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Consensus-Based Coordinated Frequency Regulation for VSC-HVDC Interconnected Power Systems with Heterogeneous Resources

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ABSTRACT

As converter-interfaced renewable generation continues to increase, voltage-source-converter-based high-voltage direct current (VSC-HVDC) interconnected power systems suffer from reduced inertia, heterogeneous frequency responses, and limited inter-area frequency support. To address these issues, this paper proposes a consensus-based coordinated frequency regulation method for VSC-HVDC interconnected power systems with heterogeneous frequency regulation resources (HFRRs). Firstly, a unified multi-area frequency response model is developed to characterize the coordinated dynamics of synchronous generators (SG), grid-forming converters (GFM), grid-following converters (GFL), and VSC-HVDC links, where VSC-HVDC links are modeled as dual-role agents providing both local frequency support and inter-area power coordination. Then, a two-layer consensus control method is developed according to the multiple frequency regulation process. At the resource layer, a frequency-deviation-driven consensus algorithm coordinates inertial response and primary frequency regulation among HFRRs to provide fast intra-area support after disturbances. At the area layer, the consensus algorithm coordinates VSC-HVDC power transmission and secondary frequency regulation power distribution to achieve steady-state frequency recovery. Furthermore, frequency security indicators and operational constraints on HFRRs are incorporated into the iterative control process. Finally, case studies on a modified IEEE 39-bus three-area VSC-HVDC interconnected system demonstrate that the proposed method improves transient frequency performance and reduces regulation cost.

Keywords: Heterogeneous frequency regulation resources; Consensus algorithm; VSC-HVDC interconnection; Frequency security; Frequency regulation cost

1. Introduction

As renewable energy penetration continues to increase, power-system frequency stability is shifting from a synchronous-generator-dominated regime to a converter-interfaced regime involving the hybrid or dominant participation of power electronic devices **Error! Reference source not found.**[2]. For multi-area renewable power systems interconnected through voltage-source-converter-based high-voltage direct current (VSC-HVDC), asynchronous interconnection and the large-scale integration of converter-based renewable generation result in reduced system rotational inertia and weakened frequency support, making it difficult for conventional centralized frequency regulation methods to satisfy frequency stability requirements. To address these challenges, regional coordination among diverse frequency-regulation resources and controllable VSC-HVDC links has become an important approach to enhancing system frequency support capability [3][4]. Therefore, how to realize efficient coordination and economic dispatch of HFRRs while ensuring frequency security has become a key problem in the frequency regulation of VSC-HVDC interconnected power systems.

Owing to the pronounced differences among HFRRs in dynamic models, response speeds, and control characteristics [5], existing methods mainly focus on the

frequency-support capability of specific resources or local control loops [6]. For intra-area coordination of HFRRs, [7] classifies generation resources into synchronous generators (SGs), grid-forming converters (GFMs), and grid-following converters (GFLs) according to their frequency response characteristics, and related studies have begun to explore coordinated control strategies [8],[9]. For inter-area VSC-HVDC control, [10] shows that VSC-HVDC links can provide frequency support at both sending and receiving ends through virtual inertia, droop control, and other auxiliary control schemes, thus enhancing the dynamic frequency performance of low-inertia systems. However, existing studies have rarely addressed the combined frequency-support effects of HFRRs and VSC-HVDC, and their coordinated control remains insufficiently investigated [11][13].

Consensus algorithms have been widely applied in distributed economic dispatch, secondary frequency control, and multi-agent coordinated regulation because they require only local communication and exhibit good scalability and robustness. [14] theoretically proves that the convergence of consensus algorithms under communication delays can be guaranteed by selecting sufficiently small gain parameters. Regarding agent heterogeneity, [15] first incorporates battery energy storage systems into economic dispatch while maintaining power balance. Although the heterogeneity of HFRRs has been recognized in consensus-based control studies, most existing methods are still

designed either for homogeneous agents [16] or for only a single control layer, such as the resource layer [17] or the area layer [18]. Consequently, the coupling among multiple regulation processes, inter-area VSC-HVDC power coordination, and multi-area interactions across multiple timescales has not been adequately addressed, which limits the ability of these methods to jointly ensure frequency stability and economic dispatch in multi-area VSC-HVDC interconnected power systems.

In summary, although substantial progress has been achieved in the coordination of HFRRs, VSC-HVDC-based frequency support, and consensus-based distributed control, a unified coordinated frequency regulation method is still lacking for multi-area VSC-HVDC interconnected power systems with HFRRs, particularly one that simultaneously captures resource heterogeneity, multi-timescale frequency response and inter-area mutual support. To address this gap, this paper proposes a consensus-based coordinated frequency regulation method for VSC-HVDC interconnected power systems with HFRRs.

The main contributions of this work are summarized as follows:

(1) A unified multi-area frequency response model is established for VSC-HVDC interconnected power systems with HFRRs. SGs, GFM, GFLs and VSC-HVDC links are incorporated into a common modeling framework, in which VSC-HVDC is represented as a dual-role mechanism providing both local frequency support and inter-area power coordination. This model captures the coupling among disturbance power imbalance, area frequency dynamics and inter-area power exchange.

(2) A two-layer consensus-based coordinated frequency regulation method is proposed for heterogeneous multi-agent systems. At the resource layer, a frequency-deviation-driven consensus algorithm coordinates inertial response and primary frequency regulation among HFRRs to provide fast intra-area support. At the area layer, an area control error (ACE)-corrected consensus algorithm coordinates VSC-HVDC transmission power and secondary regulation power to achieve steady-state frequency recovery and economic inter-area support.

(3) A frequency-security and constraint-aware framework is developed for the proposed two-layer consensus-based frequency regulation method. Rates of change of frequency (RoCoF), frequency nadir and steady-state frequency deviation are incorporated as frequency security requirements, while the operating limits of regulation resources and VSC-HVDC links are embedded into the iterative control process. Case studies on a modified IEEE 39-bus three-area VSC-HVDC interconnected system demonstrate the effectiveness, economic performance, and robustness of the proposed method under disturbances and communication failures.

2. A multi-area frequency response model with HFRRs and VSC-HVDC

During transients, the frequency responses of different buses in a power system may present different frequency

nadirs and RoCoF [7]. Therefore, for VSC-HVDC interconnected power systems with HFRRs, it is particularly important to establish an area-layer or system-layer frequency response model. The schematic diagram of the VSC-HVDC interconnected power system is shown in Fig. 1.

This section first establishes a single-area frequency response model with HFRRs, together with the VSC-HVDC system model and the multi-terminal VSC-HVDC frequency regulation model. Based on these models, a multi-area frequency response model is then developed.

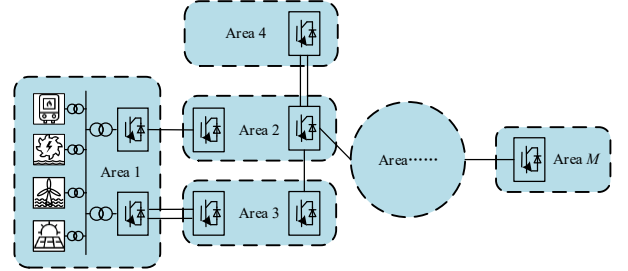


Fig. 1. Schematic diagram of the VSC-HVDC interconnected grid

2.1 Modeling of heterogeneous frequency regulation resources

To uniformly characterize the roles of different grid-connected resources in inertial response, primary frequency control and secondary frequency control, the method in [19] is adopted to establish the frequency response models of SG, GFM and GFL. The equivalent roles of these three types of frequency regulation resources in different regulation stages are illustrated in Fig. 2.

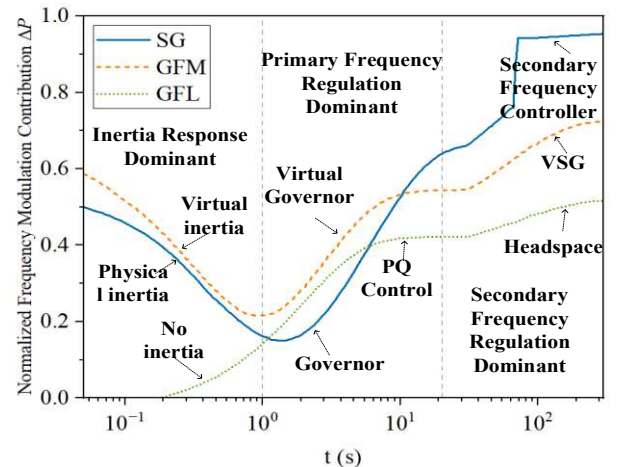


Fig. 2. Schematic comparison of the roles of the three types of frequency regulation resources in the frequency response process

(1) Frequency Response Model of the SG

The rotor mechanical angular speed of an SG is naturally coupled with system frequency, which enables a physical inertia response. When an active power imbalance occurs, the SG can release or absorb rotor kinetic energy to suppress the rate of change of frequency and thus mitigate frequency deviation. Moreover, frequency deviation triggers the governor action of the SG, which automatically adjusts the mechanical power according to the droop coefficient to provide primary frequency regulation. The

corresponding frequency response model is expressed as follows:

$$\Delta P_{sg} = \Delta P_{sg,0} + \Delta P_{sg,1} = -H_{sg} \frac{d\Delta\omega_{sg}}{dt} - \frac{\Delta\omega_{sg}}{R_{sg}} \quad (1)$$

where: H_{sg} is the inertia time constant, R_{sg} is the primary frequency regulation coefficient.

