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General structures of control area cooperation for variable renewable energy integration in electric power systems

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To integrate large-scale variable renewable energy resources (RESs) in modern power grids, the coordinating control area (CA) operation is the most cost-effective method. This article reviews the technical aspects of CA cooperation. Firstly, a brief overview of the active balancing control within each CA is discussed. Secondly, three general control structures for CA cooperation are innovatively proposed, the corresponding implementation details are analyzed, and some representative technologies are also provided in the systematic analysis. Then, some future research directions such as large-scale power sharing by DC, active power control of RES bases, and the new structure for distributed energy resources in local power grids are prospected. Finally, the changes in power systems brought about by their evolution and importance for further promoting cooperation between CAs are summarized.

KEYWORDS

renewable energy integration, control area cooperation, distributed energy resource, automatic generation control, new power systems

1 Introduction

1.1 Background

Today's power systems continue to support the energy transition for deep decarbonization (Marot et al., 2022). With the rapidly growing penetration level of renewable energy sources (RESs), such as wind and solar generation, the challenges of managing variability and the uncertainty of variable renewable generation have become more significant around the world. Different options are available to accommodate the high penetration of variable RESs (Koltsaklis and Knápek, 2023). From the traditional perspective, procuring a large number of flexible regulation resources can ensure system stability in electric power systems. Another important issue is the higher ramping capacity of controlled units in the regulating process, which requires more fast-response regulating resources to cope with ramping events. Many countries are developing effective technologies and tools to enable high penetration of RESs in electric power systems, and some effective operational practices have been discussed in Chen et al. (2023). However, frequency stability and control still faces many challenges arising from the growing integration of RESs (Kraljic, 2023; Bryant et al., 2021), and the development of automatic generation control (AGC), one of the most important functions to regulate the frequency within an acceptable operating range, has attracted great interest in recent years (Bevrani et al., 2021; Ranja et al., 2022).

1.2 Traditional methods of active power and frequency control

The AGC provides the successful operation of interconnected power systems that require active power balancing and frequency stabilization (Ibraheem et al., 2005). In general, system operators use AGC systems to maintain the balance of supply and demand within geographic boundaries known as balancing areas or control areas (CAs), such as the provincial power grid in China, the balancing authority area (BAA) in the US. power grids, and the control block/area in Europe. The interconnected power grid is operated locally and separately by individual CAs that usually calculate the area control error (ACE) under the tie-line bias mode (TBC) that aims to stabilize the frequency and tie-line power fluctuations for AGC deployment. Each CA has to use the AGC to adjust the regulating resources to achieve local balance within its territory on a minute-to-minute basis.

1.3 The motivation behind the present work

From traditional operation experiences, it is difficult for the CA to meet the requirements of self-balancing in the process of building the new power systems with high-proportion RESs. On one hand, the flexible regulating resources are expensive and may be limited within a CA's territory or part of interconnection, which could not meet the overall operational requirements with the increasing of RESs. Due to the complementarity of RESs in a wide region, the additional balancing requirements caused by the RESs could be reduced if negative impacts are accumulated over a larger geographic region, so the cooperation mechanism for multiple CAs is proposed as one of the most important technologies and tools for large-scale RES integration, and some practices in different countries are provided (Teng et al., 2023). The efficiency is achieved by sharing or coordinating the regulating resources across larger geographic boundaries at the whole power grid level, which benefits power system operation from both the economic and reliability perspectives (Polajžer et al., 2018). Coordinating the sizing, allocation, and activation of reserves (Bergh et al., 2017) and achieving the sharing of ancillary services (Frade et al., 2019) are the mainstream methods adopted by today's power grids. On the other hand, the power systems are evolving toward a more decentralized architecture, widely penetrated by RESs and distributed energy resources (DERs) (Rancilio et al., 2022), and traditional transmission-level CAs can barely deal with active power control issues at low voltage levels such as distribution networks and microgrids (Heidary et al., 2022). Wang et al. (2022) presented an efficient open-source transmission-and-distribution dynamic co-simulation framework for DER frequency response, while Pourghaderi et al. (2023) presented a new market-based framework to exploit DERs' flexibility at the distribution and transmission levels. Srivastava et al. (2022) established the power system framework consisting of AGC systems and DER aggregators, but it is still a conventional method and cannot meet the requirements of hierarchical active power balancing with large-scale DER integration in the future.

1.4 Organization of the present work

The rest of the article is organized as follows. Section 2 gives a brief overview of the active balancing control within the CA. Section 3 discusses the CA's cooperation methods in three control structures with the corresponding control strategies. Section 4 analyzes some potential problems and future works. Finally, Section 5 concludes the article.

2 Active balancing control within the control area

2.1 The time sequence of traditional frequency control

A general frequency control consists of the primary frequency control (PFC), secondary frequency control (SFC), and tertiary frequency control (TFC). The PFC is a decentralized, second-level control method. When the frequency deviation exceeds a certain threshold, the governors of the synchronous generators will automatically operate to stabilize the system frequency. When the fault is severe, load shedding will also occur. However, the PFC cannot restore the frequency to near the scheduled value and requires the SFC. The SFC is commonly known as the AGC and is the manual regulation driven by system operators to quickly restore the frequency to the rated value and to control the power deviation of the cross-area tie-line within the normal range. If the frequency deviation reaches the suspend limit of the AGC, its function is suspended and manual regulation is conducted by the system operators. In addition, the regulation capacity used during the SFR stage has to be restored in the TFC by updating the generation schedules of online generators. The time sequence of the traditional frequency control is shown in Figure 1.

