

Security Constrained Stochastic Unit Commitment Considering Fast Correction Control of Battery Storage and VSC

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Abstract—With the development of power electronics-based units such as battery storage systems (BSS) and voltage source converters (VSC) that can quickly respond, the power system will receive a lot of security benefits from these fast control units. To fully utilize fast correction controls from the BSS and grid coupling VSC (GCVSC), this paper presents a new $N - 1$ security-constrained stochastic unit commitment (SUC) model for hybrid AC and DC grids. In the proposed model, those fast-control units are used to avoid overloading and voltage violations in the post-contingency short-term period. In order to maintain good voltage profiles during pre- and post-contingency periods, the reactive power support ability of the BSS and the GCVSC is also considered. To improve calculation speed, the Bilinear Benders decomposition-based method is used to solve the proposed SUC model. Results on two examples, hybrid AC and DC grids, show that the proposed method can provide highly effective unit commitment solutions with post-contingency corrective actions, especially suitable for avoiding post-contingency short-term security problems in day-ahead dispatch.

Index Terms—Fast corrective control, hybrid AC and DC grids, post-contingency short-term security, stochastic unit commitment.

NOMENCLATURE

A. Abbreviation

Bi-BD	Bilinear Benders Decomposition.
BMP	Bilinear Master Problem.
BSS	Battery storage system.
FCS-PLR	Feasibility check subproblem for the post-contingency long-term rescheduling.
FCS-PR	Feasibility check subproblem for the pre-contingency rescheduling.
FCS-PSR	Feasibility check subproblem for the post-contingency short-term rescheduling.
FL	Flexible load.
GCVSC	Grid coupling voltage source converter.

PLR	Post-contingency long-term rescheduling.
PR	Pre-contingency rescheduling.
PSR	Post-contingency short-term rescheduling.
SUC	Stochastic unit commitment.
TG	Thermal generator.
UC	Unit commitment.
VSC-HVDC	Voltage source converter high voltage direct current.

B. Indices and Sets

i, j	Index of buses.
τ, w	Index of iterations.
t, k, s	Index of time, contingency and scenario, respectively.
g, v, w, b, l	Indexes of TG, GCVSC, the offshore wind farm, BSS and FL, respectively.
f	Index of the first stage.
n, e, h	Index of the pre-contingency period, the post-contingency short-term and long-term periods in the second stage, respectively.
N_T	Set of time intervals.
Ω^{AC}, Ω^{DC}	Set of buses in AC grid and DC grid, respectively.
Ω_i^{AC}	Set of buses connected with the bus i in AC grid.
Ω_i^{DC}	Set of buses connected with the bus i in DC grid.
$\Omega_i^G, \Omega_i^{pcc}$	Sets of TG and GCVSC connected with the bus i in AC grid, respectively.
Ω_i^B, Ω_i^L	Sets of BSS and FL connected with the bus i in AC grid, respectively.
$\Omega_i^{WG}, \Omega_i^{conv}$	Sets of the offshore wind farms and GCVSC connected with the bus i in DC grid, respectively.

C. Variables

$P_{(\cdot),ij,t}^{ac,(k)}$	Active power of branch ij in AC grid at time t .
$Q_{(\cdot),ij,t}^{ac,(k)}$	Reactive power of branch ij in AC grid at time t .
$R_{(\cdot),g,t}^{\pm}$	Up/down spinning reserve provided by TG g .
$R_{(\cdot),l,t}^{\pm}$	Up/down spinning reserve provided by FL l .
$u_{(\cdot),g,t}$	Commitment status that is equal to 1 if TG g is online at time t , otherwise it is equal to 0.
$y_{f,g,t}^{on}$	Startup status that is equal to 1 if TG g .

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$y_{f,g,t}^{\text{off}}$	Shutdown status that is equal to 1 if TG g .
$P_{(\cdot),g,t}^{(k)}, Q_{(\cdot),g,t}^{(k)}$	Active and reactive power of TG g at time t , respectively.
$P_{(\cdot),v,t}^{\text{pcc},(k)}$	Active power injected into AC grid by the GCVSC v at time t .
$Q_{(\cdot),v,t}^{\text{pcc},(k)}$	Reactive power injected into AC grid by the GCVSC v at time t .
$P_{(\cdot),v,t}^{\text{conv},(k)}$	Active power flowing from DC grid by the GCVSC v at time t .
$Q_{(\cdot),v,t}^{\text{conv},(k)}$	Reactive power flowing from DC grid by the GCVSC v at time t .
$P_{(\cdot),i,j,t}^{\text{dc},(k)}$	Active power of branch ij in DC grid at time t .
$U_{(\cdot),i,t}^{\text{ac}}, \delta_{(\cdot),i,t}^{\text{ac}}$	Voltage magnitude and phase angle of AC bus i at time t , respectively.
$U_{(\cdot),i,t}^{\text{dc}}$	Voltage magnitude of DC bus i at time t .
$U_{(\cdot),v,s,t}^{\text{ac}}$	Voltage magnitude of the PCC bus in the equivalent branch of GCVSC v at time t .
$U_{(\cdot),v,c,t}^{\text{ac}}$	Voltage magnitude of the converter bus in the equivalent branch of GCVSC v at time t .
$U_{(\cdot),v,j,t}^{\text{dc}}$	Voltage magnitude of DC bus j connected with GCVSC v at time t .
$R_{(\cdot),v,t}^{(k)}$	Droop variable of GCVSC v at time t .
$r_{(\cdot),l,t}^k$	Spinning reserve deployment of FL l at time t .
$\delta_{f,v,s,t}$	Phase angle of the PCC bus in the equivalent branch of GCVSC v at time t .
$\delta_{f,v,c,t}$	Phase angle of the converter bus in the equivalent branch of GCVSC v at time t .
$P_{(\cdot),i,t}^{\text{load},k}$	Active power demand in bus i at time t after post-contingency rescheduling.
$r_{(\cdot),g,t}^k$	Spinning reserve deployment of TG g at time t .
$E_{(\cdot),b,t}^{(k)}$	Energy stored in BSS b at time t .
$D_{(\cdot),b,t}^{(k)}, C_{(\cdot),b,t}^{(k)}$	Discharge and charge states of BSS b at time t , respectively.
$DP_{(\cdot),b,t}^{(k)}$	Discharge active power of BSS b at time t .
$CP_{(\cdot),b,t}^{(k)}$	Charge active power of BSS b at time t .
$P_{(\cdot),b,t}^{(k)}, Q_{(\cdot),b,t}^{(k)}$	Active and reactive power of BSS b at time t , respectively.
$\hat{x}_{\Delta,s,(\cdot),t}^{\tau,(k)}$	Dual variables for the variable transfer equations ($x_{f,(\cdot),t} = \hat{x}_{f,(\cdot),t}^w$) between these two stages where $\hat{x}_{f,(\cdot),t}^w$ is the solution of the first stage.
$P_{\text{real},i,t}^{\text{load}}$	Active power demand which are random variables at bus i at time t .
$Q_{\text{real},i,t}^{\text{load}}$	Reactive power demand which are random variables at bus i at time t .
$P_{\text{real},w,t}^{\text{wind}}$	Active power output of offshore wind farm w at time t as the random variable.
$\phi_{(\cdot),s,i,t}^{p,w,(k),\pm}$	Slack variables for relaxing AC power balance.
$\phi_{(\cdot),s,i,t}^{\text{ac},v,w,(k),\pm}$	Slack variables for relaxing AC voltage limit.
$\phi_{(\cdot),s,i,t}^{\text{dc},v,w,(k),\pm}$	Slack variables for relaxing DC voltage limit.
$\phi_{(\cdot),s,i,j,t}^{\text{ac},l,w,(k),+}$	Slack variables for relaxing AC branch power

$\phi_{(\cdot),s,i,j,t}^{\text{dc},l,w,(k),+}$

limit.

Slack variables for relaxing DC branch power limit.

D. Parameters

C_g	Fuel cost of TG g .
$C_g^{\text{on/off}}$	Startup/shutdown cost of TG g .
$C_{b,t}, C_{l,t}$	Unit compensation costs of BSS b and FL l at time t , respectively.
$C_g^{\pm}$	Up/down spinning reserve cost of TG g .
$\hat{\varphi}_{\Delta,s}^{\tau,(k)}$	Optimal objective of subproblem at scenarios s .
$P_{\text{pre},i,t}^{\text{load}}$	Predicted active power demand at bus i .
$Q_{\text{pre},i,t}^{\text{load}}$	Predicted reactive load at bus i at time t .
$P_{i,t,s}, Q_{i,t,s}$	Active and reactive demand at bus i at time t in scenario s , respectively.
$P_{\text{pre},w,t}^{\text{wind}}$	Predicted active power of offshore wind farm w at time t .
$G_{i,j}^{\text{ac}}, B_{i,j}^{\text{ac}}$	Conductance and susceptance of branch ij in AC grid, respectively.
$G_{i,j}^{\text{dc}}$	Conductance of branch ij in DC grid.
$G_{v,c,s}, B_{v,c,s}$	Conductance and susceptance of the equivalent branch at GCVSC v , respectively.
$S_{v,\text{max}}^{\text{conv}}$	Upper limit of apparent power of the converter at GCVSC v .
$\eta_{\text{cha/dis},b}$	Charging/discharging efficiency of BSS.
$E_{b,\text{max/min}}$	Upper/ lower limit of energy limit of BSS.
$DP_{b,\text{max}}$	Maximum discharging power of BSS b .
$CP_{b,\text{max}}$	Maximum charging power of BSS b .
$S_{b,\text{max}}$	Maximum apparent power of BSS b .
α	Predefined confidence level.
$P_g^{\text{up/down}}$	Ramp up/down rate of TG g .
$Q_{g,\text{max/min}}$	Maximum/minimum limit of reactive power output of TG g .
$R_{v,\text{max/min}}$	Maximum/minimum limit of the droop value at GCVSC v .
$R_{l,t,\text{max}}^{\pm}$	Maximum amount of up/down spinning reserve capability provided by FL l at time t .
$S_{i,j,\text{max}}^{\text{ac}}$	Apparent power capacity of branch ij in AC grid.
$P_{i,j,\text{max}}^{\text{dc}}$	Active power capacity of branch ij in DC grid.
H	Parameter defining how much the short-term emergency rating of branch can be temporarily relaxed from their long-term rating.
$U_v^{\text{ref}}, P_v^{\text{ref}}$	Voltage reference and power reference of the droop control strategy at GCVSC v , respectively.
τ_1, τ_2	Response time and ramping time of TG, respectively.