The corresponding closed-loop transfer function is shown in (2).

$$G_{sg}(s) = (sH_{sg} + D_{sg}) + \frac{K_{sg}(1 + sF_{sg}T_{sg})}{R_{sg}(1 + sT_{sg})} \quad (2)$$

where: D_{sg} , K_{sg} and F_{sg} are the damping coefficient, power gain coefficient and power fraction of SG, respectively.

The secondary frequency regulation of an SG is typically realized through automatic generation control (AGC). According to the frequency deviation and tie-line power deviation, the dispatch center issues control commands to regulating units to modify their power reference values, thereby restoring the system frequency to its nominal value without steady-state error.

(2) Frequency Response Model of the GFM

GFMs do not possess physical rotational inertia, but can provide virtual inertia through voltage-source control strategies such as V/f control, P-f droop control and virtual synchronous generator (VSG) control. Unlike GFL, GFM resources do not rely on a phase-locked loop (PLL) to track the external grid phase and therefore can provide stronger frequency and voltage support under weak-grid or low-short-circuit-ratio conditions. The corresponding frequency response model of the GFM is expressed as follows:

$$\Delta P_{GFM} = \Delta P_{GFM,0} + \Delta P_{GFM,1} = -H_{GFM} \frac{d\Delta\omega_{GFM}}{dt} - D_{GFM} \Delta\omega_{GFM} \quad (3)$$

where: H_{GFM} is the virtual inertia coefficient of the GFM, which exhibits a fast response and can be adjusted through control algorithms; D_{GFM} is the virtual damping coefficient, which can also be flexibly modified online.

The corresponding closed-loop transfer function is shown in (4).

$$G_{GFM}(s) = \frac{sH_{GFM} + D_{GFM}}{1 + sT_{GFM}} \quad (4)$$

GFM can accurately track and execute AGC instructions, and participate in secondary frequency modulation independently through droop and distributed secondary control [20][21].

(3) Frequency Response Model of the GFL

In contrast, GFL resources are synchronized through a PLL and typically employ current-source control to regulate active/reactive power or current commands. They are well established under strong-grid conditions and provide clear dispatch interfaces. GFL resources can participate in primary frequency regulation by incorporating additional fast frequency response or power droop loops, although their performance in weak grids may be limited by PLL stability and current-limiting constraints. The corresponding

frequency response model of the GFL is expressed as follows:

$$\Delta P_{GFL} = \Delta P_{GFL,1} = -D_{GFL} \cdot \Delta\omega_{GFL} \quad (5)$$

where: D_{GFL} is the droop coefficient of the GFL.

The corresponding closed-loop transfer function is shown in (6).

$$G_{GFL}(s) = \frac{D_{GFL}}{1 + sT_{GFL}} \quad (6)$$

GFL indirectly participates in secondary frequency regulation through reserved capacity, AGC command tracking and emulated distributed consistent synchronous output [22]. Such participation is typically conditional on reserved capacity and control design. To enhance performance and reliability, GFL is usually coordinated with energy storage systems.

2.2 Frequency response model of a single area

Different types of resources exhibit significant differences in dynamic response characteristics, control modes and frequency regulation capabilities. To effectively integrate these resources into a coordinated frequency regulation method, a unified frequency regulation model is required to characterize their frequency response behaviors and power regulation capabilities.

For the purpose of resource-layer coordination, the fast frequency response of each resource is further represented by a first-order equivalent form.

$$\Delta P_i(s) = -\left(\frac{1}{R_i} + H_i s\right) \Delta f(s) \quad (7)$$

The aggregated power adjustment can be expressed as follows:

$$\Delta P_{total,\alpha} = \sum_{i \in V_\alpha} \Delta P_i \quad (8)$$

where: $V_\alpha = \{SG, GFM, GFL\}$ denotes the set of frequency regulation resources in area α and H_i is set to 0 for GFL resources without inertial response.

For a single area, Fig. 3 presents a frequency response model consisting of SG, GFM and GFL resources. In this model, the GFM adopts the VSG control method, through which the effects of inertia support and primary frequency regulation in virtual synchronous control are represented from the perspective of control performance.

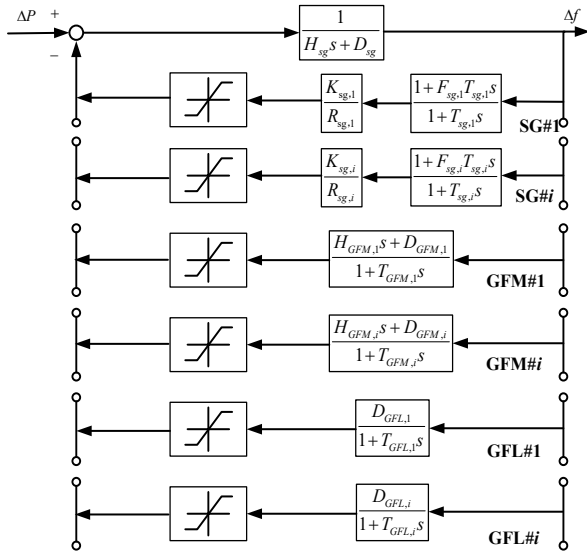


Fig. 3. Frequency response model of a single-area power system

The closed-loop transfer function of the system shown in Fig. 3 is given as follows:

$$G_i(s) = \frac{\Delta f_i(s)}{\Delta P_i(s)} = \left\{ (sH_{sg} + D_{sg}) + \sum_{sg \in V_\alpha} \frac{K_{sg} (1 + sF_{sg} T_{sg})}{R_{sg} (1 + sT_{sg})} + \underbrace{\sum_{GFM \in V_\alpha} \frac{sH_{GFM} + D_{GFM}}{1 + sT_{GFM}}}_{GFM_s} + \underbrace{\sum_{GFL \in V_\alpha} \frac{D_{GFL}}{1 + sT_{GFL}}}_{GFL_s} \right\}^{-1} \quad (9)$$

The base capacity of area α is denoted by $S_{base,\alpha}$ and is expressed as follows:

$$S_{base,\alpha} = \sum_{SG \in V_\alpha} S_{SG} + \sum_{GFM \in V_\alpha} S_{GFM} + \sum_{GFL \in V_\alpha} S_{GFL} \quad (10)$$

To describe the system frequency dynamics in a more

tractable form, the aggregation-based equivalent method in [23] is adopted to simplify (9). On the one hand, the time constants of synchronous generators are close to each other and are therefore assumed to be identical. On the other hand, for inverter-based renewable energy and energy storage units, the time constant T is typically in the millisecond range, which is two to three orders of magnitude smaller than that of conventional generating units. Hence, the time delay represented by T can be neglected. As a result, (9) can be rewritten as follows:

$$G_\alpha(s) = \left[(sH_\alpha + D_\alpha) + \frac{R_\alpha (1 + sF_\alpha T_\alpha)}{1 + sT_\alpha} \right]^{-1} \quad (11)$$

where:

$$\begin{cases} H_\alpha = \frac{\sum_{sg \in V_\alpha} H_{sg} S_{sg} + \sum_{GFM \in V_\alpha} H_{GFM} S_{GFM}}{S_{base,\alpha}} \\ D_\alpha = \frac{\sum_{sg \in V_\alpha} D_{sg} S_{sg} + \sum_{GFM \in V_\alpha} D_{GFM} S_{GFM} + \sum_{GFL \in V_\alpha} D_{GFL} S_{GFL}}{S_{base,\alpha}} \\ R_\alpha = \frac{\sum_{sg \in V_\alpha} K_{sg} S_{sg} / R_{sg}}{S_{base,\alpha}} \\ F_\alpha = \frac{\sum_{sg \in V_\alpha} K_{sg} F_{sg} S_{sg} / R_{sg}}{S_{base,\alpha}} \end{cases} \quad (12)$$

2.3 Frequency response model of the VSC-HVDC

When point-to-point transmission is employed between area α and area β , the rectifier side and inverter side of the VSC-HVDC system are operated under constant active power control and constant dc voltage control, respectively. By incorporating a VSG control structure into the power control loop, the VSC-HVDC link can directly provide frequency support to the receiving-end system. The corresponding control structure is shown in Fig. 4.

