ij}\cdot (I_{ij}^{\max})^2\ \ \forall (i,j)\in\Gamma_D,\ \forall t \tag{20}$$

$$\gamma_j\cdot (V_j^{\min})^2 \le U_{j,t} \le \gamma_j\cdot (V_j^{\max})^2\ \ \forall j\in\Omega_D,\ \forall t \tag{21}$$

Constraints (22)-(24) denote the radial topology constraints of distribution network. Constraint (25) ensures the connectivity of distribution network after removing the islanding buses. N_{DS} represents the number of buses in distribution network. Constraint (26) ensures the switch-on of the tie-line between TS and DS. Constraint (27) expresses the logic relationship between branch status, hardening and damage. ε_{ij} is the damage status of distribution line, if it is damaged by typhoons, $\varepsilon_{ij}=0$, or $\varepsilon_{ij}=1$.

$$\beta_{ji} + \beta_{ij} = \alpha_{ij} \tag{22}$$

$$\sum_{i\in\Omega_D\ j} \beta_{ji} = \gamma_j \tag{23}$$

$$\beta_{1j} = 0 \tag{24}$$

$$\sum_{(i,j)\in\Gamma_D} \alpha_{ij} = \sum_{j\in\Omega_D} \gamma_j - 1 \tag{25}$$

$$\alpha_{1j} = 1\ \ \forall j\in\Omega_{D(sub)} \tag{26}$$

$$\alpha_{ij} \le x_{ij}^{distri} + \varepsilon_{ij} - \varepsilon_{ij}x_{ij}^{distri}\ \ \forall (i,j)\in\Gamma_D \tag{27}$$

III. Distributed Optimization Framework For Resilient ITDN Hardening Planning

To excavate the potential of the ITDN for enhancing resilience, a distributed optimization framework is designed to prevent the adverse effects of typhoons for TNHP coordinated with the defensive strategies of subordinated DS faced with the adjacent disasters. In this paper, an ADMM-based distributed optimization algorithm is designed to coordinate the optimization subproblems of TS and DS.

A. Formulation of the Augmented Lagrangian Function

The new objective function reformulated with its augmented Lagrangian function for TNHP model is rewritten as (28).

$$\begin{aligned}\min &\sum_{(i,j)\in\Gamma_T} C_{ij}^{trans} x_{ij}^{trans} + \sum_{t\in\Psi}\Big(\sum_{j\in\Omega_T} C^{LS} P_{j,t}^{TS,c} + \sum_{w\in\Theta} C^{cur} P_{w,t}^{c} + \\ &\sum_{g\in\Xi}(C_g P_{g,t} + C_g^U SU_{g,t} + C_g^D SD_{g,t})\Big) + \\ &\sum_{t\in\Psi}\sum_{j\in\Omega_{T(sub)}}\left(\lambda_{j,t}^{TS}(P_{TD,j,t}-\overline{P_{j,t}}) + \frac{\rho_j}{2}\left\|P_{TD,j,t}-\overline{P_{j,t}}\right\|_2^2\right)\end{aligned} \tag{28}$$

where $\lambda_{j,t}^{TS}$ denotes the Lagrangian multiplier parameter of TS optimization problem. ρ_j denotes the adaptive penalty parameter during the ADMM iterative process. Note that the exchanged active power $P_{TD,j,t}$ and $P_{DT,j,t}$ represent the coupled boundary variables between TS and DS, they should satisfy the consistency constraint ($P_{TD,j,t} = P_{DT,j,t}$) after the iteration of ADMM process. The exchanged reactive power is not chosen for boundary variable in this work for simplicity. $\overline{P_{j,t}}$ is the average value of boundary variables which is expressed below.

$$\overline{P_{j,t}} = \frac{P_{TD,j,t} + P_{DT,j,t}}{2} \quad \forall j \in \Omega_{D(sub)},\ \forall t \tag{29}$$

The new objective function reformulated for DNDP model is rewritten as (30).

$$\begin{aligned} \min \sum_{(i,j)\in\Gamma_D} C_{ij}^{distri} x_{ij}^{distri} + \sum_{t\in\Psi} \Big(\sum_{j\in\Omega_D} C^{LS} P_{j,t}^{DS,c} + \sum_{j\in\Omega_{D(DG)}} C_{DG,j} P_{DG,j,t} + \\ \sum_{j\in\Omega_D} C^{LS}(1-\gamma_j) P_{j,t}^{DS} + \sum_{j\in\Omega_{D(sub)}} C^{EX} P_{DT,j,t} \Big) + \\ \sum_{t\in\Psi} \sum_{j\in\Omega_{D(sub)}} \left(\lambda_{j,t}^{DS} (P_{DT,j,t} - \overline{P_{j,t}}) + \frac{\rho_j}{2} \left\| P_{DT,j,t} - \overline{P_{j,t}} \right\|_2^2 \right) \end{aligned} \tag{30}$$

where $\lambda_{j,t}^{DS}$ denotes the Lagrangian multiplier parameter of DS optimization subproblem.