As shown in Figure 1, the SFC (AGC and manual regulation) and TFC are both area-based control methods; they only control their respective ACEs and do not care about the control demand from the whole power grid level (e.g., grid frequency). With the increasingly close connections between CAs and the increasingly complex operating environment of the power grid, the main driving forces for achieving real-time collaborative control of multiple CAs are as follows:

1) Reducing the adverse effects of different CAs. On the one hand is the mutual influence of the regulation behavior between the CAs. An AGC system within a CA usually follows its own ACE under the TBC mode, which is calculated by equation (1). If the algebraic sign of the ACE values is different, the counteract regulation process is produced by the AGC systems. From the perspective of the interconnected power grid, this operational condition may not only increase the wear and tear of the generators but also cause ACE and frequency oscillations.

$$ACE_i = -10B_i\left(f_a - f_s\right) + \left(NI_a - NI_s\right), \tag{1}$$

where ACE_i is the ACE of the i-th CA, B_i is the frequency bias of the i-th CA in MW/0.1 Hz, f_a and f_s are the actual and scheduled grid frequencies, respectively, and NI_a and NI_s are the actual and

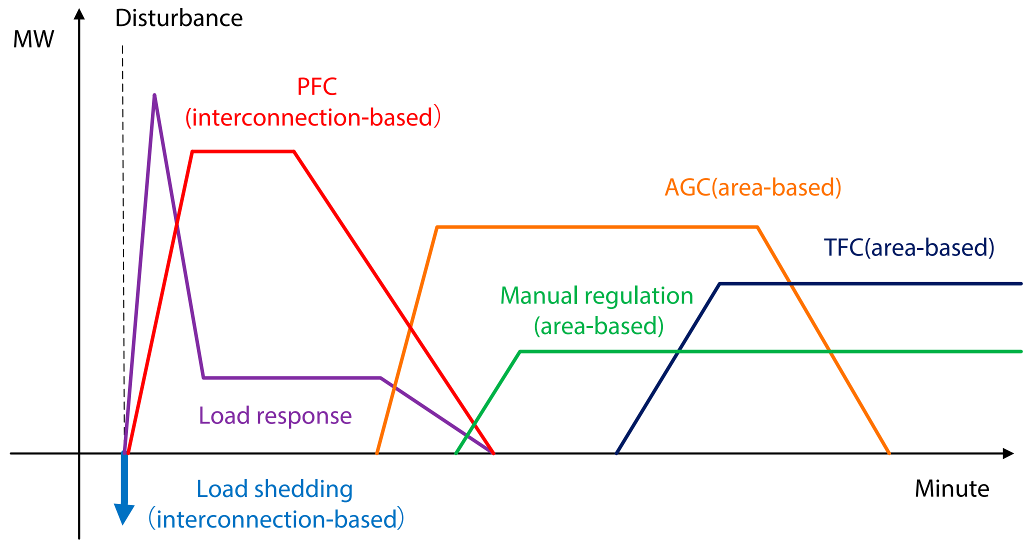

FIGURE 1
Time sequence of traditional frequency control.

scheduled net interchange between the *i*-th CA and the other CAs, respectively.

2) Accommodating the power mismatches at high RES penetration levels. The gradual increase in the penetration rate of the RES causes great operational pressure on active power balancing control. Therefore, it is difficult for a CA to ensure the full guaranteed consumption of the RES within a small geographical region. Especially with the construction of ultra-high-voltage direct current (UHVDC) transmission lines in China, the receiving-end power grid faces challenges due to the large-scale transmission capacities of the UHVDC being fixed in dispatch intervals.
3) Ensuring the safe operation of the power grid. The high-voltage direct current (HVDC) or large-capacity generators are continuously put into operation, and once a blocking fault of the HVDC or tripping of generators occurs, the CA will face a huge active power shortage. The available contingency reserve capacity in a single CA cannot meet the control requirements under a large-scale power loss, which is not conducive to the rapid recovery of frequency. Under extreme weather conditions, such as the solar eclipse that occurred in Europe on 20 March 2015 (Máslo, 2016), the reserve capacity within a CA makes it difficult to maintain the balance between generation and demand. The existing self-balancing mode for individual CAs limits the potential utilization of wide-region regulation capacity.
4) The costs of regulation services are high due to the increasing regulating reserve that has to be procured. From the perspective of an interconnected power grid, counteracting the regulation is unnecessary, and the costs can be reduced if AGC can be activated in a centralized scheme. With the implementation of regional regulating markets in Europe and the Southern China region, a centralized scheme is more cost-effective than a decentralized scheme. Individual CAs cope with local RESs by purchasing high-cost regulation services, but the regulation reserve is an expensive product.

Therefore, a coordination scheme for multiple CAs over a large geographical region should be established, which could benefit the diversity of power mismatches that exist within different CAs. It triggers a transition from self-balancing implemented toward a centralized and hierarchical scheme. The power mismatches of individual CAs will be less correlated within larger geographic regions.

2.2 Renewable energy participation in AGC systems

Large-scale RES integration brings regulation pressure to the power grids, and the RESs are not yet dispatchable resources and should be treated as negative loads in the traditional concept, but they should have the ability to control the power outputs in response to the dispatch signals sent by the AGC systems similar to conventional generators (CGs). Recently, some operational experiences show that the RESs have the acceptable regulation capacity to participate in AGC with a higher ramp rate than CGs (Rebello et al., 2019; National Renewable Energy Laboratory, 2017). In China, RESs have been controlled by the AGC systems in actual grid operations, but few of them have provided regulation services. In US power grids, the Independent System Operator New England (ISO-NE) has proposed a do-not-exceed (DNE) limit calculation for RESs, which are maximum generation levels that a system can accommodate without sacrificing its reliability (Zhao et al., 2015), and renewable sources–based units can freely increase generation without violating the DNE limit. A similar method has been implemented in the North China power grid, where a regional-wide wind power generation schedule considering the grid balance constraints and grid security constraints is formulated and then implemented by the AGC system of the regional control center (RCC) (Xie et al., 2017).