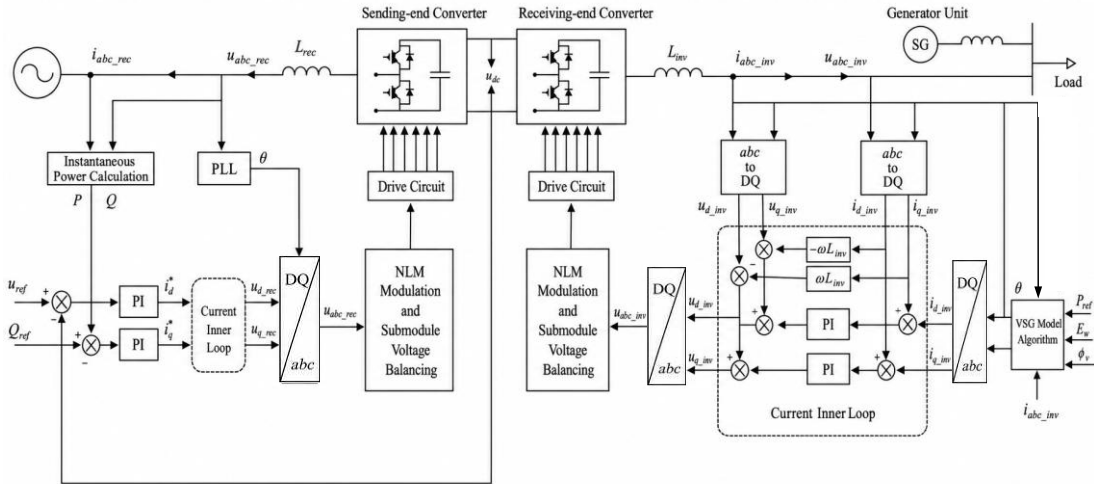


Fig. 4. Control block diagram of the VSG-based VSC-HVDC system

as follows:

For the VSC-HVDC converter station connected to area α , when VSG control or an equivalent grid-forming control method is employed, the local frequency support power provided to the corresponding area can be expressed

as follows:

$$\Delta P_{dc,\alpha}^{loc}(s) = - \left(\frac{1}{R_{dc}} + H_{dc} s \right) \Delta f_\alpha(s) \quad (13)$$

In practice, the time constant of the low-pass filter is typically set to $T_f=0.1$ s and that of the high-pass filter is set to $T_w=1000$ s. Their effects on the frequency response are therefore negligible. Accordingly, the active power adjustment transmitted from area β to area α through the VSC-HVDC link is given as follows:

$$\Delta P_{dc,(\alpha,\beta)} = \frac{1}{R^C} (\Delta f_\beta(s) - \Delta f_\alpha(s)) \quad (14)$$

where: $\frac{1}{R^C}$ is the droop coefficient of the VSC-HVDC system. $\Delta f_\alpha(s)$ and $\Delta f_\beta(s)$ are the frequency deviations of the two interconnected areas, respectively.

If multiple DC links are connected between the two areas, (14) can be further extended to (15), which denotes the frequency regulation power adjustment exchanged between the two areas.

$$\Delta P_{dc,(\alpha,\beta)} = \sum_{l \in \zeta(\alpha, \beta)} \frac{1}{R_l^C} (\Delta f_\beta(s) - \Delta f_\alpha(s)) \quad (15)$$

For multi-area interconnection, a multi-terminal DC frequency control method is adopted in this paper. The reference signal is calculated from global measurements and can reflect the overall frequency dynamics of all interconnected AC systems.

Taking area α as an example, the active power adjustment of the VSC-HVDC link connected to area α can be expressed as in (16).

$$\Delta P_{dc,\alpha} = \frac{1}{R_\alpha^C} (\Delta f_\alpha(s) - \Delta f_{ref}(s)) \quad (16)$$

where: R_α^C is the droop coefficient of the VSC-HVDC link connected to area α .

The global frequency reference signal $\Delta f_{ref}(s)$ of the multi-terminal VSC-HVDC interconnected system is obtained from the weighted average of the frequencies of the interconnected AC systems, as expressed in (17).

$$\Delta f_{ref}(s) = \sum_{\alpha=1}^M \varsigma_\alpha \Delta f_\alpha(s) \quad (17)$$

$$\varsigma_\alpha = \frac{1}{\sum_{\alpha=1}^M \left(\frac{1}{R_\alpha^C} \right)} \frac{1}{R_\alpha^C} \quad (18)$$

where: M is the number of areas in the system and ς_α is the weighting factor of the frequency deviation of each AC system.

2.4 Frequency response model of the multi-area system

By integrating the models developed in Sections 2.2 and 2.3, Fig. 5 presents a frequency response model for the inter-area VSC-HVDC interconnected power system that comprehensively accounts for intra-area frequency response characteristics.

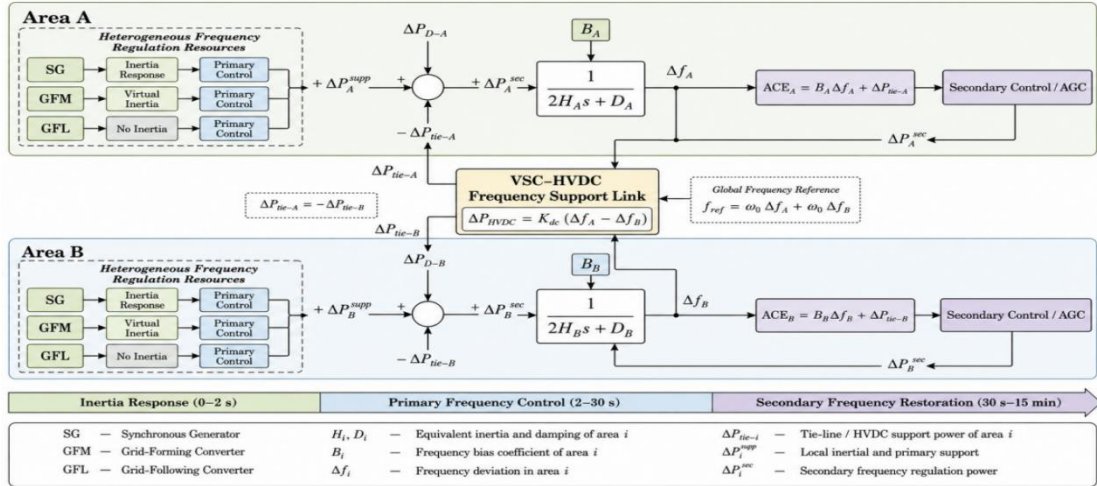


Fig. 5. Frequency regulation model of the multi-area system

Taking area α as an example, when a disturbance occurs in the area, the resulting power imbalance is expressed as in (19).

$$\Delta P_\alpha^e(s) = \Delta P_\alpha^{dis}(s) - \sum_{\gamma \in \Omega(\alpha)} \Delta P_{dc,(\alpha,\gamma)}(s) \quad (19)$$

where: ΔP_α^{dis} is the initial power imbalance in area α and $\Delta P_{dc,(\alpha,\gamma)}$ is the VSC-HVDC transmitted power associated with the areas connected to area α , where $\gamma \in \Omega(\alpha)$ denotes the set of all other areas connected to area α .

By substituting (15) into the above equation, (19) can be further expressed as follows:

$$\Delta P_\alpha^e(s) = \Delta P_\alpha^{dis}(s) - \sum_{\gamma \in \Omega(\alpha)} \frac{1}{R_{(\alpha,\gamma)}^C} (\Delta f_\gamma(s) - \Delta f_\alpha(s)) \quad (20)$$

According to the single-area frequency response model presented in Section 2.2, the closed-loop transfer function of area α is described by (21)–(22).

$$\Delta P_\alpha(s) = \frac{1}{G_\alpha(s)} \Delta f_\alpha(s) \quad (21)$$

$$G_\alpha(s) = (sH_\alpha + D_\alpha) + \frac{R(1 + sF_\alpha T_\alpha)}{(1 + sT_\alpha)} \quad (22)$$

In summary, by incorporating the regulation capability of the VSC-HVDC system, the frequency dynamic equation

$$\left(\frac{1}{G_\alpha(s)} + \sum_{\gamma \in \Omega(\alpha)} \frac{1}{R_{(\alpha, \gamma)}^c} \right) \Delta f_\alpha(s) - \sum_{\gamma \in \Omega(\alpha)} \frac{\Delta f_\gamma(s)}{R_{(\alpha, \gamma)}^c} = \Delta P_\alpha^{dis}(s) \quad (23)$$
$$G_{\alpha}^{eq}(s) = (sH_{\alpha}^{eq} + D_{\alpha}^{eq}) + \frac{R_{\alpha}^{eq}(1 + sF_{\alpha}^{eq}T_{\alpha})}{(1 + sT_{\alpha})} \quad (24)$$

When a step disturbance ΔP_{α}^{dis} occurs in area α , the frequency response equation can be further expressed as follows:

$$\Delta f_{\alpha}(s) = \frac{\Delta P_{\alpha}^{dis}}{H_{\alpha}^{eq} T_{\alpha}} \frac{1 + s T_{\alpha}}{(s^2 + 2\zeta_{\alpha} \omega_{n,\alpha} s + \omega_{n,\alpha}^2)} \quad (25)$$

where: $\omega_{n,\alpha} = \sqrt{\frac{D_{\alpha}^{eq} + R_{\alpha}^{eq}}{H_{\alpha}^{eq} T_{\alpha}^{eq}}}$ and