I. INTRODUCTION

AS a clean and renewable energy source, wind energy has been widely used around the world. Compared with onshore wind power, offshore wind power is characterized by advantages such as high wind speed and low noise [1], [2]. Offshore wind power is usually connected to the AC grid by

using voltage source converter based HVDC (VSC-HVDC) [3]–[6], which is able to implement fast and independent active and reactive power control and supply power to passive networks [7], [8]. This has promoted the development of VSC based hybrid AC and DC grids around the world.

For the secure power supply, post-contingency operation (e.g., well-known $N-1$ secure operation) is usually considered in power systems. In the post-contingency period, system state can be divided into short-term state and long-term state if the state before the action of traditional controllable units (e.g., thermal generator) is considered [9]–[11]. Traditionally, $N-1$ secure operation was mainly focused on post-contingency long-term operation, which is common in the field of unit commitment research (e.g., [12]–[14]). The corrective operation of the post-contingency short-term period requires the action of fast control units to avoid overloading and voltage violations. In hybrid AC and DC grids with VSC-HVDC, flexible and fast control of grid-coupling voltage source converter (GCVSC) and battery storage system (BSS) is very advantageous to ensure secure operation in the post-contingency short-term period. For example, Cao *et al.* proposed an improved corrective security-constrained optimal power flow method by using the post-contingency fast corrective action of VSC-HVDC [11]. In unit commitment (UC) of AC power systems, utility-scale energy storage is used to alleviate short-term emergency overloading when slow-ramping generators cannot be adjusted [14]. However, in UC of hybrid AC and DC grids, fast control of the GCVSC and the BSS has not been considered in post $N-1$ contingency short-term state.

Reactive power of BSS and GCVSC is useful for improving the voltage profile, especially during the post-contingency period. However, only fast active power control of GCVSC and BSS is considered in security-constrained optimal power flow [11] and unit commitment of AC power system [15]. In [16], a decentralized coordinated voltage control scheme was proposed, considering the reactive power support ability of GCVSC, but it omitted post $N-1$ secure operation. Besides BSS and GCVSC, flexible load (FL) [17], [18] is also a useful fast control resource in the post-contingency short-term period. For example, a two-stage robust optimization model was proposed for multiple reserve resources, including the reserve capacity of demand response to improve system flexibility in the post-contingency period in [19]. A novel speed load shedding scheme based on emergency demand response was proposed to improve short-term voltage stability in regional power systems [20]. In this paper, fast active and reactive power control of BSS and GCVSC, and flexible control of FL will be considered for the UC problem of hybrid AC and DC grids.

Due to the randomness of wind power and load, it is wellknown that they are difficult to predict precisely in the day-ahead stage. Two-stage stochastic programming is an effective approach to consider the impacts of uncertainties in power system UC [21], [22]. This method is known to have the ability to consider specific realizations of stochastic variables. Chance-constrained optimization is also a useful stochastic optimization approach when considering uncertain wind power in the UC problem [23], [24]. This method can

provide a good balance between operational economy and security level by a predefined confidence level in UC problem [24]. By combining the advantages of the aforementioned two methods, Zhang *et al.* [25] proposed a chance-constrained two-stage UC model to accommodate large-scale renewable energy. Besides, in [26], the chance-constrained two-stage UC model is proposed to co-optimize day-ahead energy and reserve schedules with consideration of battery storage and wind power. In this paper, this hybrid approach is adopted to find unit-commitment plans that utilize fast correction control while considering uncertainties in pre- and post-contingency states.

The contributions of this paper can be summarized as follows:

1) A stochastic UC (SUC) model is proposed for considering fast active and reactive power control of the GCVSC and BSS in post-contingency short-term operation. This is beneficial in avoiding post-contingency short-term overloading and voltage violations in the presence of uncertain wind power and load. Also, it will be shown that the cost can be reduced if fast BSS and GCVSC controls are considered in post $N-1$ contingency short-term state.

2) The proposed SUC model is a large-scale mixed integer non-linear stochastic optimization problem. This paper converts it into a deterministic mixed integer linear model. To improve calculation speed, a deterministic optimization model is then solved by the Bilinear Benders decomposition [24] based method. Test results show this method can solve the proposed SUC model efficiently.

The remainder of this paper is organized as follows. Section II provides the mathematical formulation of the proposed stochastic UC model. Section III presents the Bilinear Benders decomposition based method for solving the proposed stochastic UC model. The effectiveness of the proposed method is validated by two example hybrid AC and DC grids in Section IV, and finally, conclusions are given in Section V.

II. MATHEMATICAL FORMULATION

In this section, we present an SUC model considering fast correction control in the framework of chance-constrained two-stage optimization for hybrid AC and DC grids. The first stage refers to day-ahead dispatch considering zero-error prediction of wind power and load. The second stage refers to the rescheduling of control resources considering uncertainties of wind power and load in pre- and post-contingency periods.

A. Objective Function

The objective function aims to minimize day-ahead operational cost, including fuel cost, startup/shutdown cost, and up/down spinning reserve cost of thermal generator (TG), operation cost of BSS, and up/down spinning reserve cost of FL as follows:

$$\begin{aligned} \min F = & \sum_{t \in N_T} \left\{ \sum_{i \in \Omega^{AC}} \left[\sum_{l \in \Omega_i^L} C_{l,t} (R_{f,l,t}^+ + R_{f,l,t}^-) \right. \right. \\ & \left. \left. + \sum_{g \in \Omega_i^G} (C_g^+ R_{f,g,t}^+ + C_g^- R_{f,g,t}^- + C_g^{\text{on}} y_{f,g,t}^{\text{on}}) \right] \right\} \end{aligned}$$

$$+ C_g^{\text{off}} y_{f,g,t}^{\text{off}} + C_g P_{f,g,t} + \sum_{b \in \Omega_i^B} C_b P_{f,b,t} \Big] \Big\} \quad (1)$$

B. Constraints for the First Stage

The first stage refers to deterministic day-ahead dispatch of hybrid AC and DC grids in which the following constraints are considered:

$$\sum_{g \in \Omega_i^G} P_{f,g,t} + \sum_{v \in \Omega_i^{\text{pcc}}} P_{f,v,t}^{\text{pcc}} + \sum_{b \in \Omega_i^B} P_{f,b,t} - P_{\text{pre},i,t}^{\text{load}} = \sum_{j \in \Omega_i^{\text{AC}}} P_{f,i,j,t}^{\text{ac}} \quad (2)$$

$$\sum_{g \in \Omega_i^G} Q_{f,g,t} + \sum_{v \in \Omega_i^{\text{pcc}}} Q_{f,v,t}^{\text{pcc}} + \sum_{b \in \Omega_i^B} Q_{f,b,t} - Q_{\text{pre},i,t}^{\text{load}} = \sum_{j \in \Omega_i^{\text{AC}}} Q_{f,i,j,t}^{\text{ac}} \quad (3)$$

$$\sum_{j \in \Omega_i^{\text{DC}}} P_{f,i,j,t}^{\text{dc}} = \sum_{w \in \Omega_i^{\text{WG}}} P_{\text{pre},w,t}^{\text{wind}} - \sum_{v \in \Omega_i^{\text{conv}}} P_{f,v,t}^{\text{conv}} \quad (4)$$

$$P_{f,i,j,t}^{\text{ac}} = G_{i,j}^{\text{ac}} (U_{f,i,t}^{\text{ac}} - U_{f,j,t}^{\text{ac}}) - B_{i,j}^{\text{ac}} (\delta_{f,i,t} - \delta_{f,j,t}) \quad (5)$$

$$Q_{f,i,j,t}^{\text{ac}} = -B_{i,j}^{\text{ac}} (U_{f,i,t}^{\text{ac}} - U_{f,j,t}^{\text{ac}}) - G_{i,j}^{\text{ac}} (\delta_{f,i,t} - \delta_{f,j,t}) \quad (6)$$

$$P_{f,i,j,t}^{\text{dc}} = G_{i,j}^{\text{dc}} (U_{f,i,t}^{\text{dc}} - U_{f,j,t}^{\text{dc}}) \quad (7)$$

$$(P_{f,i,j,t}^{\text{ac}})^2 + (Q_{f,i,j,t}^{\text{ac}})^2 \leq (S_{i,j,\text{max}}^{\text{ac}})^2 \quad (8)$$

$$-P_{i,j,\text{max}}^{\text{dc}} \leq P_{f,i,j,t}^{\text{dc}} \leq P_{i,j,\text{max}}^{\text{dc}} \quad (9)$$

$$P_{f,v,t}^{\text{pcc}} = G_{v,c,s} (U_{f,v,c,t}^{\text{ac}} - U_{f,v,s,t}^{\text{ac}}) - B_{v,c,s} (\delta_{f,v,c,t} - \delta_{f,v,s,t}) \quad (10)$$

$$Q_{f,v,t}^{\text{pcc}} = -B_{v,c,s} (U_{f,v,c,t}^{\text{ac}} - U_{f,v,s,t}^{\text{ac}}) - G_{v,c,s} (\delta_{f,v,c,t} - \delta_{f,v,s,t}) \quad (11)$$

$$P_{f,v,t}^{\text{conv}} = P_{f,v,t}^{\text{pcc}}, Q_{f,v,t}^{\text{conv}} = Q_{f,v,t}^{\text{pcc}} \quad (12)$$

$$(P_{f,v,t}^{\text{conv}})^2 + (Q_{f,v,t}^{\text{conv}})^2 \leq (S_{v,\text{max}}^{\text{conv}})^2 \quad (13)$$

$$R_{v,\text{min}} \leq R_{f,v,t} \leq R_{v,\text{max}} \quad (14)$$

$$P_{f,v,t}^{\text{pcc}} = R_{f,v,t} (U_v^{\text{ref}} - U_{f,v,t}^{\text{dc}}) + P_v^{\text{ref}} \quad (15)$$