However, due to the continuous improvement of the installed scale of RESs, the regulation pressure of CGs continues to increase, and the regulation capacity of some coal power units gradually decreases after the transformation, so the demand for RES and conventional generators to participate in AGC is increasingly urgent. Tan et al. (2022) considered the real-time control strategy of minimizing the weighted regulation mileage of conventional power supply and the power rejection level of new energy. The advantages of RESs participating in AGC systems are explained by the replacement of the regulation capacity and reduction of the regulation cost. Lyu et al. (2022) proposed a rolling time domain control method considering the dynamic operation constraints and internal kinetic energy of wind turbines. This strategy applies to the grids with large-scale wind power integration and insufficient frequency regulation capability of conventional resources. At present, there are many research results on RESs participating in AGC around the world, but if the large-scale application in the power grid is required, the following two key issues must be studied.

2.2.1 Does RES participation in AGC affect its consumption?

AGC units are traditionally required to have the ability to regulate up and down at the same time, and the regulation upward for the RES generator is realized through the derating operation. In addition to affecting their maximum consumption, it is not economical to limit their power generation level due to the relatively low cost of new energy power generation. Therefore, at present, few RESs are required to participate in AGC worldwide and mainly provide downward regulation services, which can be identified as power curtailment. However, downward regulation also means power restriction on the output of RESs, which results in lost revenue for generators, so they are limited to specific scenarios such as section control or auxiliary peak shaving. In recent years, many scholars have been analyzing the effective ways and effects of new energy participation in power grid regulation. Fang et al. (2021) studied the economy and reliability of RESs providing regulating services, which show that RESs participating in AGC can reduce the number of online CGs to meet the total ramp rate and thus reduce power curtailment in the long term. RESs can get more revenue for the energy market due to the reduced generation provided by the CGs. However, the conclusion may be limited due to the lack of validation for the actual operation.

2.2.2 Can the regulation performance of RES meet the operational requirements?

Many operational experiences have shown that RES generators' regulation performance at the optimal operation stage (stable wind speed or light) is far from that due to thermal power, hydropower, and energy storage (ES) (National Renewable Energy Laboratory, 2019), but due to the uncertainty of weather conditions, it cannot have stable and reliable power generation capacity. Therefore, how RES generators can participate in AGC like CGs has been a hotspot of research in recent years. Colorado in the west of the USA is the only BAA that requires all new energy sources to have AGC conditions. Because it does not trust the assessment of the upward regulation capability based on power generation prediction, the RES cannot provide bi-directional regulation reserves and only can provide downward regulation, mainly relying on the upward regulation of the thermal power units. Although in theory, RES generators have a good regulation capacity, as Belgium, Germany, Denmark, and other countries have carried out pilot projects to verify that new energy is capable of providing highly reliable regulatory services (Joos and Staffell, 2018), the feasibility of its participation in the regulation markets or balancing power markets is low due to the characteristics of wind and light (Spyrou et al., 2022). In addition, to improve the stable output capacity of grid-connected RES generators, it is a convenient way to add ES at the side of the power station. Through wind storage, optical storage, wind and solar storage, and other forms, new energy power stations can be connected to the grid in a friendly manner, such as wind and solar storage combined power generation (Teng et al., 2014). The regulation capacity of RESs is limited and mainly relies on other control methods and regulating resources to maintain the power balance in the short term.

To sum up, RESs, technically speaking, can provide a regulation capacity in today's power systems, but the power imbalance produced by RESs is massive and barely mitigated by limited CGs dispatched by individual CAs. Some effective electricity market rules such as reasonable imbalance pricing can get RESs to improve the forecasting technology and reduce the corresponding imbalance (Wu et al., 2020), but the dispatch and operation modes for active power balancing require some changes and breakthroughs.

3 Three general classes of structures for control area cooperation

In real-world electric power systems, a variety of methods currently exist to increase cooperation among different CAs. The key idea of these methods is sharing variability and uncertainty over larger geographic regions, and then the netted variability and uncertainty can be reduced, which will reduce power curtailment, operating reserve requirements, and regulation mileages of regulating resources such as CGs and ES without deteriorating system reliability.

There is often a tradeoff between operational benefits and complexity when considering the control area's cooperation mechanisms. Three cooperation mechanisms exist and represent the main development stages in electric power systems around the world. There is no one-size-fits-all approach, and thus each country or region has crafted its combination of control structures, market designs, and system operations to achieve the control areas' cooperation. There are three typical structures for CA cooperation, and the technical aspects are shown in Table 1.

3.1 Imbalance sharing with the decentralized structure

In general, the decentralized structure makes all CAs comply with the self-balancing regulation duties, but if one of them cannot effectively regulate ACE within the defined limits, neither frequency nor interchange would be within the acceptable ranges since each CA only knows its own information. Therefore, the North American Electric Reliability Corporation (NERC) approved the control

TABLE 1 Technical aspects for CA cooperation fall into three major structures.