Applying the inverse Laplace transform to (25) yields the corresponding time-domain frequency response expression as follows:

$$f(t) = \begin{cases} \frac{\Delta P_{\alpha}^{dis}}{H_{\alpha}^{eq} T_{\alpha} \omega_{n,\alpha}^2} (1 - \kappa_1 e^{\omega_1 t} - \kappa_2 e^{\omega_2 t}), \zeta = 1 \\ \frac{\Delta P_{\alpha}^{dis}}{H_{\alpha}^{eq} T_{\alpha} \omega_{n,\alpha}^2} [1 - e^{-\omega_n t} + (T \omega_{n,\alpha}^2 - \omega_{n,\alpha}) t e^{-\omega_{n,\alpha} t}], \zeta \neq 1 \end{cases} \quad (26)$$

$$\left\{ \begin{aligned} \omega_1 &= \omega_{n,\alpha} \left(-\zeta_\alpha + \sqrt{\zeta_\alpha^2 - 1} \right) \\ \omega_2 &= \omega_{n,\alpha} \left(-\zeta_\alpha - \sqrt{\zeta_\alpha^2 - 1} \right) \\ \kappa_1 &= \frac{\sqrt{\zeta_\alpha^2 - 1} + \zeta_\alpha - T_\alpha \omega_{n,\alpha}}{2\sqrt{\zeta_\alpha^2 - 1}} \\ \kappa_2 &= \frac{\sqrt{\zeta_\alpha^2 - 1} - \zeta_\alpha + T_\alpha \omega_{n,\alpha}}{2\sqrt{\zeta_\alpha^2 - 1}} \end{aligned} \right. \quad (27)$$

3. Two-layer consensus-based frequency regulation method for VSC-HVDC interconnected power systems with

To this end, a two-layer consensus-based frequency regulation method for heterogeneous multi-agent systems is proposed in this paper. The objective is to achieve economical coordination of HFRRs under frequency feedback, rather than pursue a purely static economic frequency regulation objective. Unlike conventional consensus algorithms that are mainly applied to static power optimization, the proposed method realizes a new frequency regulation mechanism characterized by disturbance-driven response, online iterative regulation and two-layer coordinated restoration. The overall algorithmic method and the frequency-regulation roles of heterogeneous agents are illustrated in Fig. 6 and Table 1.

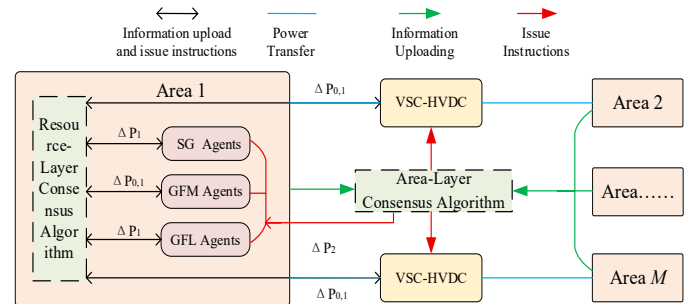


Fig. 6. Framework of the two-Layer consensus algorithm

Table 1 Regulation scope of frequency regulation resources

Frequency Regulation Resources	Inertial Response		Primary frequency regulation		Secondary frequency regulation	
	Partic ipatio	Dispa tchabl	Partic ipatio	Dispa tchabl	Partic ipatio	Dispa tchabl
	n	e	n	e	n	e
SG	√	×	√	√	√	√
GFM	√	√	√	√	√	√
GFL	×	×	√	√	√	√
VSC-HVDC	√	√	√	√	√	√

$$V_{\alpha}^r = V_{\alpha}^{SG} \cup V_{\alpha}^{GFM} \cup V_{\alpha}^{GFL} \cup V_{\alpha}^{VSC} \quad (28)$$

where: V_{α}^{SG} , V_{α}^{GFM} and V_{α}^{GFL} are the sets of SG, GFM

and GFL agents in area α , respectively, while V_{α}^{VSC} is the set of VSC-HVDC terminal agents connected to this area.

The resource-layer communication topology in area α is represented as follows:

$$G_{\alpha}^r = (V_{\alpha}^r, E_{\alpha}^r, A_{\alpha}^r) \quad (29)$$

where: E_{α}^r is the set of information exchange edges among agents within the area and $A_{\alpha}^r = [a_{ij}^r]$ is the adjacency matrix. If the local information of agent j is available to agent i , then $a_{ij}^r > 0$; otherwise, $a_{ij}^r = 0$. This topology enables HFRRs within the area to achieve fast coordinated regulation based on local frequency measurements and neighboring information.

At the area layer, each area is treated as an area-layer agent and an area-layer communication topology is established for inter-area coordinated control.

$$G^a = (V^a, E^a, A^a) \quad (30)$$

$$V^a = \{A_1^a, A_2^a, \dots, A_M^a\} \quad (31)$$

where: V^a is the set of area α nodes, E^a denotes the inter-area coupling relationships formed by VSC-HVDC channels and their associated control information and $A^a = [a_{\alpha\beta}]$ is the area-layer adjacency matrix. If a VSC-HVDC tie line exists between area α and area β , information exchange and power regulation are permitted, then $a_{\alpha\beta} > 0$ holds. This topology is mainly used for inter-ACE coordination and tie-line power redistribution in the post-disturbance stage, so as to achieve steady-state frequency restoration and inter-area mutual support.

In the two-layer multi-agent system proposed in this paper, VSC-HVDC is not modeled as a conventional single-role agent. Instead, it plays a dual role in the consensus-based frequency regulation process. The total active power injection increment from the VSC-HVDC terminals into area α during the whole frequency regulation process can be written as follows:

$$\Delta P_{\alpha, VSC}(k) = \Delta P_{\alpha, VSC}^r(k) + \Delta P_{\alpha, VSC}^a(k) \quad (32)$$

where: $\Delta P_{\alpha, VSC}^r(k)$ denotes the power increment provided by VSC-HVDC for local frequency support under resource-layer consensus, while $\Delta P_{\alpha, VSC}^a(k)$ denotes the inter-area power coordination increment provided under area-layer consensus. Equation (32) shows that VSC-HVDC is neither a conventional tie line nor a typical intra-area regulation resource; rather, it serves as a key coupling agent linking intra-area and inter-area consensus processes across different timescales.

3.2 Resource-layer consensus algorithm for heterogeneous multi-agent systems

To account for the dynamic heterogeneity of HFRRs during inertial response and primary frequency control, the resource-layer consensus algorithm is not formulated as a conventional static economic dispatch problem. Instead, a frequency-disturbance-driven dynamic marginal cost

consensus mechanism is established. Let P_i be the frequency regulation power of the i -th regulation agent in area α and its equivalent regulation cost function is defined as follows:

$$C_i(P_i) = a_i(P_i)^2 + b_i P_i + c_i \quad (33)$$

where: a_i , b_i , c_i are the cost coefficients. For SGs, these coefficients represent the additional fuel consumption and regulation-related wear costs. For converter-based GFM/GFL/VSC resources, they characterize the equivalent frequency regulation cost associated with reserve capacity opportunity loss, device lifetime degradation and renewable energy deloading [24][25].

Accordingly, the marginal frequency regulation cost is given by

$$\lambda_i = \frac{\partial C_i}{\partial \Delta P_i} = 2a_i \Delta P_i + b_i \quad (34)$$

where: λ_i is the marginal regulation cost of agent i , which is adopted as the consensus state variable in the proposed resource-layer consensus algorithm. Based on (34), the mapping between the power increment and the marginal cost can be further derived as follows:

$$\Delta P_i = \frac{\lambda_i - b_i}{2a_i} \quad (35)$$

Equation (35) shows that λ_i serves as the core decision variable in the resource-layer consensus algorithm, while the corresponding power command is obtained through its mapping relationship. Conventional consensus-based optimal frequency regulation strategies have been widely investigated and a typical update form can be written as follows [26]:

$$\lambda_i(k+1) = \sum_{j=1}^n d_{ij}(k) \lambda_j(k) + \mu \Delta \hat{P}_i^k \quad (36)$$

$$P_i(k+1) = \frac{\lambda_i(k+1) - b_i}{2a_i} \quad (37)$$

$$\Delta \hat{P}_i^k = \Delta P_{\alpha} + \Delta P_l - \sum_{i=1}^n \Delta P_i \quad (38)$$

where: $\Delta \hat{P}_i^k$ is the power imbalance, P_i is the active power output of the i -th node, μ is the area constraint correction coefficient, ΔP_{α} denotes the power variation within the area and ΔP_l represents the power exchange between this area and other areas.