$$0 \leq R_{f,l,t}^+ \leq R_{l,\text{max}}^+ \quad (16)$$

$$0 \leq R_{f,l,t}^- \leq R_{l,\text{max}}^- \quad (17)$$

$$E_{f,b,t} = E_{f,b,t-1} + (\eta_{\text{cha},b} C P_{f,b,t} - D P_{f,b,t} / \eta_{\text{dis},b}) T_d \quad (18)$$

$$E_{f,b,\text{start}} = E_{f,b,\text{final}} \quad (19)$$

$$E_{b,\text{min}} \leq E_{f,b,t} \leq E_{b,\text{max}} \quad (20)$$

$$0 \leq D P_{f,b,t} \leq D_{f,b,t} D P_{b,\text{max}} \quad (21)$$

$$0 \leq C P_{f,b,t} \leq C_{f,b,t} C P_{b,\text{max}} \quad (22)$$

$$D_{f,b,t} + C_{f,b,t} \leq 1 \quad (23)$$

$$P_{f,b,t} = D P_{f,b,t} - C P_{f,b,t} \quad (24)$$

$$(P_{f,b,t})^2 + (Q_{f,b,t})^2 \leq (S_{b,\text{max}})^2 \quad (25)$$

where constraints (2)–(3) represent AC nodal power balance, and constraint (4) represents DC nodal power balance. Constraints (5)–(7) are linear branch flow equations [27], [28]. Constraints (8)–(9) are to limit the long-term power flow of AC and DC branches, respectively. In this paper, GCVSC refers to VSC between AC grid and DC grid. Modelling of the GCVSC has omitted the low-pass filter and loss in the

phase reactor [29], [30]. Also, the phase reactor and converter transformer are combined as a single equivalent branch. Thus, active and reactive power flow equations of the GCVSC station are formulated in the form of (10)–(12) [18]. Furthermore, this paper employs the most common DC voltage droop control, which is shown in (15) [11]. Other operational constraints of GCVSC include apparent power constraint (13) and droop control coefficient constraints (14). In (16)–(17), spinning reserve constraints of FL are also considered [19]. Operational constraints of BSS include energy constraints (18)–(20), discharging and charging constraints (21)–(22), state constraint (23), and apparent power constraint (25) [31]. In addition, TG constraints, including minimum startup/shutdown time constraints, ramping rate constraints, active power constraints, reactive power constraints, and spinning reserve constraints [25], are also taken into account. Meanwhile, lower and upper voltage bounds are considered for AC and DC buses, respectively.

C. Constraints for the Pre-contingency Rescheduling (PR) in the Second Stage

In PR of the second stage, rescheduling is to improve the voltage profile by the reactive power support ability of BSS and GCVSC, and power balance is ensured with a predefined confidence level. In this period, chance constraints (26)–(28) are considered to guarantee that the probability of power balance is larger than a predefined confidence level. Also, constraint (29) for GCVSC, i.e., droop control equation, is considered. In PR, operational TG constraints include up/down spinning reserve deployment constraint (30), TG power constraint considering reschedule (31), ramping constraint (32), and reactive power constraint (33). Besides the above constraints in PR, this paper also considers branch flow equations, branch long-term power constraint, GCVSC power flow equations, GCVSC apparent power constraint, and GCVSC droop control coefficient constraints. Those constraints are similar to (5)–(7), (8)–(9), (10)–(12), (13), and (14), respectively. Also, lower and upper voltage bounds for AC and DC buses are considered in the PR of the second stage.

$$\Pr \left\{ \sum_{g \in \Omega_i^G} P_{n,g,t} + \sum_{v \in \Omega_i^{\text{pcc}}} P_{n,v,t}^{\text{pcc}} + \sum_{b \in \Omega_i^B} P_{f,b,t} - P_{\text{real},i,t}^{\text{load}} = \sum_{j \in \Omega_i^{\text{AC}}} P_{n,i,j,t}^{\text{ac}} \right\} \geq \alpha \quad (26)$$

$$\sum_{j \in \Omega_i^{\text{DC}}} P_{n,i,j,t}^{\text{dc}} = \sum_{w \in \Omega_i^{\text{WG}}} P_{\text{real},w,t}^{\text{wind}} - \sum_{v \in \Omega_i^{\text{conv}}} P_{n,v,t}^{\text{conv}} \quad (27)$$

$$\sum_{g \in \Omega_i^G} Q_{n,g,t} + \sum_{v \in \Omega_i^{\text{pcc}}} Q_{n,v,t}^{\text{pcc}} + \sum_{b \in \Omega_i^B} Q_{f,b,t} - Q_{\text{real},i,t}^{\text{load}} = \sum_{j \in \Omega_i^{\text{AC}}} Q_{n,i,j,t}^{\text{ac}} \quad (28)$$

$$P_{n,v,t}^{\text{pcc}} = R_{n,v,t} (U_v^{\text{ref}} - U_{n,v,t}^{\text{dc}}) + P_v^{\text{ref}} \quad (29)$$

$$-R_{f,g,t}^- \leq r_{n,g,t}^{\text{gn}} \leq R_{f,g,t}^+ \quad (30)$$

$$P_{n,g,t} = P_{f,g,t} + r_{sn,g,t}^{\text{gn}} \quad (31)$$

$$-P_g^{\text{down}} \leq P_{n,g,t} - P_{n,g,t-1} \leq P_g^{\text{up}} \quad (32)$$

$$u_{f,g,t}Q_{g,\min} \leq Q_{n,g,t} \leq u_{f,g,t}Q_{g,\max} \quad (33)$$

D. Constraints for the Post-contingency Short-term Rescheduling (PSR) in the Second Stage

During the initial period of the post-contingency state, the active power of the thermal generator cannot be adjusted immediately due to the inertial constraint [11]. Therefore, PSR is to coordinate active and reactive power of fast control resources (e.g., BSS, GCVSC, and FL) to ensure all branch flows are below their short-term emergency rating and avoid voltage violation. During this period, constraints (34)–(36) ensure that the power balance is satisfied with a predefined confidence level. Besides, constraints (37)–(38) are considered to ensure branch flow below their short-term emergency rating. In PSR, constraints (39)–(40) are used to enforce limitations of up/down spinning reserve deployment of FL. Rescheduling constraints of BSS in PSR are formulated in (41)–(47). Among rescheduling constraints of BSS, (41) and (44) are the constraints related to energy stored in BSS [15].

$$\Pr \left\{ \sum_{j \in \Omega_i^{AC}} P_{e,i,j,t}^{ac,k} = \sum_{v \in \Omega_i^{pcc}} P_{e,v,t}^{pcc,k} + \sum_{b \in \Omega_i^B} P_{e,b,t}^k + \sum_{g \in \Omega_i^G} P_{f,g,t} - P_{e,i,t}^{load,k} \right\} \geq \alpha \quad (34)$$

$$\sum_{j \in \Omega_i^{AC}} Q_{e,i,j,t}^{ac,k} = \sum_{g \in \Omega_i^G} Q_{e,g,t}^k + \sum_{v \in \Omega_i^{pcc}} Q_{e,v,t}^{pcc,k} + \sum_{b \in \Omega_i^B} Q_{e,b,t}^k - Q_{real,i,t}^{load} \quad (35)$$

$$\sum_{j \in \Omega_i^{DC}} P_{e,i,j,t}^{dc,k} = \sum_{w \in \Omega_i^{WG}} P_{real,w,t}^{wind} - \sum_{v \in \Omega_i^{conv}} P_{e,v,t}^{conv,k} \quad (36)$$

$$(P_{e,i,j,t}^{ac,k})^2 + (Q_{e,i,j,t}^{ac,k})^2 \leq (S_{i,j,\max}^H)^2 \quad (37)$$

$$-P_{i,j,\max}^{dc} H \leq P_{e,i,j,t}^{dc,k} \leq P_{i,j,\max}^{dc} H \quad (38)$$

$$-R_{f,l,t}^- \leq r_{e,l,t}^k \leq R_{f,l,t}^+ \quad (39)$$

$$P_{e,i,t}^{load,k} = P_{i,t}^{real} + \sum_{l \in \Omega_i^L} r_{e,l,t}^k \quad (40)$$

$$E_{b,\min} \leq E_{e,b,t}^k \leq E_{b,\max} \quad (41)$$

$$0 \leq DP_{e,b,t}^k \leq D_{e,b,t}^k DP_{b,\max} \quad (42)$$

$$0 \leq CP_{e,b,t}^k \leq C_{e,b,t}^k CP_{b,\max} \quad (43)$$

$$E_{e,b,t}^k = E_{f,b,t} + (\eta_{cha,b} CP_{e,b,t}^k - DP_{e,b,t}^k / \eta_{dis,b}) (\tau_1 + 0.5\tau_2) \quad (44)$$

$$D_{e,b,t}^k + C_{e,b,t}^k \leq 1 \quad (45)$$

$$P_{e,b,t}^k = DP_{e,b,t}^k - CP_{e,b,t}^k \quad (46)$$

$$(P_{e,b,t}^k)^2 + (Q_{e,b,t}^k)^2 \leq (S_{b,\max})^2 \quad (47)$$

In the PSR period, this paper also considers branch flow equations, GCVSC power flow constraints, GCVSC apparent power constraint, GCVSC droop control coefficient constraints, GCVSC droop control equation, and reactive power constraint of TG. They are similar to (5)–(7), (10)–(14), (29), and (33). Also, the lower and upper voltage bounds for AC and DC buses are considered in the PSR period.