Classification	Imbalance sharing with the decentralized structure	Consolidated operation with the hierarchical structure	Consolidated operation with the centralized structure
Change of control modes	No	Yes	Yes
Date sharing requirements	Part of CA's operational data	Part of CA's operational data	All of CA's operational data
Typical shared data	Reserve requirements	Reserve requirements and basic characteristics of CA's power system	Generator characteristics of available capacity and basic characteristics of the whole power system
The role of regulating resources	Dispatched by CA	Dispatched by CA	Dispatched by RCC or the new single CA

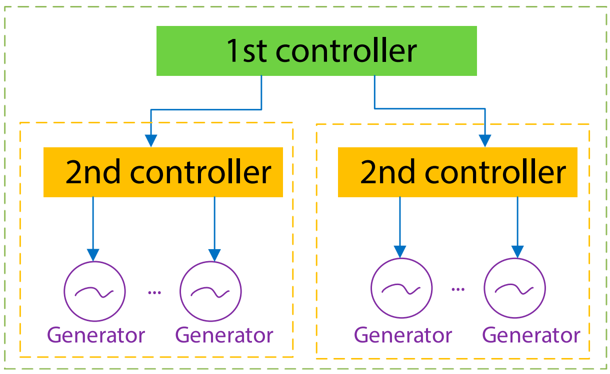

FIGURE 2
Decentralized structure with power imbalance sharing.

performance standards (CPSs), such as the CPS1 and Balancing Authority ACE Limit (BAAL) compliance evaluation (Standard BAL-001-2 in NERC, 2022) in 2016, which aim to drive each CA to stabilize the frequency and ACE that cannot be continuously controlled to zero. However, this kind of active power sharing or support is limited. For example, when the MW power generated in one area is equal to the MW power consumed in another, the whole power grid can be well balanced. However, each CA still has to adjust its AGC units to stabilize the ACE, which would produce unnecessary wear-and-tear costs and larger frequencies or tie-line power fluctuations. Some balancing functions can be shared if CA cooperation exists. The basic decentralized structure for power imbalance sharing is shown in Figure 2. It shows the two-level hierarchical structure, which is divided into the first and second controllers. The first controller mainly represents the RCC in China, ISO or the regional transmission operator in the US power grids, or the European Network of Transmission System Operators for Electricity (ENTSO-E) in Europe. The second controller is the provincial power grid in China, the BAA in the US, or the control block/area in Europe. In imbalance sharing with the decentralized structure, the first and second controllers both have clear control boundaries, especially the control boundaries of the second controller are non-overlapping.

3.1.1 Close-loop ACE sharing

As is known, the signs of their ACEs are frequently different, and relaxed control can be achieved because of the ACE diversity. Therefore, a classical method of cooperation between CAs called ACE diversity interchange (ADI) was first organized and implemented by Enerex Company located in Iowa, USA (Oneal, 1995), and put into operational practice by New York ISO, ISO New England, and Maritime in the Northeast USA in 2002. Midwest ISO (MISO) implemented the ADI in 2005 but discontinued its use in 2009. ADI can achieve a relaxed control for multiple CAs due to the sign diversity among ACEs that usually exists in real-time operation, which is expected to be smaller than the sum of their ACEs. Therefore, the participating CAs can reduce their ACEs and corresponding regulation movements through coordination, respectively. Then, the relative variability and uncertainty in the net load can be lowered and the corresponding regulation burdens be reduced.

For instance, the ADI-based ACE is calculated based on raw ACE. To calculate the sum of ACEs of participating CAs ACE_{ADI} and dividing CAs into large and small groups are the basic methods. The CAs in the large group and ACE_{ADI} have the same sign, and the other CAs in the small group ideally can avoid any regulation action due to the reserve regulation for ACE_{ADI}. The specific values are calculated by Eqs (2) and (3).

$$ACE_{u,\mathrm{SG}} = 0, \tag{2}$$

$$ACE_{v,\mathrm{LG}} = \frac{ACE_v}{\sum_{v=1}^{V} ACE_v} ACE_{\mathrm{ADI}}, \tag{3}$$

where $ACE_{u,SG}$ and $ACE_{v,LG}$ are the ACEs of the u-th in the small group and the v-th in the large group, respectively. V is the number of CAs in large groups.

The process of action of ADI can be understood from CPS1/BAAL. If all CAs participate in ADI within the interconnection when CPS1 scores are over 200%, it means that the sign between the ACE and frequency deviation is different. Thus, ADI would move the corresponding ACE toward zero without changing the ACE sign, and the CPS1 scores will decrease and be fixed at 200%. When some areas' CPS1 scores are <100%, ADI turns its raw ACE to ADI-based ACE, which may increase the CPS1 scores by >100%. There is a similar negative impact on BAAL if some areas cannot comply with the predefined operation limits. Some limitations of ADI are analyzed in detail as follows.

(1) The ADI adjustment limits for potential excessive unscheduled power flows. When implementing the ADI, it should be noted that the ADI could cause some congestion problems in heavily loaded transmission sections. Therefore,

an experience-based restriction cap has been adopted for ADI adjustment, which would decrease the efficiency of ADI implementation. In other words, the improper value would result in overconservative adjustments that reduce the efficiency of ACE diversity sharing or in overaggressive adjustments that jeopardize the system's reliability and thus be penalized financially. Some modified methods have been proposed in Etingov et al. (2010) and Zhou et al. (2010), but transmission-based ACE limits are impossible to calculate due to the net interchange component of the ACE being composed of multiple tie lines.

(2) ADI aims to make ACEs more effective. Participating ACEs could become smaller or tend toward zero, but it may make the CA's regulation process unclear within the NERC standards, just like CPS1 and CPS2. The experience from the US power grids shows that ADI can improve the CPS2 compliance scores due to less ACE, making it easier to control within L_{10}, which was replaced by BAAL in 2016. For the CPS1 compliance scores, the impact on each CA is relevantly complicated.