Considering that power imbalance in a power system is inherently reflected by frequency deviation, which can be locally measured by each regulation agent, a target asymptotic term $T_i^*(k)$ is introduced in this paper. Accordingly, the global power imbalance information is replaced by a target correction mechanism driven by local frequency measurements and the resource-layer consensus update equation is reformulated as follows:

$$\lambda_i(k+1) = \sum_{j=1}^n d_{ij}(k) \lambda_j(k) + T_i^*(k) \quad (39)$$

When the consensus algorithm reaches convergence, the marginal regulation costs of all agents satisfy the following condition:

$$\lambda_1(k) = \lambda_2(k) = \dots = \lambda_i(k) = \lambda^* \quad (40)$$

where: λ^* is the optimal consensus value satisfying the intra-area economic coordination requirement. For a system with HFRRs, however, exact consensus may not be strictly attainable and the marginal costs may instead converge to a bounded range. From (34), (35) and (40), if the desired power correction is $\Delta P_i^*(k)$, the corresponding ideal marginal cost should satisfy the following condition:

$$\lambda_i^*(k) = 2a_i \Delta P_i^*(k) + b_i \quad (41)$$

Since b_i is a constant term and does not affect the relative correction direction of the consensus variables during iteration, the target asymptotic term is designed as the incremental marginal cost component. Accordingly, the resource-layer consensus regulation algorithm is formulated as follows:

$$\lambda_i(k+1) = \sum_{j=1}^n d_{ij}(k) \lambda_j(k) + T_i^*(k) \quad (42)$$

$$T_i^*(k) = 2a_i \Delta P_i(k) = 2a_i [\Delta P_{i,0}(k) + \Delta P_{i,1}(k)] \quad (43)$$

$$\Delta P_{i,0}(k) = \begin{cases} \frac{\varepsilon_k^0}{\delta_H} \frac{d\Delta f(k)}{dt} & i \in V_{GFM} \cup V_{VSC} \\ H_i \frac{d\Delta f(k)}{dt} & i \in V_{SG} \\ 0 & i \in V_{GFLM} \end{cases} \quad (44)$$

$$\Delta P_{i,1}(k) = \frac{\varepsilon_k^1 \cdot \Delta f(k)}{\delta_D} \quad i \in V_{SG} \cup V_{GFM} \cup V_{GFL} \cup V_{VSC} \quad (45)$$

$$\Delta f(k) = f^* - f(k) \quad (46)$$

where: $\Delta P_{i,0}(k)$ and $\Delta P_{i,1}(k)$ denote the inertia response adjustment term and the primary frequency regulation adjustment term of the consensus algorithm, respectively. $\Delta f(k)$ is the frequency value at the k -th iteration, $f(k)$ is the frequency measured by the regulation agent at the k -th iteration and $f^*(k)$ is the rated system frequency. When power balance is achieved, the system frequency is equal to f^* . Since SG and GFL do not include controllable, only $\Delta P_{i,1}(k)$ can be adjusted.

The iteration time of the consensus algorithm depends on the communication network performance, controller processing speed and system scale. For instance, the iteration time is typically 1–10 ms in a five-machine system and about 5–50 ms in the IEEE 10-machine 39-bus system. As the simulation scale increases, more time is required for each iteration. Therefore, when consensus algorithms are applied to practical power grids, their convergence speed should be carefully considered. In this paper, an adaptive correction parameter ε_k^* is designed according to the response characteristics of different

frequency regulation resources in different regulation stages to accelerate the convergence of the iterative process. It is incorporated into the consensus algorithm as follows:

$$\varepsilon_k^0 = \begin{cases} K_{H,VSC}^{eq} & |\Delta \dot{f}| \leq \Delta \dot{f}^{\text{middle}} \\ K_{H,VSC}^{eq} + K_{H,GFM}^{eq} & |\Delta \dot{f}| \geq \Delta \dot{f}^{\text{middle}} \end{cases} \quad (47)$$

$$\varepsilon_k^1 = \begin{cases} K_{D,VSC}^{eq} & |\Delta f| \leq \Delta f^{\text{lower}} \\ K_{D,VSC}^{eq} + K_{D,GFM}^{eq} & \Delta f^{\text{lower}} \leq |\Delta f| \leq \Delta f^{\text{middle}} \\ K_{D,VSC}^{eq} + K_{D,GFM}^{eq} + K_{D,GFL}^{eq} & \Delta f^{\text{middle}} \leq |\Delta f| \leq \Delta f^{\text{upper}} \\ K_{D,VSC}^{eq} + K_{D,GFM}^{eq} + K_{D,GFL}^{eq} + K_{D,SG}^{eq} & |\Delta f| \geq \Delta f^{\text{upper}} \end{cases} \quad (48)$$

where: $K_{H,i}^{eq}$ and $K_{D,i}^{eq}$ are the equivalent inertia time constant and equivalent primary frequency regulation coefficient of the unit, respectively, which are used to characterize the unified frequency response characteristics of a specific type of unit.

3.3 Area-layer consensus algorithm considering ACE correction

After the resource-layer consensus algorithm completes the rapid allocation of inertia response and primary frequency regulation power within each area, the system frequency deviation can be effectively suppressed. However, a certain steady-state frequency deviation may still remain and the VSC-HVDC tie-line power among areas may deviate from its original scheduled value due to algorithmic regulation. To address this issue, an area-layer control algorithm is further designed in this paper and the ACE is corrected accordingly, so as to realize secondary frequency restoration and inter-area power allocation.

Let ΔP_α denote the secondary frequency regulation power increment of area α . The corresponding equivalent regulation cost function is defined as follows:

$$C_\alpha(P_\alpha) = a_\alpha P_\alpha^2 + b_\alpha P_\alpha + c_\alpha \quad (49)$$

where: $a_\alpha = \left(\sum_{i=1}^n \frac{1}{a_i} \right)^{-1}$ and $b_\alpha = \frac{\sum_{i=1}^n b_i}{\sum_{i=1}^n \frac{1}{a_i}}$ are the equivalent

area-layer frequency regulation cost coefficients.

The marginal regulation cost of area α is defined as

$$\lambda_\alpha = \frac{\partial C_\alpha}{\partial \Delta P_\alpha} = 2a_\alpha \Delta P_\alpha + b_\alpha \quad (50)$$

Accordingly, the update algorithm of the area-layer consensus state variable λ_α is given by:

$$\lambda_\alpha(k+1) = \sum_{\beta=1}^m d_{\alpha\beta}(k) \lambda_\beta(k) + \sigma_\alpha \xi_\alpha(k) \quad (51)$$

where: σ_α is the global constraint correction coefficient and $\xi_\alpha(k)$ is the ACE of area α at the k -th iteration.

The area-layer consensus is not merely a static equilibrium process driven by marginal-cost information from neighboring areas; rather, its consensus state is continuously updated through an ACE-based correction term. In this way, the area-layer regulation process can

simultaneously satisfy economic coordination and frequency restoration requirements. Accordingly, the area-layer power increment of area α is obtained as follows:

$$\Delta P_{\alpha}(k+1) = \frac{\lambda_{\alpha}(k+1) - b_{\alpha}}{2a_{\alpha}} \quad (52)$$

At the area layer, VSC-HVDC provides inter-area mutual support regulation. Therefore, the VSC-HVDC transmission power increment between area α and area β is given by:

$$\Delta P_{\alpha, VSC}^A(k+1) = K_{\alpha\beta} [f_{\beta}(k+1) - f_{\alpha}(k+1)] + \Delta P_{\alpha}(k+1) \quad (53)$$

After the VSC-HVDC transmission power is obtained, the modified ACE of area α is defined to evaluate the current frequency restoration and tie-line power recovery performance, as follows:

$$\hat{\xi}_{\alpha}(k+1) = \delta_{\alpha} \Delta f_{\alpha}(k+1) + \Delta P_{\alpha, VSC}^A(k+1) \quad (54)$$

where: δ_{α} is the frequency deviation coefficient of area α .

Since the conventional centralized PI control in AGC suffers from slow response and poor adaptability to multiple HFRRs, the distributed cooperative AGC method proposed in [27] is introduced in this paper. The corresponding distributed fixed-time ACE estimation algorithm is expressed as follows:

$$\begin{aligned} \hat{\xi}(k) = & \eta \left[\sum_{j=1}^n d_{ij} \left(\hat{\xi}_j(k) - \hat{\xi}_i(k) \right)^{[u]} + e_i \left(\hat{\xi}(k) - \hat{\xi}_i(k) \right)^{[u]} \right] \\ & + \eta \left[\sum_{j=1}^M d_{ij} \left(\hat{\xi}_j(k) - \hat{\xi}_i(k) \right)^{[v]} + e_i \left(\hat{\xi}(k) - \hat{\xi}_i(k) \right)^{[v]} \right] \end{aligned} \quad (55)$$

where: $\hat{\xi}(k)$ denotes the modified ACE signal measured by the control center or the VSC-HVDC controller; $\hat{\xi}_i(s)$ and $\hat{\xi}_j(s)$ denote the ACE estimates of regulation agents i and j , respectively; $\eta > 0$ is the gain coefficient, with $0 < u < 1$ and $v > 1$; and $e_i = 1$ if regulation agent i is connected to the control center, otherwise $e_i = 0$.