B. ADMM-based Distributed Algorithm Procedure

The ADMM-based distributed algorithm solution process is illustrated as the following procedure.

Step 1: Initialize the coupled boundary variables ($P_{TD,j,t}$, $P_{DT,j,t}$, $\overline{P_{j,t}}$), multiplier parameters ($\lambda_{j,t}^{TS}$, $\lambda_{j,t}^{DS}$), penalty parameter (ρ_j). Set the iteration indice $k = 0$ and the iteration convergence thresholds σ_1, σ_2;

Step 2: Let $k = k + 1$. Solve TNHP subproblems ((28) and (2)-(10)). Preserve the corresponding value of boundary variable obtained from the optimization results.

Step 3: Solve DNDP subproblems ((30), (12)-(27)). Preserve the optimized value of boundary variable and update the average value of boundary variables.

Step 4: Update the multiplier parameters and penalty parameter with preserved boundary values based on (31)-(32). K^u, K^d and v are the updating coefficients of penalty parameter.

$$\begin{cases} \lambda_{j,t}^{TS,(k+1)} = \lambda_{j,t}^{TS,(k)} + \rho_j^{(k)} (P_{TD,j,t}^{(k)} - (\overline{P_{j,t}})^{(k)}) \\ \lambda_{j,t}^{DS,(k+1)} = \lambda_{j,t}^{DS,(k)} + \rho_j^{(k)} (P_{DT,j,t}^{(k)} - (\overline{P_{j,t}})^{(k)}) \end{cases} \tag{31}$$

$$\rho_j^{(k+1)} = \begin{cases} K^u \rho_j^{(k)} & D_1 > v D_2 \\ \dfrac{\rho_j^{(k)}}{K^d} & D_2 > v D_1 \\ \rho_j^{(k)} & else \end{cases} \tag{32}$$

Step 5: Calculate the residuals of updated boundary exchanged power as is expressed in (33).

$$\begin{cases} D_1 = \left\| P_{TD,j,t}^{(k)} - (\overline{P_{j,t}})^{(k+1)} \right\|_2 \\ D_2 = \left\| (\overline{P_{j,t}})^{(k+1)} - (\overline{P_{j,t}})^{(k)} \right\|_2 \end{cases} \tag{33}$$

Step 6: Check the following stopping criterion. If it is satisfied, the iteration suspends and the optimal solution of distributed optimization problem is obtained. Otherwise, go back to Step 2 and continue the next iteration.

$$\begin{cases} D_1 \le \sigma_1 \\ D_2 \le \sigma_2 \end{cases} \tag{34}$$

IV. Numerical Results

The modified IEEE-14 transmission system [15] and IEEE-33 distribution system are selected to verify the effectiveness of the proposed method, where the ITDN are shown as Fig. 1 and Fig. 2. A distribution network is linked to transmission network at bus 11 by the substation. The typhoons' motion is set in Fig. 1 and the trajectory is adjacent to the distribution network.

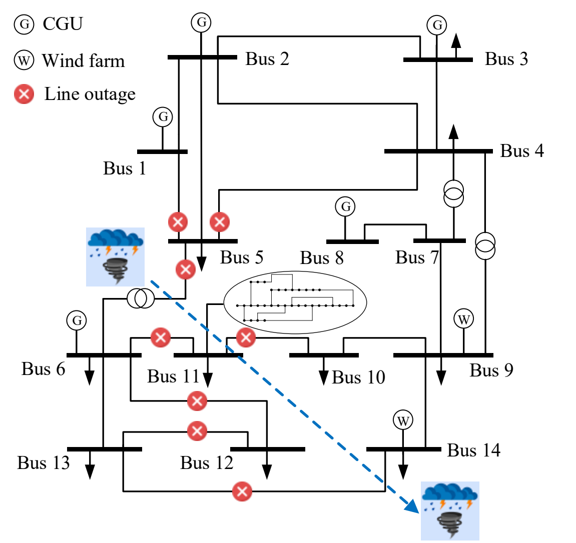


Fig. 1. The schematic diagram of IEEE-14 transmission system integrated with distribution system at bus 11