(3) ADI is not a mandatory rule for CAs. Any CA can suspend participating in ADI if they want to operate independently, and the flexible options make the ADI unstable. Specifically, every CA that participates in ADI has to procure sufficient regulating reserves for its independent operation conditions, and it seems that the benefit of ADI is possibly limited to reducing the regulation mileage and real-time burdens. The procurement of regulating reserves seems not to reduce when compared with not participating in the ADI if the number of participating CAs is small.

3.1.2 Open-loop ACE sharing

In Europe, the International Grid Control Cooperation (IGCC) is similar to ADI due to the usage of ACE diversity. IGCC is a promotion of the Grid Control Cooperation, where the four CAs within Germany optimize the control reserve provision, which is technically implemented by AGC systems (Zolotarev et al., 2012). IGCC was launched in October 2010 as a regional project and has grown to cover 27 European countries supported by the Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO). Remarkable benefits have been obtained by its practical application; the "German Paradox" shows a decrease in regulating requirements with increasing proportions of RESs in the German power grid due to CA cooperation (Hirth and Ziegenhagen, 2015), and the international and national CA cooperation that consist of GCC or IGCC lead to efficiency savings and reduced requirements for balancing power (Ocker and Ehrhart, 2017). In 2022, ENTSO-E gave an overview of the IGCC's achievements, which shows that it has enabled energy savings to reach more than 2,700 GWh per quarter, corresponding to a value of quarterly savings of 118 million euros in Q4 2021 (European Network of Transmission System Operators for Electricity, 2022). Therefore, an interesting issue is to find the difference between ADI and IGCC. Tokumitsu et al. (2020) proposed some points such as the difference between raw ACE and open-loop ACE that make ADI have a better control performance due to real-time sharing. It should be noted that when we compare the differences between the two methods, the basic concept and background should be considered.

1) From the reliability perspective, the experiences of Europe and the USA are different. European interconnected power grids use IGCC to create a reduction in regulation reserve requirements while the US power grids use ADI to create a reduction in regulation burdens and movements. ADI is based on the real-time ACE and focuses on the future regulation directions of participating CAs, but IGCC is based on the open-loop ACE and cares about the last regulation directions and the corresponding amount of regulating reserves activated by the CAs, which is calculated by Eq. (4).

$$ACE_{i,\text{open-loop}} = ACE_i + \sum_{j=1}^{J}\left(Sche_j - Gen_j\right), \quad (4)$$

where $ACE_{i,\text{open-loop}}$ is the open-loop ACE of the i-th CA. $Sche_j$ and Gen_j are the scheduled and actual power of the j-th market entity that provides regulating services, respectively.

Therefore, the IGCC may have lower reliability than ADI in the actual operation. In some cases, IGCC will even increase the wear and tear of the generators and bring the reverse regulation process for frequency recovery.

2) From the economic perspective, IGCC is established in the process of the European centralized market with the open-loop ACE composed of activated regulating reserves and raw ACE. It should be noted that the open-loop ACE represents power imbalance in the case of only the spot market operation and is the basic data to determine the total amount of reserves that should be procured (Abbaspourtorbati and Zima, 2016). By sharing the open-loop ACE, the regulating reserve of each CA will be reallocated, and the uneconomical reserve is not procured and unnecessary AGC deployment is reduced. However, the relationship between ADI and provision of the regulating reserve is relatively small; the unscheduled flows when ADI operates is not specifically measured and the corresponding compensation will be adopted. It is similar to promoting mutual power support between different CAs under CPSs, with the main purpose of improving the frequency quality of the interconnection.

Recently, more new regulating resources have brought challenges to IGCC due to the large range in response times of different resources. In Europe, Full Activation Time (FAT) is defined to determine the overall regulating reserves for all CAs, which is the period between sending a new control signal by the AGC system and the corresponding activation or deactivation of generators (ENTSO-E, 2015). However, the response times of thermal power generators and new regulating resources such as RESs and ESs have obvious differences, therefore a new setting of FAT considering the standardized prerequisite response time is required for future IGCC operations (ENTSO-E, 2021).

3.1.3 Contingency reserve sharing

Contingency reserve sharing is the simplest in multi-type reserve sharing because the exchange of significant amounts of electricity is relatively small and rare, which may not require extra market transactions and specific financial compensation. Large-scale power loss such as large generator trips or HVDC faults increases stress on secure and stable operations, especially in China, with massive electricity power being transmitted from the west to east by the UHVDC transmission lines. The UHVDC faults cause severe frequency deviation to the receiving power grids. In 2015, a bipole block of UHVDC made the frequency of the East China power grid drop to 49.563 Hz, which was the lowest frequency nadir in the last 10 years. The contingency reserve owned by one CA can barely fill the power loss, thus the dynamic ACE (DACE) has been proposed for coping with large-scale power loss. The DACE allocates specific regulation power to all CAs based on *pro rata* principles, and then, the AGC systems of the i-th CA recalculate the ACE combined with the allocated regulation power $P_{i,\mathrm{reg}}$. The basic DACE algorithm is expressed in Eq. (5).

$$ACE_{i,\mathrm{DACE}} = -10B_i\left(f_a - f_s\right) + \left[\left(NI_a - NI_s\right) + P_{i,\mathrm{reg}}\right]. \qquad (5)$$

Based on the actual operations, some modified strategies for DACE have been proposed in Tan et al. (2017), where a calculation model was developed for the available transfer capacity of tie-lines used for estimating reserve capacity deliverables and an improved algorithm was provided to activate AGC and contingency reserve among multiple CAs in the same direction.