Through the ACE discovery algorithm, each secondary frequency regulation agent can acquire the ACE signal and derive the secondary power regulation term through its local controller, as follows:

$$x_{i,\alpha}^I(k+1) = x_{i,\alpha}^I(k) + T_s \dot{\hat{\xi}}(k) \quad (56)$$

$$\Delta P_{i,2}(k+1) = \zeta_i \left(K_p^{\text{ACE}} \dot{\hat{\xi}}(k+1) + K_I^{\text{ACE}} x_{i,\alpha}^I(k+1) \right) \quad (57)$$

where: T_s denotes the iteration step size, ζ_i denotes the preset participation factor of the secondary frequency regulation agent in area α , K_p^{ACE} and K_I^{ACE} denote the proportional and integral gains of the i -th secondary frequency regulation agent, respectively.

The area-layer consensus algorithm generates the net regulation target of each area, whereas the resource-layer secondary frequency regulation control executes the corresponding allocation result under the power balance constraint. During the overall frequency regulation process, let $\Delta P_i^{\text{total}} = \Delta P_{i,0} + \Delta P_{i,1} + \Delta P_{i,2}$ denote the incremental power of each regulation agent. The total frequency

regulation cost of area α is expressed as follows:

$$C_{\text{all}}(P_i^{\text{total}}) = \sum_{i=1}^n \left[a_i (P_i^{\text{total}})^2 + b_i P_i^{\text{total}} + c_i \right] \quad (58)$$

4. Frequency regulation process based on the proposed algorithm

4.1 Frequency security indicators

(1) RoCoF: By differentiating (26), it can be found that, regardless of the damping condition, the maximum RoCoF occurs at $t=t_0^+$, as shown in (59):

$$\dot{f}_{\alpha} = \frac{\Delta P_{\alpha}^{\text{dis}}}{H_{\alpha}^{\text{equ}} T_{\alpha} \omega_{n,\alpha}^2} (\kappa_1 \omega_1 + \kappa_2 \omega_2) = \frac{\Delta P_{\alpha}^{\text{dis}}}{H_{\alpha}^{\text{equ}}} \quad (59)$$

(2) Frequency nadir: By identifying the instant at which the derivative of (26) is equal to zero, the frequency nadir can be determined as follows:

$$\Delta f_{\alpha}^{\text{nadir}} = \begin{cases} \frac{\Delta P_{\alpha}^{\text{dis}}}{H_{\alpha}^{\text{equ}} T_{\alpha} \omega_{n,\alpha}^2} (1 - \kappa_1 e^{\omega_1 t_m} + \kappa_2 e^{\omega_2 t_m}), & \zeta = 1 \\ \frac{\Delta P_{\alpha}^{\text{dis}}}{H_{\alpha}^{\text{equ}} T_{\alpha} \omega_{n,\alpha}^2} \left[1 - e^{-\omega_n t'_m} + (T_{\alpha} \omega_{n,\alpha}^2 - \omega_n) t'_m e^{-\omega_n t'_m} \right], & \zeta \neq 1 \end{cases} \quad (60)$$

where: $t_m = \frac{\ln(-\kappa_1 \omega_1 / \kappa_2 \omega_2)}{\omega_2 - \omega_1}$ and $t'_m = T_{\alpha} / (T_{\alpha} \omega_{n,\alpha} - 1)$

are the time instants corresponding to the frequency nadir under different damping conditions, respectively.

(3) Steady-state frequency deviation: Primary frequency regulation arrests the frequency decline and restores it to a quasi-steady state. The steady-state frequency deviation is obtained as t approaches infinity, as shown in (61):

$$\Delta f_{\alpha}^{\text{ss}} = \frac{\Delta P_{\alpha}^{\text{dis}}}{H_{\alpha}^{\text{equ}} T_{\alpha} \omega_n^2} = \frac{\Delta P_{\alpha}^{\text{dis}}}{R_{\alpha}^{\text{equ}} + D_{\alpha}^{\text{equ}}} \quad (61)$$

The three indices, RoCoF, frequency nadir and steady-state frequency deviation, should remain within the permissible limits:

$$\begin{cases} |\Delta \dot{f}_{\alpha}| \leq \dot{f}_{\alpha}^{\text{lim}} \\ |\Delta f_{\alpha}^{\text{ss}}| \leq \Delta f_{\text{ss},\alpha}^{\text{lim}} \\ |\Delta f_{\alpha}^{\text{nadir}}| \leq \Delta f_{\text{max},\alpha}^{\text{lim}} \end{cases} \quad (62)$$

4.2 Operating constraints of frequency regulation resources and VSC-HVDC

To ensure that the proposed two-layer consensus-based frequency regulation method satisfies both frequency security requirements during disturbances and engineering implementation requirements, constraints should be imposed on the adjustable power range, regulation rate and key control parameters of various frequency regulation resources and VSC-HVDC channels.

(1) Operating Constraints of SG

The operating constraints of conventional synchronous generator i participating in coordinated frequency regulation

are expressed as follows:

$$-r_i^\downarrow \Delta t \leq \Delta P_i(t) - \Delta P_i(t - \Delta t) \leq r_i^\uparrow \Delta t \quad (63)$$

$$P_i^{\min} \leq P_i(t) \leq P_i^{\max} \quad (64)$$

$$0 \leq R_i^{\text{up}}(t) \leq P_i^{\max} - P_i(t) \quad (65)$$

$$0 \leq R_i^{\text{down}}(t) \leq P_i(t) - P_i^{\min} \quad (66)$$

where: $r_i^\downarrow$ and $r_i^\uparrow$ are the upper limits of the upward and downward regulation rates of the synchronous generator, respectively; Δt is the iteration period; $P_i^{\min}$ and $P_i^{\max}$ are the lower and upper limits of the unit active power output, respectively; and $R_i^{\text{up}}(t)$ and $R_i^{\text{down}}(t)$ are the upward and downward reserve capacities of the unit at time t , respectively.

(2) Operating Constraints of GFM and GFL

The output and reserve constraints of converter-based frequency regulation resource r (including GFM and GFL) are expressed as follows:

$$P_r^{\min}(t) \leq P_r(t) \leq P_r^{\text{ava}}(t) \quad (67)$$

$$-R_r^{\text{down}}(t) \leq \Delta P_r(t) \leq R_r^{\text{up}}(t) \quad (68)$$

where: $P_r^{\text{ava}}(t)$ and $P_r^{\min}(t)$ denote the maximum available active power and the minimum allowable output of resource r at time t , respectively. For a deloaded renewable energy unit, $P_r^{\min}(t)$ is usually set to 0; for an energy-storage-based GFM or GFL, the corresponding lower bound can be determined according to its charging/discharging state. Meanwhile, $R_r^{\text{up}}(t)$ and $R_r^{\text{down}}(t)$ represent its upward and downward reserve capacities, respectively.

(3) Operating Constraints of VSC-HVDC

The operating constraints of VSC-HVDC channel h can be uniformly expressed as follows:

$$\begin{cases} -P_{dc,h}^{\max} \leq P_{dc,h}(t) \leq P_{dc,h}^{\max} \\ |P_{dc,h}(t) - P_{dc,h}(t - \Delta t)| \leq R_{dc,h} \Delta t \end{cases} \quad (69)$$

where: $P_{dc,h}(t)$ is the total active power transmission at time t , $P_{dc,h}^{\max}$ is the rated transmission capacity and $R_{dc,h}$ is the upper limit of the active power regulation rate.

(4) Equivalent Constraints of Frequency Regulation Parameters

Since GFM and VSC-HVDC can regulate virtual inertia and virtual damping online through their controllers, the corresponding adjustable parameters should satisfy:

$$0 \leq H_{i,t} \leq \bar{H}_i, \forall i, t \quad (70)$$

$$0 \leq D_{i,t} \leq \bar{D}_i, \forall i, t \quad (71)$$

$$H_{a,t}^{\text{equ}} = \frac{\sum_{g \in V_a} H_{sg} S_{sg} + \sum_{GFM \in V_a} H_{GFM,t} S_{GFM} + \sum_{VSC \in V_a} H_{VSC,t} S_{VSC}}{S_{\text{base}}} \quad (72)$$

$$D_{a,t}^{\text{equ}} = \frac{\sum_{g \in V_a} D_{sg} S_{sg} + \sum_{GFM \in V_a} D_{GFM,t} S_{GFM} + \sum_{GFL \in V_a} D_{GFL,t} S_{GFL} + \sum_{VSC \in V_a} D_{VSC,t} S_{VSC}}{S_{\text{base}}} \quad (73)$$

where: equations (70)–(73) specify the permissible adjustment ranges of virtual inertia and virtual damping and their upper bounds are constrained by the relevant technical standards.