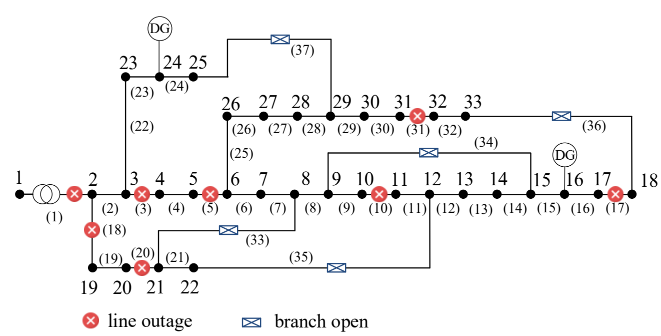
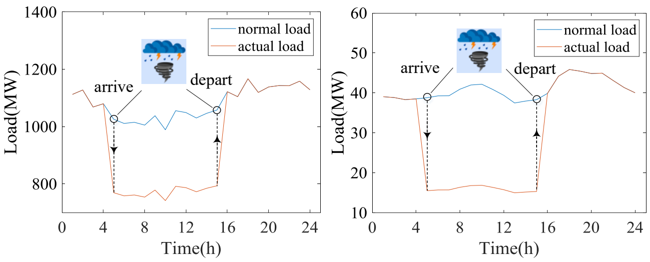


Fig. 2. The scehmatic diagram of IEEE-33 distribution system

A. Basic Settings

For transmission network, two wind farms are deployed at bus 9 and bus 14 with 200MW and 250 MW. For distribution network, two DGs are deployed at bus 16 and bus 24 both with 16 MW. It is assumed that the transmission lines and distribution lines which are on typhoons' path or adjacent to typhoons' path probably suffer an outage [16]. Impacted by typhoons, transmission line 1-5, 4-5, 5-6, 6-11, 6-12, 10-11, 12-13 and 13-14 are assumed to be on outage. Tie-line 1 and branch 3, 5, 10, 17, 18, 20 and 31 in DS are on outage because of the location near typhoons' path. A typical day is used to simulate the typhoons' arrival. Load demand power in TS and DS are shown as Fig. 3. As depicted in the figures, the actual load demand power in ITDN will descend from their normal load power when typhoons arrive at time 5h and restore when typhoons depart the system area at time 15h.



(a) transmission system (b) distribution system

Fig. 3. Load demand power profie in transmission and distribution system

The penalty cost for load curtailment and wind curtailment are set as 1000 \$/MWh and 200 \$/MWh. The initial lagrangian multiplier parameters of transmission and distribution optimization subproblems are set as 0. The initial penalty parameter is set as 1. Convergence thresholds are set as 0.01.

B. Results and Discussion

The distributed planning results of transmission network hardening coordinated with distribution network defensive strategies are compared with the separate transmission network hardening planning results, which are shown as Table I. It should be noted that the load demand power at bus 11 in TS and DGs' output power in DS are amount to 0 owing to the impact of typhoons on tie-line 1 in DS when implementing separate planning. From the transmission network hardening planning results, both planning methods can prevent the load curtailment from typhoons' damage with four identical transmission lines hardened. The critical hardened lines can guarantee the uninterrupted power supply in the emergency circumstance before the damaged lines are repaired. Note that the total cost of separate planning is 10.32% higher than the total cost of distributed planning. It is because that the TS after separate hardening planning can only survive the typhoons by CGUs' commitment and dispatch with its own generation resources. The disregard of DS boundary information makes the mutual support between TS and DS unavailable which can reduce the dispatching burden of intrinsic generations and enhance the TS resilience in a more economical way. For distributed planning, the boundary exchange power can be shown as Fig. 4, where the blue curve represents the power from TS to DS, the orange curve represents the power from DS to TS. It can be seen that owing to the decreased load demand during typhoons (from time 5h to 15h), the surplus power provided by DGs can be delivered from DS to TS for emergence service under the condition of distribution lines reinforcement, thus reduce the dispatch cost of CGUs. Besides, the power support from TS to DS can facilitate the consumption of wind energy and thus eliminate wind curtailment.