E. Constraints for the Post-contingency Long-term Rescheduling (PLR) in the Second Stage

In the PLR, TG can respond to rescheduling instructions. Therefore, the PLR is to coordinate TG, GCVSC, and FL to ensure safe post-contingency long-term operation of hybrid AC and DC grids. In the PLR, branch flow equations, branch long-term power constraints, GCVSC power flow equations, GCVSC apparent power constraints, GCVSC droop control coefficient constraints, GCVSC droop control equations, and rescheduling constraints for TG and FL are also considered. They are similar to (5)–(7), (8)–(9), (10)–(12), (13), (14), (29), (30)–(33), and (39)–(40). Also, lower and upper voltage bounds are considered in the PLR period. Power balance in the PLR period of the k -th contingency is required to be satisfied with a predefined confidence level as follows:

$$\Pr \left\{ \sum_{j \in \Omega_i^{AC}} P_{h,i,j,t}^{ac,k} = \sum_{v \in \Omega_i^{pcc}} P_{h,v,t}^{pcc,k} + \sum_{b \in \Omega_i^B} P_{f,b,t} + \sum_{g \in \Omega_i^G} P_{h,g,t}^k - P_{h,i,t}^{load,k} \right\} \geq \alpha \quad (48)$$

$$\sum_{j \in \Omega_i^{AC}} Q_{h,i,j,t}^{ac,k} = \sum_{g \in \Omega_i^G} Q_{h,g,t}^k + \sum_{v \in \Omega_i^{pcc}} Q_{h,v,t}^{pcc,k} + \sum_{b \in \Omega_i^B} Q_{f,b,t} - Q_{real,i,t}^{load} \quad (49)$$

$$\sum_{j \in \Omega_i^{DC}} P_{h,i,j,t}^{dc,k} = \sum_{w \in \Omega_i^{WG}} P_{real,w,t}^{wind} - \sum_{v \in \Omega_i^{conv}} P_{h,v,t}^{conv,k} \quad (50)$$

III. SOLUTION METHODOLOGY

The proposed model is inherently a stochastic, large-scale, mixed integer nonlinear optimization model. To effectively solve this model, we first convert chance constraints into deterministic constraints by the Monte Carlo sampling method, and then use binary variables to characterize whether the constraints of the s -th scenario need to be met. In addition, this paper uses the McCormick approximation method [32] and the Hexagon approximation method [33] to linearize the nonlinear constraints (e.g., branch flow constraints, GCVSC droop control constraints, apparent power constraints for the BSS and GCVSC). Finally, the transformed optimization problem is solved by the bilinear variant of the Benders decomposition based method [24].

A. Linearizing Nonlinear Operational Constraints

GCVSC droop control equations (15) and (29) include bilinear terms, e.g., $R_{f,v,t}U_{f,v,j,t}^{dc}$ in (15). In order to eliminate bilinear terms, new constraints are added, and these bilinear terms can be replaced with new variables by the McCormick linearization method [32]. Take $R_{f,v,t}U_{f,v,j,t}^{dc}$ for example, it is replaced by $Z_{f,v,t}$ and constraints (51)–(54) are added:

$$Z_{f,v,t} \geq R_{f,v,t}U_{v,j,\min}^{dc} + R_{v,\min}U_{f,v,j,t}^{dc} - R_{v,\min}U_{v,j,\min}^{dc} \quad (51)$$

$$Z_{f,v,t} \geq R_{f,v,t}U_{v,j,\max}^{dc} + R_{v,\max}U_{f,v,j,t}^{dc} - R_{v,\max}U_{v,j,\max}^{dc} \quad (52)$$

$$Z_{f,v,t} \leq R_{f,v,t} U_{v,j,\max}^{\text{dc}} + R_{v,\min} U_{f,v,j,t}^{\text{dc}} - R_{v,\min} U_{v,j,\max}^{\text{dc}} \quad (53)$$

$$Z_{f,v,t} \leq R_{f,v,t} U_{v,j,\min}^{\text{dc}} + R_{v,\max} U_{f,v,j,t}^{\text{dc}} - R_{v,\max} U_{v,j,\min}^{\text{dc}} \quad (54)$$

In the proposed model, there are several constraints in the quadratic form of (15), e.g., constraints (8) and (13).

$$x^2 + y^2 \leq r^2 \quad (55)$$

By the Hexagon approximation method [33], this paper replaces the quadratic constraint with a set of linear constraints. Taking constraint (8) as an example, the following constraints (56)–(58) are used to replace (8):

$$\begin{aligned} -\sqrt{3}(P_{f,i,j,t}^{\text{ac}} + S_{i,j,\max}^{\text{ac}}) &\leq Q_{f,i,j,t}^{\text{ac}} \\ &\leq -\sqrt{3}(P_{f,i,j,t}^{\text{ac}} - S_{i,j,\max}^{\text{ac}}) \end{aligned} \quad (56)$$

$$-(\sqrt{3}S_{i,j,\max}^{\text{ac}})/2 \leq Q_{f,i,j,t}^{\text{ac}} \leq (\sqrt{3}S_{i,j,\max}^{\text{ac}})/2 \quad (57)$$

$$\sqrt{3}(P_{f,i,j,t}^{\text{ac}} - S_{i,j,\max}^{\text{ac}}) \leq Q_{f,i,j,t}^{\text{ac}} \leq \sqrt{3}(P_{f,i,j,t}^{\text{ac}} + S_{i,j,\max}^{\text{ac}}) \quad (58)$$

Note equation (26) of [32] is not used in (56)–(58).

B. Bilinear Reformulation of Chance Constraint

In this paper, the autoregressive moving average method is used to calculate predicted values of wind power and load [34]. Based on probability density functions of prediction errors and predicted values, scenarios of wind power and load can be generated by the Monte Carlo simulation. In order to reduce the number of the similar scenarios, these scenarios are further clustered into several typical scenarios by K-means algorithm [35].

This paper converts chance constraints into the bilinear mixed integer reformulation [25]. Take (26) as an example, equations (59)–(60) can replace the chance constraint (26) as follows:

$$\sum_{s=1}^{N_s} \pi_s Z_s \leq 1 - \alpha \quad (59)$$

$$\begin{aligned} (1 - Z_s) \left[\sum_{j \in \Omega_i^{\text{AC}}} P_{n,i,j,t,s}^{\text{ac}} - \sum_{g \in \Omega_i^{\text{G}}} P_{n,g,t,s} \right. \\ \left. + \sum_{v \in \Omega_i^{\text{PCC}}} P_{n,v,t,s}^{\text{PCC}} - \sum_{b \in \Omega_i^{\text{B}}} P_{f,b,t} + P_{i,t,s}^{\text{load}} \right] = 0 \end{aligned} \quad (60)$$

where Z_s is a binary variable, i.e., $Z_s = 0$ indicates that the power balance of scenario s must be met for all t , otherwise $Z_s = 1$.

Considering the probability of a failure is relatively low, constraint (26) has a higher priority than constraints (34) and (48). Therefore, only those scenarios that have passed the feasibility check in pre-contingency periods will be further checked for post-contingency operation.

C. Bilinear Benders Decomposition Algorithm (BI-BD)

In this section, the Bilinear Benders decomposition (Bi-BD) based method is used to efficiently solve the proposed model. By using the Bi-BD, the proposed model is decomposed into the master problem and subproblems, which are solved

iteratively. The master problem is to minimize day-ahead operation cost with constraints of the first stage and the Benders infeasibility cuts. The subproblem is used to check whether the day-ahead scheduling plan in the first stage can ensure safe operation in the pre- and post-contingency periods when considering wind power and load uncertainties. In the following, symbol “ Δ ” is used to represent periods of PR, PSR, and PLR.

1) Bilinear Master Problem (BMP)

The bilinear master problem at iteration w uses the objective function (1). In addition to these constraints of the first stage and (59), Benders infeasibility cuts returned from subproblems are included in the master problem. Constraint (61) shown at the bottom of this page represents the general expression of the returned Benders infeasibility cut when the subproblem in scenario s is not feasible. Note that $\hat{\lambda}_{\Delta,s,g,t}^{\tau,(k)}$, $\hat{\rho}_{\Delta,s,g,t}^{\tau,(k)}$, $\hat{\theta}_{\Delta,s,g,t}^{\tau,(k)}$, $\hat{\eta}_{\Delta,s,g,t}^{\tau,(k)}$, $\hat{\mu}_{\Delta,s,l,t}^{\tau,(k)}$, $\hat{\nu}_{\Delta,s,b,t}^{\tau,(k)}$, $\hat{\zeta}_{\Delta,s,b,t}^{\tau,(k)}$ and $\hat{o}_{\Delta,s,b,t}^{\tau,(k)}$ in (61) represent dual variables in the transfer equation of these decision variables $\hat{u}_{f,g,t}^{\tau}$, $\hat{P}_{f,g,t}^{\tau}$, $\hat{R}_{f,g,t}^{+, \tau}$, $\hat{R}_{f,g,t}^{-, \tau}$, $\hat{R}_{f,l,t}^{+, \tau}$, $\hat{R}_{f,l,t}^{-, \tau}$, $\hat{P}_{f,b,t}^{\tau}$, $\hat{Q}_{f,b,t}^{\tau}$, and $\hat{E}_{f,b,t}^{\tau}$ in the s -th scenario at the τ -th iteration, respectively. Bilinear terms (e.g., $u_{f,g,t} Z_s$) in (61) are further approximated by new variables and constraints based on the McCormick method, whose details can be found in Section III-A. Then, the bilinear master problem becomes a mixed integer linear programming problem, which can be easily solved by commercial solvers.