4.3 Flowchart of the two-layer consensus-based frequency regulation method

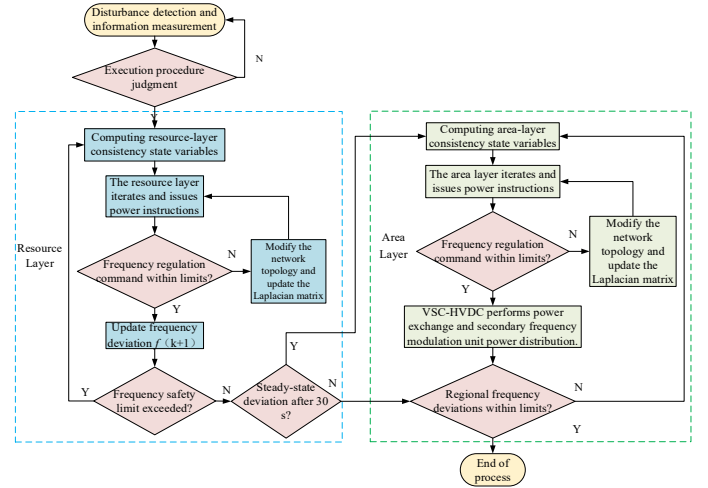


Fig. 7. Flowchart of the two-Layer consensus-based control method for the VSC-HVDC interconnected power system

Fig. 7 illustrates the flowchart of the proposed two-layer consensus-based control method for the VSC-HVDC interconnected power system. The specific implementation steps are summarized as follows:

Step 1: Disturbance detection and information measurement. Each area acquires frequency, RoCoF, unit output, power flow and communication topology information, evaluates the relevant security indices, thereby providing the initial conditions for the subsequent consensus iterations.

Step 2: Execution logic determination. The initial marginal cost of each frequency regulation agent is determined from its initial output and cost function. Subsequently, the resource-layer Laplacian matrix and state transition matrix are established and the triggering conditions associated with the frequency security indices are evaluated to decide whether the control algorithm should be executed.

Step 3: Resource-layer consensus updating and constraint verification. The consensus state variables of all agents are updated online according to (42)–(48), while the adaptive correction parameter ε_k^* is introduced to accelerate convergence. The constraints on incremental power, reserve capacity, VSC-HVDC transmission power and adjustable parameter bounds are then verified according to (63)–(73). If an agent reaches its operating upper or lower limit, its control input is saturated and the adjustable resource set, Laplacian matrix and state transition matrix are updated accordingly. When the resource-layer consensus algorithm meets the intra-area convergence criterion, the resource-layer iteration is terminated to avoid excessive controller sensitivity and repeated actions.

Step 4: Area-layer coordinated restoration activation. If a steady-state frequency deviation still remains when $t > 30$ s, the control process switches to area-layer consensus control.

In this stage, each area is regarded as an agent and the area-layer marginal cost, ACE signal and secondary frequency regulation power allocation are updated according to (51)–(57). If any operating constraint is violated, the unmet regulation demand is redistributed among the remaining available areas and resources until the requirements of power balance and operating limits are satisfied.

Step 5: Convergence checking and result output. If the frequency deviations of all areas and the associated operating constraints fall within the prescribed tolerances, the two-layer consensus-based frequency regulation process is considered converged. The incremental power of each regulation resource, the VSC-HVDC support power and the final frequency restoration states are then output and recorded

5. Case analysis

5.1 Simulation system configuration

An modified three-area IEEE 39-bus system is modeled in this paper, where asynchronous interconnection among areas is achieved through VSC-HVDC tie lines. The schematic of the optimized system partition, the allocation of frequency regulation resources and the relevant parameters are shown in Fig. 8, Table 2 and Table 3, respectively. To accommodate the timescale difference between the frequency dynamic process and the iterative process of the consensus algorithm, the dynamic simulation step is set at the millisecond layer, while the consensus controller updates the consensus state variables and frequency regulation power commands with a fixed sampling period of $T_s=5$ ms. The frequency security indices are specified as follows: $\dot{f}_\alpha^{\lim} = 0.6 \text{ Hz/s}$, $\Delta f_{\max, \alpha}^{\lim} = 0.05 \text{ Hz}$, $\Delta f_{ss, \alpha}^{\lim} = 0.02 \text{ Hz}$ and the adaptive correction parameter ε_k^* is set in proportion to these indices.

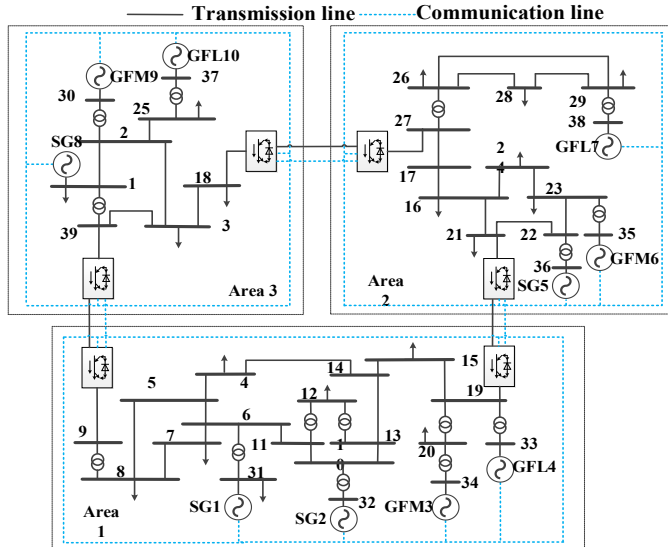


Fig. 8. Topology of the optimized IEEE 39-Bus three-area VSC-HVDC interconnected system

Table 2 Bus and frequency regulation resource partitioning

Area	Bus	SG	GFM	GFL
Area 1	4,5,6,7,8,9,10,11,12,13,14,15,19,20,31,32,33,34	SG1, SG2	GFM3	GFL4
Area 2	16,17,21,22,23,24,26,27,28,29,35,36,38	SG5	GFM6	GFL7
Area 3	1,2,3,18,25,30,37,39	SG8	GFM9	GFL10

Table 3 Parameter settings of frequency regulation resources

Frequency Regulation Resources	Parameter			
	a_i	b_i	$P_{\min}$ (MW)	$P_{\max}$ (MW)
SG1	0.0082	7.58	0	179.18
SG2	0.0094	7.53	89.15	193.82
GFM3	0.0169	6.09	0	147.19
GFL4	0.0217	6.56	0	92.17
SG5	0.0083	7.26	92.84	143.41
GFM6	0.0154	6.30	0	163.12
GFL7	0.0231	6.69	0	106.41
SG8	0.0074	7.71	0	113.23
GFM9	0.0194	6.25	0	118.03
GFL10	0.0234	6.83	0	77.19

5.2 Validation of constraint effectiveness

To validate the effectiveness of the operating constraints on frequency regulation resources and VSC-HVDC established in Section 4.2 under disturbance conditions, Area1, the load center area, is selected as the disturbed area. A load disturbance is applied at Bus 4, where the load increases from 70 MW to 120 MW at $t=1$ s. The resulting variations in active power output and incremental cost of each frequency regulation agent are shown in Figs. 9 and 10, respectively.

According to the simulation results, under the unconstrained case, the active power outputs of the agents may violate their operating limits. For example, the output of GFM3 slightly exceeds its normalized upper limit of 100% and the incremental costs rapidly converge once the consensus iteration is activated. These results correspond to the case without operating constraints on frequency regulation resources. In practical systems, however, the ramping rate of generating units limits the rapid increase in active power output and, accordingly, restricts the variation of incremental cost. In contrast, under the constrained case, no operating limit violation is observed and the incremental costs of the agents finally converge to a bounded coordinated range, thereby demonstrating the effectiveness of the proposed constraints and the regulation performance of the proposed method.

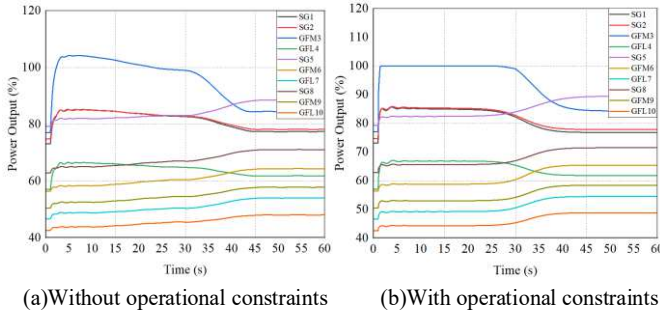


Fig. 9. Active power output variations of frequency regulation agents

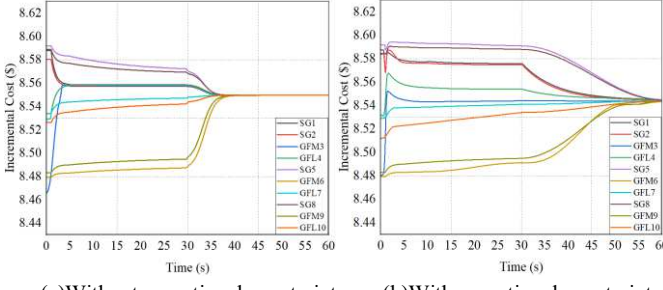


Fig. 10. Incremental cost variations of frequency regulation agents

5.3 Validation of control effectiveness

(1) Validation of the Effectiveness of the Resource-Layer Consensus Algorithm and the Adaptive Fast Convergence Mechanism

To evaluate the fast support capability of the proposed resource-layer consensus algorithm on area frequency dynamics during the initial stage of a disturbance, the same disturbance scenario as in Section 5.2 is adopted. To highlight the role of the resource-layer mechanism itself, three simulation cases are considered as follows:

Case 1: Only local droop control and conventional primary frequency regulation of each frequency regulation resource are considered, while the resource-layer consensus algorithm is not applied.