TABLE I. TRANSMISSION NETWORK PLANNING RESULTS THROUTH DISTRIBUTED AND SEPARATE OPTIMIZATION METHOD

Method	Hardening plan	Wind curtailment (MWh)	Load curtailment (MWh)	Total cost (M\$)
distributed	1-5, 5-6 6-12, 10-11	0	0	249.60
separate	1-5, 5-6 6-12, 10-11	3.76	0	275.35

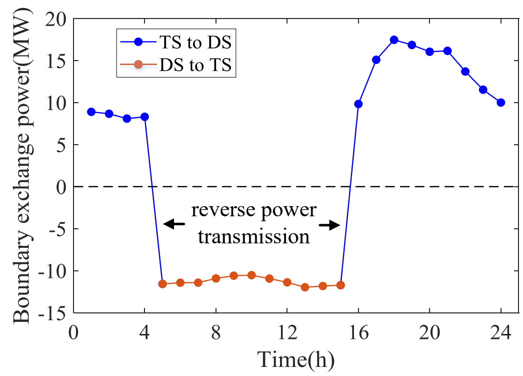


Fig. 4. The boundary exchange power at bus 11 between TS and DS during typhoons

The distribution network defensive planning results collaborated with transmission network hardening planning is listed in Table II. The hardening and reconfiguration strategies are shown as Fig. 5. It can be seen that the defensive strategies also prevent the load curtailment with DGs' output power and exchange power from TS. To receive or deliver the support power, the tie-line and lines around it are hardened for the interaction of TS and DS. Branch 22 and 33 are switched off with the damaged lines to remain the radial distribution network. Besides, no buses are islanded under the adequate budgets.

TABLE II. DISTRIBUTION NETWORK DEFENSIVE PLANNING RESULTS

Hardening plan	Branches open	Load curtailment (MWh)	Investment cost (k\$)	Total cost (k\$)
1, 3, 5, 17, 18	10, 20, 22, 31, 33	0	6320	12599.24

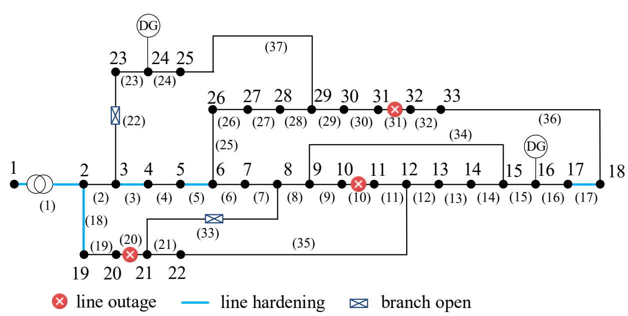


Fig. 5. The defensive strategies of distribution network collaborated with transmission network hardening planning

The iteration curve of the ADMM-based distributed algorithm is shown as Fig. 6. After 25 iterations, the two residuals of updated boundary power reach thresholds of this algorithm, which means the interactive power of TS and DS attain the same at last.

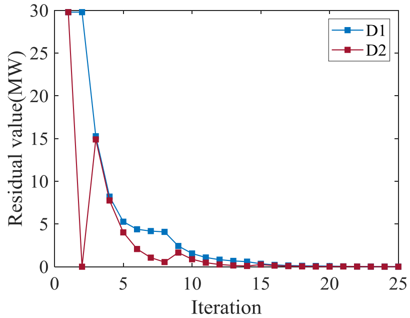


Fig. 6. The iteration curve of the proposed algorithm

V. Conclusion

To sum up, the resilient TNHP model considering the generation hourly operational constraints and the resilient DNDP model considering distribution network reconfiguration, islanding, DGs' dispatch are formulated to cope with the hazards of typhoons. Both models seek the hardening plans and defensive strategies which reduce the load curtailment with a minimal cost. In addition, the ADMM-based distributed optimization framework of the integrated TNHP and DNDP is proposed to support the interaction between TS and DS confronted with typhoons. The information of boundary power is exchanged and updated in each iteration until the residual values reach thresholds. Numerical results show that the resilient TNHP with distribution network defensive strategies prevent the load curtailment with 10.32% total cost reduced compared to separate TNHP, which means that the proposed method can enhance the system resilience against typhoons in an economical way and ensure the perpetual power supply before principal components are repaired. The coordination of the ITDN can also boost the consumption of renewable energy.

In the future, the distributed optimization problem of TNHP and DNDP will be expanded to stochastic optimization problem incorporating multiple uncertainties including renewable energy, typhoons' motion, line outage, etc. The dynamic multi-year planning problem will also be investigated to prevent the long-term impact of typhoons.

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