$$\begin{aligned} \hat{\varphi}_{\Delta,s}^{\tau,(k)} (1 - Z_s) + \sum_{t \in N_T} \left[\sum_{i \in \Omega^{\text{AC}}} \left(\sum_{g \in \Omega_i^{\text{G}}} \{ \hat{\lambda}_{\Delta,s,g,t}^{\tau,(k)} [u_{f,g,t} \right. \right. \\ - u_{f,g,t} Z_s - \hat{u}_{f,g,t}^{\tau} (1 - Z_s)] + \hat{\rho}_{\Delta,s,g,t}^{\tau,(k)} [P_{f,g,t} - P_{f,g,t} Z_s \\ - \hat{P}_{f,g,t}^{\tau} (1 - Z_s)] + \hat{\theta}_{\Delta,s,g,t}^{\tau,(k)} [R_{f,g,t}^{+} - R_{f,g,t}^{+} Z_s \\ - \hat{R}_{f,g,t}^{+, \tau} (1 - Z_s)] + \hat{\eta}_{\Delta,s,g,t}^{\tau,(k)} [R_{f,g,t}^{-} - R_{f,g,t}^{-} Z_s \\ - \hat{R}_{f,g,t}^{-, \tau} (1 - Z_s)] \} + \sum_{l \in \Omega_i^{\text{L}}} \{ \hat{\eta}_{\Delta,s,l,t}^{\tau,(k)} [R_{f,l,t}^{+} - R_{f,l,t}^{+} Z_s \\ - \hat{R}_{f,l,t}^{+, \tau} (1 - Z_s)] + \hat{\mu}_{\Delta,s,l,t}^{\tau,(k)} [R_{f,l,t}^{-} - R_{f,l,t}^{-} Z_s \\ - \hat{R}_{f,l,t}^{-, \tau} (1 - Z_s)] \} + \sum_{b \in \Omega_i^{\text{B}}} \{ \hat{\nu}_{\Delta,s,b,t}^{\tau,(k)} [P_{f,b,t} - P_{f,b,t} Z_s \\ - \hat{P}_{f,b,t}^{\tau} (1 - Z_s)] + \hat{\zeta}_{\Delta,s,b,t}^{\tau,(k)} [Q_{f,b,t} - Q_{f,b,t} Z_s \\ - \hat{Q}_{f,b,t}^{\tau} (1 - Z_s)] + \hat{o}_{\Delta,s,b,t}^{\tau,(k)} [E_{f,b,t} - E_{f,b,t} Z_s \\ - \hat{E}_{f,b,t}^{\tau} (1 - Z_s)] \} \} \right] \leq 0 \quad \forall n, \tau = 1, \dots, w-1 \end{aligned} \quad (61)$$

By solving the master problem, values of the first-stage decision variable, i.e., $\hat{u}_{f,g,t}^w$, $\hat{P}_{f,g,t}^w$, $\hat{R}_{f,g,t}^{+,w}$, $\hat{R}_{f,g,t}^{-,w}$, $\hat{R}_{f,l,t}^{+,w}$, $\hat{R}_{f,l,t}^{-,w}$, $\hat{P}_{f,b,t}^w$, $\hat{Q}_{f,b,t}^w$, $\hat{E}_{f,b,t}^w$ and Z_s^w , can be obtained. They will be passed to subproblems for checking the feasibility of the PR, PSR, and PLR states in the second stage.

2) Check Feasibility of the Subproblem for Each Scenario

The whole problem of the second stage in the s -th scenario at w -th iteration is divided into three feasibility check subproblems, i.e., feasibility check subproblem for pre-contingency rescheduling (FCS-PR _{s,w}), feasibility check subproblem for post-contingency short-term rescheduling (FCS-PSR _{s,w,k}),

and feasibility check subproblem for post-contingency long-term rescheduling (FCS-PLR_{s,w,k}).

Constraints of FCS-PR_{s,w}, FCS-PSR_{s,w,k}, and FCS-PLR_{s,w,k} have been shown in Section II.C, Section II.D, and Section II.E, respectively. In addition to these constraints, variable transfer equations ($x_{f,(\cdot),t} = \hat{x}_{f,(\cdot),t}^w$) between the first stage and the second stage are included in FCS-PR_{s,w}, FCS-PSR_{s,w,k}, and FCS-PLR_{s,w,k}. To ensure subproblems of the second stage are feasible, the non-negative slack variable-based method [25] is used to relax the AC power balance constraint, the voltage constraint, and the branch power constraint. Thus, relaxed constraints are used, and the objective functions of the three subproblems are the sum of corresponding non-negative variables, whose general expression is (62). If $\hat{\phi}_{\Delta,s}^{w,(k)}$ is larger than a preset threshold (ε), it means the corresponding subproblem is infeasible, given the solution from the first-stage in the s -th scenario at w -th iteration. Then, corresponding Benders infeasibility cuts will be generated and added to the master problem.

$$\begin{aligned} \min \hat{\phi}_{\Delta,s}^{w,(k)} = & \sum_{t \in N_T} \left[\sum_{i \in \Omega} \text{AC} \left(\phi_{\Delta,s,i,t}^{p,w,(k),+} + \phi_{\Delta,s,i,t}^{p,w,(k),-} \right. \right. \\ & + \phi_{\Delta,s,i,t}^{ac,v,w,(k),+} + \phi_{\Delta,s,i,t}^{ac,v,w,(k),-} \\ & \left. \left. + \sum_{j \in \Omega_i^{AC}} \phi_{\Delta,s,i,j,t}^{ac,l,w,(k),+} \right) \right. \\ & + \sum_{i \in \Omega} \text{DC} \left(\phi_{\Delta,s,i,t}^{dc,v,w,(k),+} + \phi_{\Delta,s,i,t}^{dc,v,w,(k),-} \right. \\ & \left. \left. + \sum_{j \in \Omega_i^{DC}} \phi_{\Delta,s,i,j,t}^{dc,l,w,(k),+} \right) \right] \quad (62) \end{aligned}$$

3) Iterative Procedure

As shown in Fig. 1, the basic iterative procedure for solving the proposed model is as follows:

Step 1) Initialization: set iteration counter (i.e., $w = 1$) and $\hat{Z}_s^w = 0$.

Step 2) BMP is solved to obtain the optimal solution of the first stage problem. If $w = 1$, obtain $\hat{u}_{f,g,t}^w$, $\hat{P}_{f,g,t}^w$, $\hat{R}_{f,g,t}^{+,w}$, $\hat{R}_{f,g,t}^{-,w}$, $\hat{R}_{f,l,t}^{+,w}$, $\hat{P}_{f,b,t}^w$, $\hat{Q}_{f,b,t}^w$, and $\hat{E}_{f,b,t}^w$; Otherwise, obtain $\hat{u}_{f,g,t}^w$, $\hat{P}_{f,g,t}^w$, $\hat{R}_{f,g,t}^{+,w}$, $\hat{R}_{f,g,t}^{-,w}$, $\hat{R}_{f,l,t}^{+,w}$, $\hat{R}_{f,l,t}^{-,w}$, $\hat{P}_{f,b,t}^w$, $\hat{Q}_{f,b,t}^w$, $\hat{E}_{f,b,t}^w$, and $\hat{Z}_s^w$. Then go to step 3). If BMP is infeasible, the proposed SUC model will be infeasible, and then the process will stop.

Step 3) For all scenarios with $\hat{Z}_s^w = 0$, FCS-PR_{s,w} needs to be checked for the solution of the first stage. For each scenario with $\hat{Z}_s^w = 0$, generate corresponding Benders Cut of FCS-PR_{s,w} when $\hat{\phi}_{n,s}^w \geq \varepsilon$. Then, update iteration $w=w+1$, add new cuts to generate the new BMP, and return to step 2). Otherwise, go to Step 4);

Step 4) If it is not the first time to have $\hat{\phi}_{n,s}^w \leq \varepsilon$, then go to Step 5); Otherwise, the value of $\hat{Z}_s^w$ will be fixed, and not changed in all subsequent iterations, and then go to step 5).

Step 5) For all scenarios with $\hat{Z}_s^w = 0$ and all contingencies, FCS-PSR_{s,w,k} needs to be checked for solution of the first stage. For each scenario with $\hat{Z}_s^w = 0$ and each

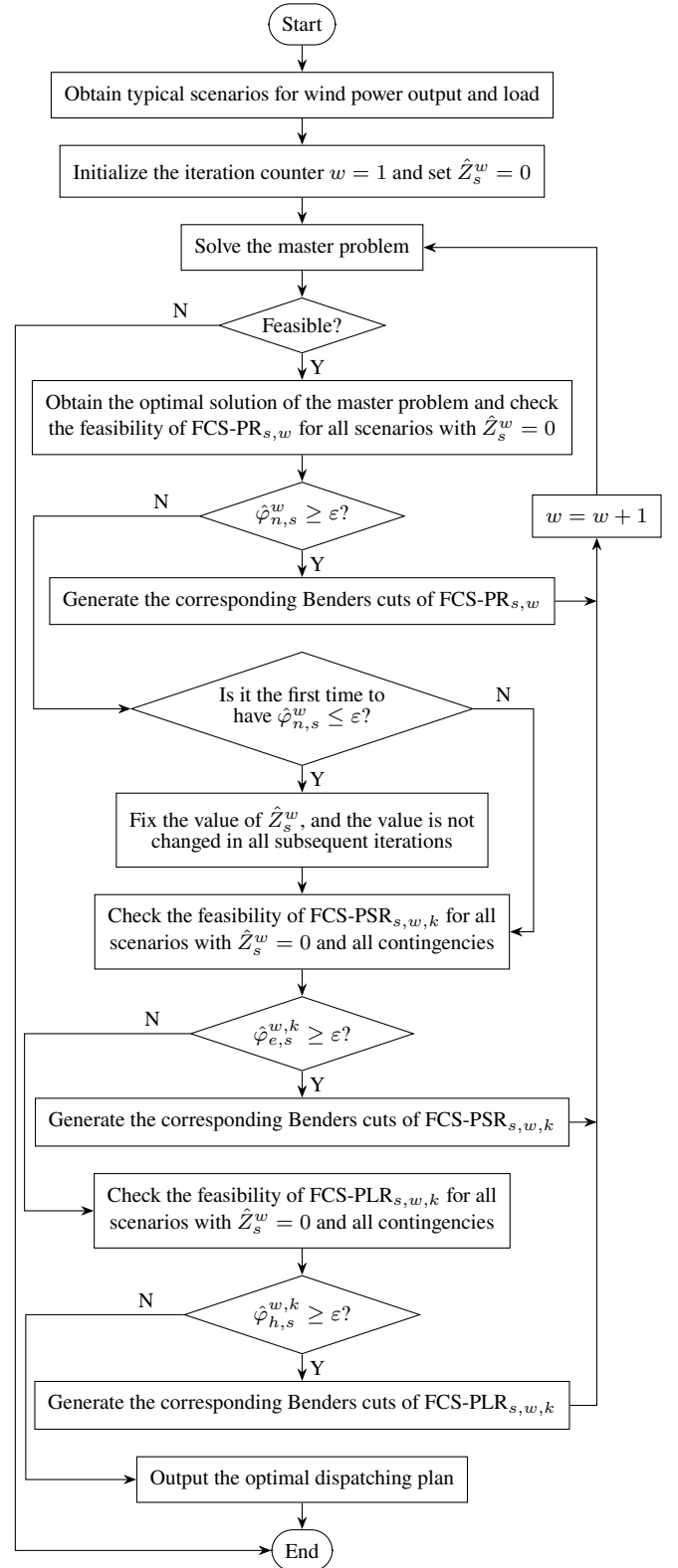


Fig. 1. Flowchart of the Bilinear Benders decomposition based method.

contingency, generate corresponding Benders cuts of FCS-PSR_{s,w,k} if $\hat{\phi}_{e,s}^w \geq \varepsilon$. Then, update iteration $w = w + 1$, add the new cuts to generate the new BMP, and return to step 2). If no new Benders cuts are generated, go to step 6).