Case 2: The resource-layer consensus algorithm is implemented, while the adaptive fast convergence term is not included.

Case 3: The full resource-layer consensus algorithm proposed in this paper is implemented.

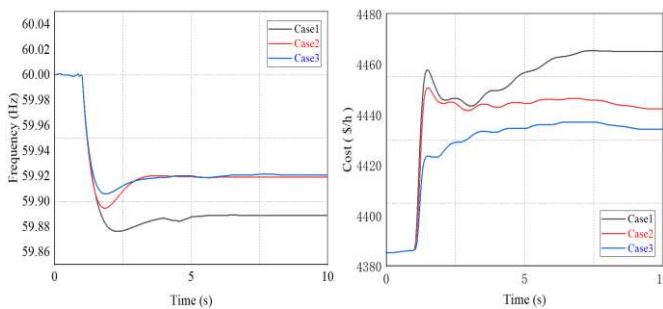


Fig. 11. Comparison of area 1 results under different cases

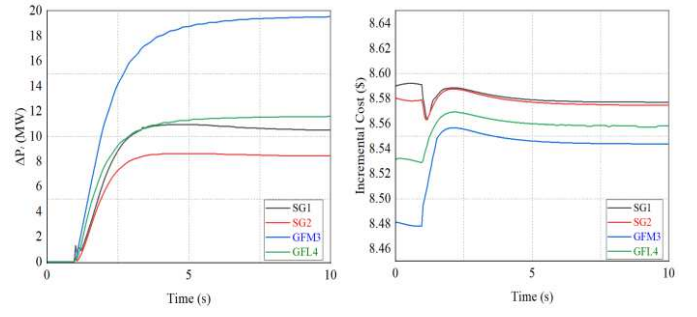


Fig. 12. Dynamic responses of frequency regulation agents in area 1 under case 3

As shown in Fig. 11, after a 50 MW step load increase is imposed on Area1 at $t=1$ s, transient frequency drops occur under all three cases, whereas Case 3 achieves the smallest frequency deviation and the fastest recovery. Meanwhile, the frequency regulation cost per unit time in Case 3 remains the lowest throughout the process, which verifies the superiority of the proposed method in terms of both frequency stability and economic performance. Fig. 12 shows that, under Case 3, GFM3 responds first and rapidly increases its output, while SG1, SG2 and GFL4 subsequently coordinate their responses to share the disturbance power in a reasonable manner. In addition, the incremental costs of all agents are rapidly adjusted after the disturbance and converge to a coordinated range. These results demonstrate that the proposed resource-layer consensus algorithm together with the adaptive fast convergence mechanism can effectively enhance frequency support capability and regulation economy.

(2) Effectiveness Verification of the Area-Layer Consensus Restoration Mechanism

Building upon the simulation settings in Section 5.1, the area-layer consensus restoration control is activated when $t>30$ s and a non-negligible steady-state frequency deviation remains in the system. To evaluate the effectiveness of the area-layer consensus algorithm and the ACE coordination mechanism proposed in Section 3.3, the simulation duration is extended to 60 s under the same disturbance scenario as that used at the resource layer and the following three cases are defined:

Case 4: Only conventional primary and secondary frequency regulation are considered.

Case 5: The resource-layer consensus algorithm is implemented, but the area-layer consensus restoration control is not enabled.

Case 6: The full two-layer consensus-based frequency regulation method proposed in this paper is implemented.

The simulation results in Fig. 13 show that, after 30 s, Case 6 achieves faster frequency recovery under the area-layer consensus control. Moreover, Case 6 has the lowest total unit-time frequency regulation cost, which is reduced by 75 \$/h compared with Case 4. Fig. 13(c) indicates that the VSC-HVDC support to Area1 is relatively limited in Case 4; in Case 5, the support is stronger in the early stage but exhibits limited subsequent growth; whereas in Case 6, the VSC-HVDC transmitted power continues to increase significantly after 30 s, further confirming the regulation effect of the proposed method. These results demonstrate that the proposed area-layer consensus control algorithm

can further improve steady-state frequency recovery capability and the economic performance of inter-area frequency regulation.

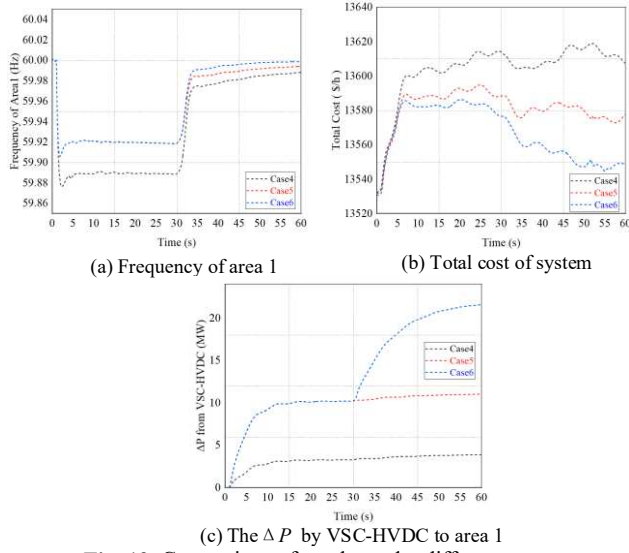


Fig. 13. Comparison of results under different cases

5.4 Verification of communication failure robustness

To further evaluate the applicability and robustness of the proposed method under practical communication conditions, a communication fault is introduced in Area2. Specifically, the communication link between SG5 and GFM6 is disconnected at 1 s and a 20 MW load at bus 24 is subsequently shed at 5 s. The simulation results are shown in Fig. 14 and Fig. 15.

Fig. 14 shows that the system remains stable after the communication link is disconnected. After the disturbance at 5 s, the frequency rises rapidly. However, under the proposed method, the frequency peak is lower, reaches approximately 60.06 Hz, and returns to around 60.02 Hz at about 7 s. In contrast, the peak frequency under the traditional consensus algorithm is approximately 60.08 Hz, with slower recovery and more pronounced oscillations in the later stage. Fig. 15 shows that, due to the influence of heterogeneous parameters, the initial incremental costs of SG5 and GFM6 are different. After the disturbance, they do not converge to an identical value, but gradually enter a narrow coordination range. Compared with the traditional algorithm, the proposed method results in smaller incremental cost overshoot, smoother correction and faster convergence. These results indicate that the proposed improved consensus algorithm maintains strong robustness under communication failure conditions, while effectively balancing heterogeneous resource coordination and frequency recovery performance.

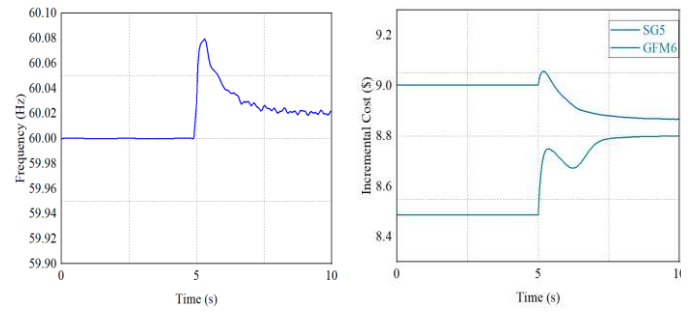


Fig. 14. Simulation results under the traditional consensus algorithm

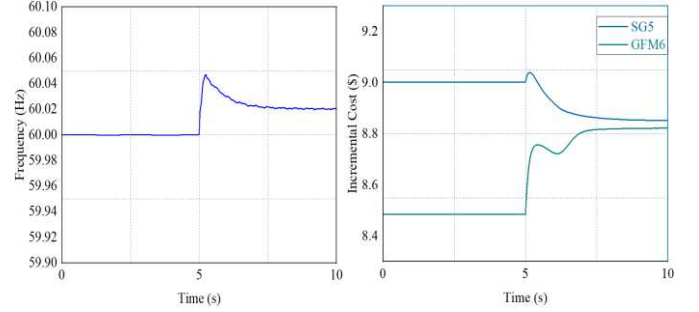


Fig. 15. Simulation results under the proposed method

6. Conclusions

This paper proposes a two-layer consensus-based coordinated frequency regulation method for VSC-HVDC interconnected power systems with HFRRs. By integrating SGs, GFMs, GFLs, and VSC-HVDC links into a unified multi-area frequency response framework, the proposed method coordinates fast intra-area inertial and primary frequency support with inter-area ACE-based secondary restoration. Simulation results on a modified IEEE 39-bus three-area system show that the proposed method can keep regulation resources and VSC-HVDC links within operating limits, reduce transient frequency deviations, accelerate steady-state frequency recovery, and lower regulation cost compared with conventional control strategies. In addition, under communication-link failure, the method still maintains stable frequency response and smoother incremental-cost convergence, demonstrating its robustness and practical applicability for high-renewable VSC-HVDC interconnected power grids.

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