In US power grids, some similar methods have been used by Southwest Power Pool (SPP) and Midcontinent ISO (MISO) for CAs. SPP uses the assistance schedule calculated based on the power loss that becomes part of each participating CA's scheduled net interchange and therefore reflects in its ACE (Southwest Power Pool, 2022). MISO uses the automatic reserve sharing (ARS) to cope with contingency events. The ARS allocates reserves requested to the MISO first using the available contingency reserves. If there are insufficient contingency reserves owned by MISO, then the allocations are expanded to include contingency reserves owned by Manitoba Hydro (Midcontinent ISO, 2023).

With the share of DERs, especially distributed RESs, increasing at the lower voltage levels in modern power grids, the operational condition faces great challenges, and local power balancing has become a new problem (Kouveliotis-Lysi et al., 2022). To cope with the situation, Ekomwenrenren et al. (2021) proposed the concept of establishing a local control area (LCA), which is smaller than the traditional CA and is partitioned into geographically small sections (e.g., several substations). The LCA quickly achieves active power balance after internal disturbances, by controlling the DER, and the upper coordination layer achieves power support between different LCAs. Ekomwenrenren et al. (2023) further proposes a direct data-driven approach that partitions the power system into LCAs. Some similar control structures have been proposed by other scholars. Chakraborty et al.(2023) considers the setting of an area-priority recovery strategy for the fluctuation of power flow in the connecting lines between LCAs, taking into account the safe distribution of power flow while improving the overall frequency regulation performance, and Mejia-Ruiz et al. (2022) proposed a similar technical approach for the operational characteristics of distributed ESs. In future power grids, the responsibility for power balancing control will inevitably gradually sink, so traditional CAs may also gradually shift toward LCAs, forming a simultaneous centralized coordination and an internal autonomy operation situation.

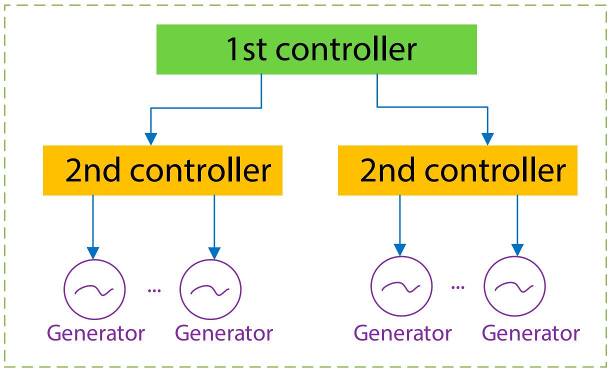

FIGURE 3
Consolidated operation with the hierarchical structure.

3.2 Consolidated operation with the hierarchical structure

Consolidated operation is the merging of two or more CAs into a virtual operational entity, which requires cooperative agreements. However, under the hierarchical structure in some countries such as China, the existing RCC and several provincial CAs cannot be combined as new control centers due to the current dispatching management structure. The basic consolidated operation with the hierarchical structure is shown in Figure 3. In the consolidated operation with the hierarchical structure, the first and second controllers are both within the same control boundary, and the first controller calculates the control target and sends it to the second controller, which then sends it to the generators for execution.

To stimulate the enthusiasm of the majority of market entities to provide regulation services, the frequency control performance of AGC units is improved, and the allocation of regulating resources optimized. On 1 April 2021, the southern regional regulation market officially launched its settlement trial operation, which was the first one in China with regulating resources as its trading product, and it was officially put into operation on 1 July 2021. China Southern Power Grid (CSPG) consists of the Guangdong, Guangxi, Yunnan, Guizhou, and Hainan provinces and the Yunnan power grid has been asynchronously interconnected with the main structure of the CSPG power grid since 2016. There are eight control areas and nine AGC systems within CSPG, and most of them maintain the balance between generation and load within their geographic boundaries. Along with the established regional regulation market, CSPG proposes the unified frequency control (UFC) within its geographic region, which aims to break the barriers between provincial control areas, improve overall frequency regulation capacity, and reduce operational costs (Chen et al., 2022). In 2019, the actual operation results showed that the qualification rate of controlling the grid frequency within 50 ± 0.04 Hz increased from 94.403% to 95.315%, and the time of ACE continuously within the emergency zone reduced from 8.114 to 5.826 s, which illustrates that the UFC improves the overall regulation quality by adopting the undifferentiated calling of generators located in different CAs.

The UFC-based AGC system is implemented in the RCC, and each provincial CA is equivalent to an AGC unit controlled by the RCC, but the hierarchical structure of the RCC and CAs still exists. To cope with the time-delay effect between different AGC systems, the UFC-based AGC system requires individual CAs' AGC systems to send the real-time regulation process and then calculate the overall regulation requirement with the unregulated power, which refers to an AGC unit that is not yet completed during the tracking process, and then calculate each CA's ACE and send it to the individual CA that directly replaces the local raw ACE. The new ACE is calculated by Eq. (6).

$$ACE_i = \frac{PF_i}{\sum_i PF_i}\left(-10B_{\text{region}}\Delta F + \sum_{j=1}^{J} Ureg_j\right), \tag{6}$$

where N is the number of CAs, B_{region} is the frequency bias of the CSPG except Yunnan power grid, and $Ureg_j$ is the unregulated power of the j-th CA. PF_a is the area participating factor based on the bid for the share of the current regional regulation market.