Step 6): For all scenarios $\hat{Z}_s^w = 0$ and all contingencies,

FCS-PLR_{*s,w,k*} needs to be checked for the solution of the first stage. For each scenario with $\hat{Z}_s^w = 0$ and each contingency, generate corresponding Benders cuts of FCS-PLR_{*s,w,k*} when $\hat{\varphi}_{h,s}^{w,k} \geq \varepsilon$. Then, update iteration $w = w + 1$, add the new cuts to generate the new BMP, and return to step 2). If no new Benders cuts are generated in an iteration, then stop the process, and the solution of the latest BMP is the optimal solution of the proposed model.

IV. SIMULATION RESULTS

The proposed SUC model considering fast correction control has been tested on a modified IEEE 14-bus system and a modified IEEE 118-bus system using the software GAMS. Data of original IEEE 14-bus system and IEEE 118-bus system are obtained from MATPOWER [36]. Response time (τ_1) and ramping time (τ_2) of thermal generators are, respectively, assumed to be 5 minutes and 10 minutes [15]. The number of random scenarios and typical scenarios is set to 5000 and 10, respectively. Parameters of GCVSC are obtained from [11]. Branch long-term flow limits are set by using assumed values. Topology information of the DC system and other related parameters of the two modified systems are shown in the Appendix. In the modified IEEE 14-bus system, AC branch $BL_{(4,7)}$ is chosen as the pre-selected faulty branch. In the modified IEEE 118-bus system, AC branches $BL_{(24,70)}$, $BL_{(30,38)}$, $BL_{(40,42)}$, $BL_{(61,62)}$, $BL_{(82,96)}$ and the DC branch $BL_{(123,125)}$ are chosen as faulty branches, where $BL_{(i,j)}$ represents the branch connecting bus *i* and bus *j*.

A. Benefits of Proposed UC Approach

In order to clearly verify the effectiveness of the proposed method, four cases are used, which are shown in Table I. In this section, the confidence level is set to 90%.

1) Post-contingency Performance

Regarding the outage of line 4–7 at $t = 17$, Table II shows maximum loading rate (MLR) and number of insecure scenarios (NIS) with overloaded branch 7–9 in those scenarios with $Z_s = 0$ in the modified IEEE 14-bus system. Solution

TABLE I
ENVIRONMENT CONFIGURATIONS OF FOUR CASES

Case	Random factor	PSR	PLR	Active and reactive power control of the GCVSC and BSS
I	✓	×	×	✓
II	✓	×	✓	✓
III	✓	✓	✓	×
IV	✓	✓	✓	✓

*The symbols “✓” and “×”, respectively, indicate whether the factor is considered or not.

TABLE II
THE MLR AND NIS OF THE BRANCH 7–9 IN MODIFIED IEEE 14-BUS SYSTEM

Case	PR		PSR		PLR	
	NIS	MLR (p.u.)	NIS	MLR	NIS	MLR (p.u.)
I	0	0.6764	9	1.3003	9	1.3003
II	0	0.5896	5	1.1150	0	1.0000
III	0	0.5628	0	1.0937	0	0.9681
IV	0	0.5768	0	1.1000	0	1.0000

of Case II cannot completely avoid short-term overloading, although MLR of branch 7–9 produced by Case II has been reduced from 1.3003 to 1.1150 as compared with Case I. In contrast, post-contingency short-term overloading and long-term overloading can be avoided in all scenarios with $Z_s = 0$ in Cases III and IV. Fig. 2 shows voltage profiles in the post-contingency short-term period of those scenarios with $Z_s = 0$ at $t = 17$ in the modified IEEE 14-bus system. Buses 1–14 and Buses 15–18 belong to the AC system and the DC system, respectively. Buses 19–20 are the AC buses in the equivalent branch of GCVSC connected with buses 15 and 16 in DC grids, respectively. From Figs. 2(a) and 2(b), the minimum values of the bus voltage in Case I and Case II are 0.923 and 0.922, respectively, which are out of the allowable range. The maximum voltages in Cases I and II are 1.098 and 1.092, respectively, which are also out of the allowable range. Voltages of Cases III and IV shown in Figs. 2(c) and 2(d) are within limits. Average absolute deviation of voltage (ABDV) from its nominal value in Case III is 0.0165 p.u. while it is 0.0151 p.u. in Case IV. Therefore, active and reactive control ability of BSS and GCVSC can improve voltage profile during post-contingency short-term period.

Table III, Fig. 3 and Fig. 4 show the post-contingency performance of the proposed model in the modified IEEE 118-bus system when the AC branch $BL_{(24,70)}$ and the DC branch $BL_{(123,125)}$ are out of service. Post-contingency performance is analyzed based on maximum voltage (Max-Vol), minimum voltage (Min-Vol), number of voltage violations (Num-VV), number of overloaded branches (Num-OB), MLR, and ABDV. Similarly, in the modified IEEE 118-bus system, the solution of Case II cannot completely avoid the post-contingency short-term overloading and voltage violation. Only the solution of Cases III and IV can ensure safe operation in all post-contingency periods, especially in the post-contingency short-term period. Furthermore, the average absolute deviation of voltage from its nominal value in Case III is larger than in

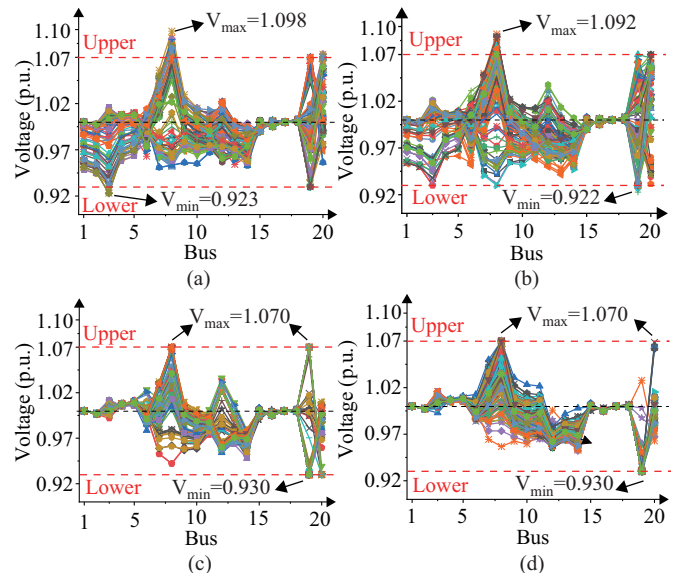


Fig. 2. The voltage profile of modified IEEE 14-bus system in the post-contingency short-term period. (a) Case I. (b) Case II. (c) Case III. (d) Case IV.

TABLE III
THE MAXIMUM VOLTAGE AND THE MINIMUM VOLTAGE IN MODIFIED
IEEE 118-BUS SYSTEM

Contingency	Stage	Type	Case I	Case II	Case III	Case IV
$BL_{(24,70)}$	PSR	Max-Vol (p.u.)	1.113	1.105	1.100	1.100
		Min-Vol (p.u.)	0.884	0.894	0.900	0.900
		Num-VV	2	2	0	0
		Num-OB	3	2	0	0
	PLR	Max-Vol (p.u.)	1.110	1.100	1.100	1.100
		Min-Vol (p.u.)	0.891	0.900	0.900	0.900
		Num-VV	2	0	0	0
		Num-OB	3	0	0	0
$BL_{(123,125)}$	PSR	Max-Vol (p.u.)	1.128	1.100	1.100	1.100
		Min-Vol (p.u.)	0.876	0.885	0.900	0.900
		Num-VV	4	3	0	0
		Num-OB	3	2	0	0
	PLR	Max-Vol (p.u.)	1.109	1.100	1.100	1.100
		Min-Vol (p.u.)	0.887	0.900	0.900	0.900
		Num-VV	4	0	0	0
		Num-OB	3	0	0	0

Case IV, indicating the advantage of considering the active and reactive control ability of the BSS and GCVSC.

2) Cost Comparison

Figure 5 compares operating cost and calculation time of the four cases in the two modified systems under different confidence levels (CL). By comparing results of Cases III and IV, it is clear total cost can be reduced if fast active and reactive control of the GCVSC and BSS is considered in the post contingency short-term period. Total costs are smaller in Cases I and II. However, as shown in Figs. 2, and 3, Table II and III, post contingency short-term security problems (e.g., overloading and voltage violation) are caused in two cases. In addition, it also shows total operational cost is increased

TABLE IV
RESULTS OF BI_BD AND CPLEX_BIGM

Test systems	CL	Bi-BD		CPLEX_BigM [17]	
		Cost (\$)	Time (sec.)	Cost (\$)	Time (sec.)
Modified IEEE-14	90%	100665.1	423.6	98767.1	17062.3
	80%	100079.5	548.7	98017.7	35673.9
	70%	99684.8	514.3	97251.5	41194.6
	60%	98589.1	486.0	96430.4	34581.4
Modified IEEE-118	90%	2399013.1	12994.8	—	—
	80%	2382573.4	14834.7	—	—
	70%	2374629.2	16535.2	—	—
	60%	2361765.5	15123.4	—	—

with rise of confidence level in the same case. Meanwhile, calculation time of Case IV considering fast control of GCVSC and BSS is much longer than other Cases.