A similar hierarchical structure exists in Spain even though it is only a CA from the perspective of the European interconnected power grid. The Spanish power system has one master regulator and four control zones that correspond to the four main companies (a large number of generating units). The control zone can be seen as a CA to easily analyze the technical features. The AGC operation in Spain is based on the hourly secondary reserve market, and each CA can compete not only when bid in the secondary reserve market (Miguélez et al., 2008) but also when providing the regulation service based on their respective dynamic performance, which is evaluated online with a sampling time of 4 s (Olmos et al., 2004). The hierarchical structure is different from the standard hierarchical structure system in Europe (Egido et al., 2009). The Spanish AGC master regulator operates from the technical and economic points of view and distributes the ACE is calculated by Eq. (7).

$$ACE_{z,\text{spain}} = \frac{K_z}{\sum_z K_z}\left[-10B_{\text{Spain}}\left(f_a - f_s\right) + \left(NI_a - NI_s\right) - \frac{1}{G}\sum_{z=1}^{Z} NID_z\right] + \frac{1}{G}NID_z, \tag{7}$$

where $\text{ACE}_{i,\text{spain}}$ is the ACE of the z-th CA in the Spanish power system. K_i is the participation factor obtained from secondary reserve market results, B_{Spain} is the frequency bias of the Spanish power system, G is the control gain and was set at 5 when the AGC system was first put into operation in the early 1980s, and NID_z is the deviation from its scheduled value in the power generation of the z-th CA.

The structures introduced above are all aimed at active power balancing or frequency control, and there is a special structure that exists in the North China power grid. In 2009, the first 1,000 kV ultra-high-voltage alternating current (UHVAC) demonstration project was put into operation between the North and Central China power grids, and any disturbance occurring anywhere in the interconnected power grid has an impact on the transmission power fluctuations of the interconnection lines. This fluctuation may disrupt the static stability of the power grid. Therefore, effective control of the interconnection line power is crucial (Gao et al., 2009). Therefore, North China RCC has adopted a control strategy of multi-area collaborative sharing of the regulation power of the interconnection lines. Each provincial power grid not only has to maintain ACE within the qualified range but also has to add components reflecting the power fluctuations of the UHVAC in the respective ACEs that are calculated by equation (8) if the direction of the ACE of a CA and the deviation power of UHVAC based on the scheduled power are consistent and the CA is the responsible one (Shang et al., 2010).

$$ACE_{i,\text{UHV}} = ACE_i + \frac{C_1 B_{i,\text{R}}}{\sum_i B_{i,\text{R}}}\left(\left|D_{\text{UHV}}\right| - C_2 L_f\right), \tag{8}$$

where $\text{ACE}_{i,\text{UHV}}$ is the ACE of the i-th CA considering the UHVAC deviation control, C_1 and C_2 are the predefined control gains, $B_{i,\text{R}}$ is the frequency bias of responsible CA, and L_f is the threshold of UHVAC deviation control.

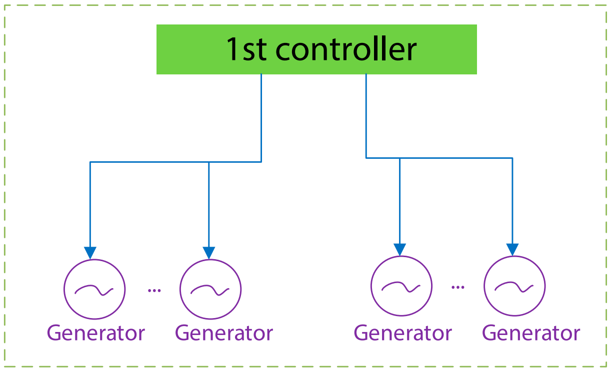

FIGURE 4
Consolidated operation with the centralized structure.

3.3 Consolidated operation with the centralized structure

The previous content has already introduced many coordinated strategies for multiple CAs. However, regardless of how these CAs cooperate, it is always difficult to eliminate the disorderly regulation between CAs and cannot surpass the control quality of a single CA. In other words, if some CAs form a single CA, the new CA could effectively make full use of the diversity factors of the original CAs. The basic consolidated operation with the centralized structure is shown in Figure 4. The consolidated operation with the centralized structure is more flattened and uses one controller to dispatch all the generators in the entire power grid.

In the US power grids, consolidating CAs provides a promising method to mitigate these problems by enabling the sharing of balancing resources through operating different CAs as a single CA (Diao et al., 2012). An actual consolidation of 26 CAs in the MISO area into a single CA was done on 6 January 2009. The original CAs were merged and all balancing functions were centralized. Also, the consolidation can become virtual or partial based on certain sharing agreements between CAs. The consolidated CA is the most cost-effective solution among the other CA cooperation methods due to it transmitting the existing CAs' structure with a limited region to all or a large part of an interconnection. Comparing the consolidated operation with the hierarchical structure, the dispatch model within the single AGC system of the entire interconnection gets more complicated with the massive numbers of AGC units when RESs, ESs, and DERs participate in the future.

It is also possible to create a coordinated operation without physical consolidation, which requires establishing some cooperative agreements. In China, the RCC and provincial CAs are all in the same geographical region, but the main purpose of the RCC's AGC system is to stabilize the frequency by its direct generators without any physical area. However, the generators dispatched by the RCC are usually located in different CAs, but the purpose of their AGC systems are all different, such as the RCC calculates the ACE under the Flat Frequency Control (FFC) mode, and provincial CAs calculate the ACE under the TBC mode. To coordinate the RCC and CAs, the provincial generalized tie-line model is proposed to divide the control boundaries between the RCC and corresponding CAs with direct generators (Gao et al., 2009; Ma et al., 2018). Then, the RCC's AGC system can operate as the first controller, as shown in Figure 4, and provincial CAs can still operate as the second controller, as shown in Figures 2 and 3, for different coordinated schemes. Some small-scale CAs could calculate the ACE under the flat tie-line control (FTC) mode to mitigate the fluctuations of tie-line power, and the frequency is mainly regulated by the RCC under FFC and other CAs under the TBC mode (Tan et al., 2020).