B. Computational Performance Test

Table IV shows calculation results and computational time in the modified IEEE 14-bus system and modified IEEE 118-bus system by using the CPLEX_BigM based method and the Bi-BD based method under different confidence levels. As shown in Table IV, under the same confidence level, convergence speed has been improved at least 40 times by the proposed method in the modified IEEE 14-bus system. Also, the cost difference between these two methods does not exceed 2.5% in the modified IEEE 14-bus system. This indicates accuracy levels of the two methods are similar. When the time limit is set to 7 hours, there is no solution given by the CPLEX_BigM method for the modified IEEE 118-bus system. In contrast, the Bi-BD based method can find the solution within 5 hours for the modified IEEE 118-bus system.

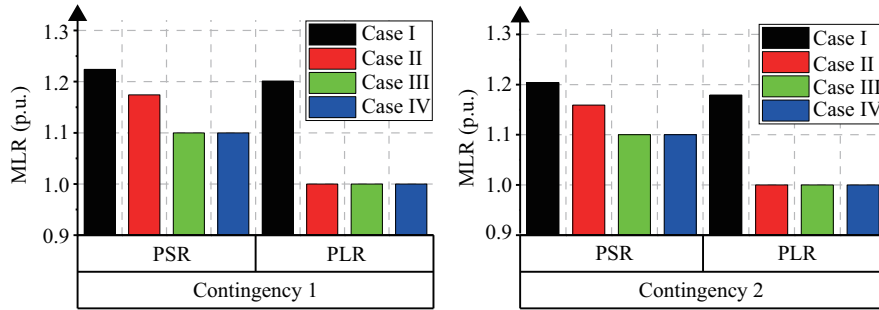


Fig. 3. The MLR of different cases in the modified IEEE 118-bus system. Contingency 1: outage of $BL_{(24,70)}$; Contingency 2: outage of $BL_{(123,125)}$.

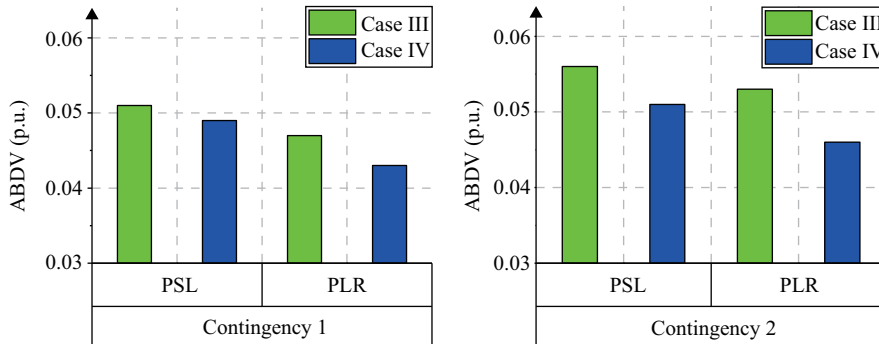


Fig. 4. The ABDV of case III and case IV in modified IEEE 118-bus system. Contingency 1: outage of $BL_{(24,70)}$; Contingency 2: outage of $BL_{(123,125)}$.

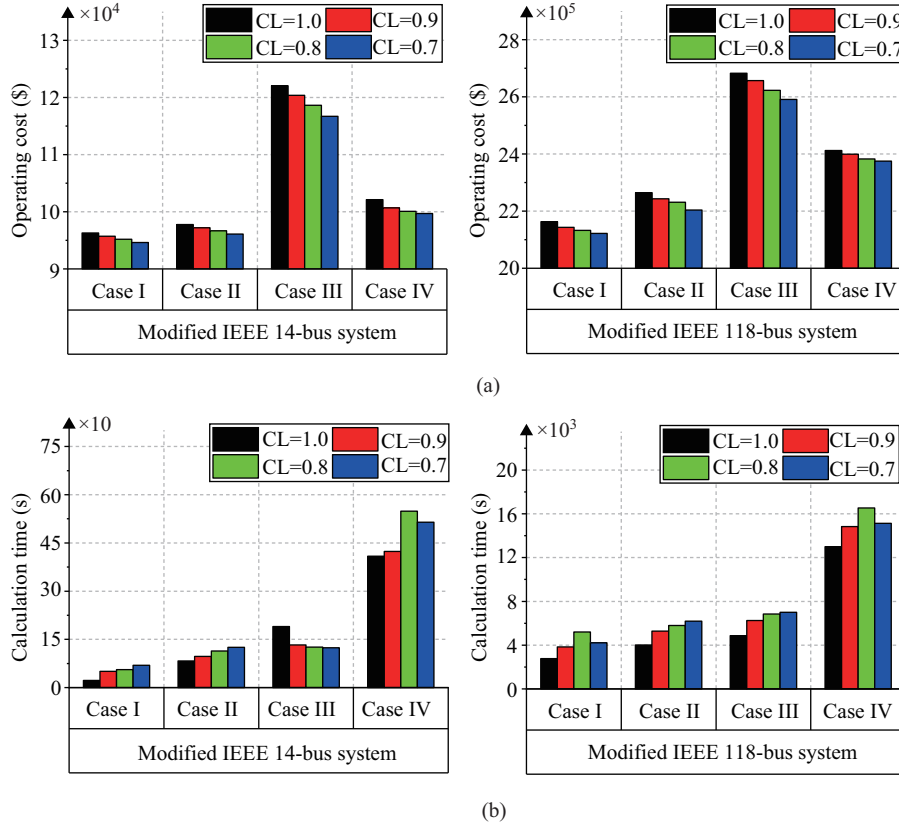


Fig. 5. The operating cost and calculation time of different cases in the two modified system under different confidence levels. (a) Operating cost. (b) Calculation time.

V. CONCLUSION

Focusing on large-scale offshore wind power in hybrid power systems, this paper presents a stochastic UC model considering fast VSC and BSS corrective control in $N - 1$ security operation. By adopting both active and reactive power control in the proposed model, branch overloading and voltage violations can be avoided during the post-contingency period, especially in the post-contingency short-term period. The bilinear Benders decomposition based method is employed to solve the proposed SUC model. Finally, simulation results on the modified IEEE 14-bus system and modified IEEE 118-bus system indicate the proposed method can provide a highly effective unit commitment solution with post-contingency short-term and long-term corrective actions.

APPENDIX

TABLE AI
CONNECTION RELATIONSHIP OF GCVSC AND WIND FARMS

Test systems	Connection relationship of GCVSC			Location of offshore wind farm
	No.	From DC bus	To AC bus	
Modified IEEE-14	1	15	9	17, 18
	2	16	12	
Modified IEEE-118	1	119	66	122, 123, 124, 125, 126
	2	120	41	
	3	121	53	
	4	122	12	

TABLE AII
RELEVANT PARAMETER OF THE SIMULATION SYSTEMS

Public Parameters					
$\tau_1 = 5 \text{ min}$	$\tau_2 = 10 \text{ min}$	$H = 1.1$	$\eta_{cha,b} = 0.94$	$\eta_{dis,b} = 0.90$	
$E_{b,min} = 0.2$	$E_{b,rate}$	$E_{b,max} = 0.9$	$E_{b,rate}$	$DP_{b,max} = CP_{b,max}$	
Modified IEEE 14-bus system					
$G_{15,17}^{dc} = 20 \text{ p.u.}$	$G_{16,17}^{dc} = 25 \text{ p.u.}$	$G_{16,18}^{dc} = \frac{1}{0.06} \text{ p.u.}$			
$G_{17,18}^{dc} = 25 \text{ p.u.}$	$R_{4,t,max}^{\pm} = 0.5 P_{4,t}$	$R_{9,t,max}^{\pm} = 0.5 P_{9,t}$			
$R_{14,t,max}^{\pm} = 0.5 P_{14,t}$	$E_{7,rate} = 20 \text{ MWh}$	$E_{11,rate} = 20 \text{ MWh}$			
$DP_{7,max} = 7 \text{ MW}$	$DP_{11,max} = 7 \text{ MW}$	$S_{7,max} = 7 \text{ MVA}$			
$S_{11,max} = 7 \text{ MVA}$	$S_{1,max}^{conv} = 20 \text{ MVA}$	$S_{2,max}^{conv} = 20 \text{ MVA}$			
$U_{i,min}^{ac} = 0.93 \text{ p.u.}$		$U_{i,max}^{ac} = 1.07 \text{ p.u.}$			
$U_{i,min}^{dc} = 0.90 \text{ p.u.}$		$U_{i,max}^{dc} = 1.10 \text{ p.u.}$			
Modified IEEE 118-bus system					
$G_{122,126}^{dc} = \frac{1}{0.06} \text{ p.u.}$	$G_{121,126}^{dc} = \frac{1}{0.06} \text{ p.u.}$	$G_{120,124}^{dc} = \frac{1}{0.06} \text{ p.u.}$			
$G_{120,125}^{dc} = 20 \text{ p.u.}$	$G_{121,125}^{dc} = 25 \text{ p.u.}$	$G_{119,124}^{dc} = 25 \text{ p.u.}$			
$G_{119,123}^{dc} = 20 \text{ p.u.}$	$G_{123,125}^{dc} = 25 \text{ p.u.}$	$G_{124,126}^{dc} = 25 \text{ p.u.}$			
$R_{15,t,max}^{\pm} = 0.5 P_{15,t}$	$R_{27,t,max}^{\pm} = 0.5 P_{27,t}$	$R_{49,t,max}^{\pm} = 0.5 P_{49,t}$			
$R_{54,t,max}^{\pm} = 0.5 P_{54,t}$	$R_{59,t,max}^{\pm} = 0.5 P_{59,t}$	$R_{80,t,max}^{\pm} = 0.5 P_{80,t}$			
$R_{90,t,max}^{\pm} = 0.5 P_{90,t}$	$R_{116,t,max}^{\pm} = 0.5 P_{116,t}$	$E_{44,rate} = 50 \text{ MW}$			
$E_{63,rate} = 50 \text{ MWh}$	$E_{69,rate} = 50 \text{ MWh}$	$E_{117,rate} = 50 \text{ MWh}$			
$DP_{44,max} = 17.5 \text{ MW}$	$DP_{63,max} = 17.5 \text{ MW}$	$DP_{69,max} = 17.5 \text{ MW}$			
$DP_{117,max} = 17.5 \text{ MW}$	$S_{44,max} = 17.5 \text{ MVA}$	$S_{63,max} = 17.5 \text{ MVA}$			
$S_{69,max} = 17.5 \text{ MVA}$	$S_{117,max} = 17.5 \text{ MVA}$	$S_{1,max}^{conv} = 100 \text{ MVA}$			
$S_{2,max}^{conv} = 100 \text{ MVA}$	$S_{3,max}^{conv} = 100 \text{ MVA}$	$S_{4,max}^{conv} = 100 \text{ MVA}$			
$U_{i,min}^{ac} = 0.90 \text{ p.u.}$		$U_{i,max}^{ac} = 1.10 \text{ p.u.}$			
$U_{i,min}^{dc} = 0.90 \text{ p.u.}$		$U_{i,max}^{dc} = 1.10 \text{ p.u.}$			

REFERENCES

- [1] A. Al-Hinai, Y. Charabi, and S. H. Aghay Kaboli, "Offshore wind energy resource assessment across the territory of Oman: A spatial-temporal

- data analysis," *Sustainability*, vol. 13, no. 5, pp. 2862, Mar. 2021.
- [2] S. H. Wu, Y. X. Zhang, B. Zhang, L. Qi, "A low-cost and low-ripple DC chopper with thyristors-based switch modules and flexible switching control strategy for the offshore wind VSC-HVDC system," *CSEE Journal of power and energy system*, doi: 10.17775/CSEEJPES.2024.01100.
 - [3] Y. Q. Dong, K. Q. Sun, J. N. Wang, S. L. Wang, H. Huang, T. Q. Liu, and Y. L. Liu, "Time-delay correction control strategy for HVDC frequency regulation services," *CSEE Journal of Power and Energy Systems*, vol. 10, no. 5, pp. 2027–2037, Sep. 2024, doi: 10.17775/CSEEJPES.2021.02770.
 - [4] X. Y. Feng, S. J. Lin, W. B. Liu, W. K. Liang and M. B. Liu, "Distributionally robust optimal dispatch of offshore wind farm cluster connected by VSC-MTDC considering wind speed correlation," *CSEE Journal of Power and Energy Systems*, vol. 9, no. 3, pp. 1021–1035, May 2023.
 - [5] A. Nikoobakht, J. Aghaei, T. Niknam, V. Vahidinasab, H. Farahmand, and M. Korpás, "Towards robust OPF solution strategy for the future AC/DC grids: case of VSC-HVDC-connected offshore wind farms," *IET Renewable Power Generation*, vol. 12, no. 6, pp. 691–701, Apr. 2018.
 - [6] S. Rahman, I. Khan, H. I. Alkhamash, and M. F. Nadeem, "A comparison review on transmission mode for onshore integration of offshore wind farms: HVDC or HVAC," *Electronics*, vol. 10, no. 12, pp. 1489, Jun. 2021.
 - [7] W. Y. Wang, A. Beddard, M. Barnes, and O. Marjanovic, "Analysis of active power control for VSC-HVDC," *IEEE Transactions on Power Delivery*, vol. 29, no. 4, pp. 1978–1988, Aug. 2014.
 - [8] C. Y. Guo and C. Y. Zhao, "Supply of an entirely passive AC network through a double-infeed HVDC system," *IEEE Transactions on Power Electronics*, vol. 25, no. 11, pp. 2835–2841, Nov. 2010.
 - [9] Y. Xu, Z. Y. Dong, R. Zhang, K. P. Wong, and M. Y. Lai, "Solving preventive-corrective SCOPF by a hybrid computational strategy," *IEEE Transactions on Power Systems*, vol. 29, no. 3, pp. 1345–1355, May 2014.
 - [10] I. A. Smadi, S. Albatran, M. Q. Alathamneh, and M. I. Alomoush, "Security-constrained economic dispatch with linear/nonlinear energy sources during short-term emergency period," *International Journal of Renewable Energy Research-IJRER*, vol. 8, no. 1, pp. 129–140, Mar. 2018.
 - [11] J. Cao, W. Du, and H. F. Wang, "An improved corrective security constrained OPF for meshed AC/DC grids with multi-terminal VSC-HVDC," *IEEE Transactions on Power Systems*, vol. 31, no. 1, pp. 485–495, Jan. 2016.
 - [12] D. A. Tejada-Arango, P. Sánchez-Martín, and A. Ramos, "Security constrained unit commitment using line outage distribution factors," *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 329–337, Jan. 2018.
 - [13] X. Zhu, Z. C. Yu, and X. Liu, "Security constrained unit commitment with extreme wind scenarios," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 3, pp. 464–472, May 2020.
 - [14] F. Safdarian, A. Mohammadi, and A. Kargarian, "Temporal decomposition for security-constrained unit commitment," *IEEE Transactions on Power Systems*, vol. 35, no. 3, pp. 1834–1845, May 2020.
 - [15] Y. F. Wen, C. X. Guo, H. Pandžić, and D. S. Kirschen, "Enhanced security-constrained unit commitment with emerging utility-scale energy storage," *IEEE Transactions on Power Systems*, vol. 31, no. 1, pp. 652–662, Jan. 2016.
 - [16] Y. F. Guo, H. L. Gao, H. Xing, Q. W. Wu, and Z. W. Lin, "Decentralized coordinated voltage control for VSC-HVDC connected wind farms based on ADMM," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 800–810, Apr. 2019.
 - [17] N. Good, K. A. Ellis, and P. Mancarella, "Review and classification of barriers and enablers of demand response in the smart grid," *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 57–72, May 2017.
 - [18] N. G. Paterakis, O. Erdinc, and J. P. S. Catalão, "An overview of demand response: key-elements and international experience," *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 871–891, Mar. 2017.
 - [19] Z. Chen, L. Y. Wang, C. X. Guo, G. Ma, and J. J. Zhang, "Robust optimization of multiple reserve resources considering reserve capacity of wind power and demand response," *Automation of Electric Power Systems*, vol. 44, no. 10, pp. 50–58, May 2020.
 - [20] Y. P. Dong, X. R. Xie, K. Wang, B. R. Zhou, and Q. R. Jiang, "An emergency-demand-response based under speed load shedding scheme to improve short-term voltage stability," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 3726–3735, Sep. 2017.
 - [21] I. Blanco and J. M. Morales, "An efficient robust solution to the two-stage stochastic unit commitment problem," *IEEE Transactions on Power Systems*, vol. 32, no. 6, pp. 4477–4488, Nov. 2017.
 - [22] V. Tumuluru and Danny H. K. Tsang, "A two-stage approach for network constrained unit commitment problem with demand response," *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 1175–1183, Mar. 2018.
 - [23] T. Ding, Z. Y. Zeng, M. Qu, J. P. S. Catalao, and M. Shahidehpour, "Two-stage chance-constrained stochastic thermal unit commitment for optimal provision of virtual inertia in wind-storage systems," *IEEE Transactions on Power Systems*, vol. 36, no. 4, pp. 3520–3530, Jul. 2021.
 - [24] K. Sundar, H. Nagarajan, L. Roald, S. Misra, R. Bent, and D. Bienstock, "Chance-constrained unit commitment with $N - 1$ security and wind uncertainty," *IEEE Transactions on Control of Network Systems*, vol. 6, no. 3, pp. 1062–1074, Sep. 2019.
 - [25] Y. Zhang, J. X. Wang, B. Zeng, and Z. C. Hu, "Chance-constrained two-stage unit commitment under uncertain load and wind power output using bilinear benders decomposition," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 3637–3647, Sep. 2017.
 - [26] Z. Chen, Z. S. Li, C. X. Guo, Y. Ding, and Y. B. He, "Two-stage chance-constrained unit commitment based on optimal wind power consumption point considering battery energy storage," *IET Generation, Transmission & Distribution*, vol. 14, no. 18, pp. 3738–3749, Sep. 2020.
 - [27] Z. F. Yang, H. W. Zhong, Q. Xia, and C. Q. Kang, "Solving OPF using linear approximations: fundamental analysis and numerical demonstration," *IET Generation, Transmission & Distribution*, vol. 11, no. 17, pp. 4115–4125, Nov. 2017.
 - [28] R. Wiget and G. Andersson, "DC optimal power flow including HVDC grids," *Proceedings of 2013 IEEE Electrical Power & Energy Conference*, 2013, pp. 1–6.
 - [29] J. Beerten, S. Cole, and R. Belmans, "A sequential AC/DC power flow algorithm for networks containing Multi-terminal VSC HVDC systems," *Proceedings of IEEE PES General Meeting*, 2010, pp. 1–7.
 - [30] B. Jacobson, P. Karlsson, G. Asplund, L. Harnefors, and T. Jonsson, "VSC-HVDC transmission with cascaded two-level converters," *Proceedings of the 43rd International Conference on Large High Voltage Electric Systems 2010*.
 - [31] A. Gabash and P. Li, et al, "Active-reactive optimal power flow in distribution networks with embedded generation and battery storage," *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 2026–2035, Nov. 2012.
 - [32] Y. Tan, Y. Li, Y. J. Cao, and M. Shahidehpour, "Integrated optimization of network topology and DG outputs for MVDC distribution systems," *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 1121–1123, Jan. 2018.
 - [33] H. Ahmadi and J. R. Martí, "Linear current flow equations with application to distribution systems reconfiguration," *IEEE Transactions on Power Systems*, vol. 30, no. 4, pp. 2073–2080, Jul. 2015.
 - [34] L. Dong, M. X. Liu, N. S. Chen, S. X. Fan, and T. J. Pu, "Coordinated optimal control of distributed energy based on stochastic model predictive control," *Power System Technology*, vol. 42, no. 10, pp. 3219–3226, Oct. 2018.
 - [35] H. Xie, H. Chen, X. Y. Deng, P. Zhang, and Q. Sun, "Electric-gas integrated energy system operational risk assessment based on improved k-means clustering technology and semi-invariant method," *Proceedings of the CSEE*, vol. 40, no. 1, pp. 59–69, Jan. 2020.
 - [36] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, "MATPOWER: steady-state operations, planning, and analysis tools for power systems research and education," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 12–19, Feb. 2011.

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