4 Future work

4.1 CA cooperation in larger geographic regions by using HVDC

Strengthening the unified balance and coordination of the whole grid is an inevitable requirement for ensuring the safe and stable operation of the new power system. The China Power Grid is continuously strengthening the construction of UHVDC projects, with the continuous expansion of cross-regional HVDC transmission lines, and the ability of power exchange and resource exchange between different regional power grids is gradually increasing. It is necessary to consider the collaborative control method of HVDC as a frequency regulation resource with the AGC systems of the sending and reserving ends' power grids and multiple provincial power grids inside, utilizing DC backup to achieve unified control of active power balance among multiple CAs within a larger range of interconnected power grids. In the face of this new research topic, it is necessary to focus on analyzing the impact of HVDC lines on current AGC systems, establishing more accurate modeling for dynamic studies in future power systems (Pathak et al., 2019).

Except for China, the three major components of the US power grids—the Western Interconnection, the Eastern Interconnection, and the Electric Reliability Council of Texas—operate almost independent of each other. Very little electricity is transferred between the interconnections due to limited transfer capacity; Bloom et al. (2022) quantified the costs and benefits of strengthening the connection (or seam) between the Eastern and Western Interconnections to encourage efficient development and utilization of US energy resources. ENTSO-E has identified that the requirement for more than 60 GW are new HVDC lines in 2030 and is trying to give more benefits of exchanging reserves between asynchronous areas using HVDC lines (Tosatto et al., 2022). The current Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) has carried out a post-process to determine the HVDC setpoint (ENTSO-E, 2022), which can adapt to future changes in the European power grids but may face challenges in computational efficiency.

4.2 Coordination of large-scale RES base and CAs

To promote large-scale development and consumption of RESs, several large-scale wind and solar energy bases will be gradually formed in Inner Mongolia, Qinghai, Gansu, and other regions in China. In response to the complex power grid form of intertwined multiple RES bases and provincial CAs in the future, and to multiple scenarios such as real-time regulation of UHVDC lines, safety constraints of specific transmission sections, and self-balancing operation of RES bases, the unified optimization scheduling and control methods within the regional power grid as well as at the sending and reserving ends' power grids should be researched and considered, and coordinated optimization and complementary control strategies for multi-level control entities and multi-type regulating resources should be proposed, which support the safe and stable operation of large-scale RES bases. Dealing with this difficult problem requires considering two aspects. One is to treat the RES base as a traditional CA and consider how to utilize various regulating power sources such as thermal power, RES, and ES within the CA to meet the local control requirements. Secondly, the new energy base itself is also a new type of power source, and it is necessary to consider the regulation performance of this new-type power resource and the strategy of its participation in the unified control of the power grid.

4.3 CA cooperation adapted to DER integration

Real-time dispatch of the power grid will transmit from a coordinated mode of dispatching at all levels to a centralized and decentralized autonomous mode, and the active power and frequency control will gradually shift toward a coordinated control mode combined with centralized and decentralized structures. On the one hand, when the grid structure of the interconnected power grid is strong and closely connected, and the regional power market is relatively mature, continuously expanding the scope of power balance is an effective method to improve the economic efficiency of power grid operation and increase the consumption of RESs in a wide area. It is necessary to continue to research active centralized control architecture and coordination mechanisms that adapt to cross-level multi-control entities. On the other hand, the rapid development of DER has enabled local power grids to have a foundation for self-balancing. Local power grids can utilize flexible resources to meet local power balancing requirements through self-organization. Therefore, an appropriate amount of active power balancing function for large power grids will be extended to local power grids, such as low-voltage distribution networks and microgrids. It is necessary to gradually establish multi-level EMS and coordinated control systems for large power grids, distribution networks, and microgrids, overcoming the challenges of decentralized autonomy in local power grids and centralized coordination and control with large power grids. The coordination schemes between transmission- and distribution-level CAs for DER and the corresponding market models (Marques et al., 2023) require further in-depth research.

5 Conclusion

Variable RESs pose significant challenges to modern power grids, especially for active power and frequency control, and some new control structures and corresponding strategies are required to cope with the situations. Increasing the coordination between different CAs can positively impact the integration of large-scale RESs into modern power grids around the world. This article discusses the general structures of CA cooperation where the corresponding methods do not require adding more flexible regulating resources but focus on utilizing the advantages of the interconnected power grid, improving mechanisms and organizational forms, and achieving the sharing of flexible resources across the entire network. At present, there are already many control strategies and methods worldwide, and the CA cooperation has various forms such as decentralized and centralized structures within different operational mechanisms. It is necessary to further strengthen and enrich the cooperation mechanism of CAs to adapt to the development characteristics and control requirements of the new power systems.

Author contributions

CT: Conceptualization, Methodology, Writing–original draft, Investigation, Writing–review and editing. XT: Investigation, Writing–original draft, Funding acquisition, Methodology, Writing–review and editing. XZ: Conceptualization, Data curation, Funding acquisition, Writing–review and editing. TP: Writing–original draft, Data curation, Investigation, Methodology. RC: Project administration, Resources, Writing–review and editing.

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Conflict of interest

CT, XT, XZ, TP, and RC were employed by NARI Group Corporation (State Grid Electric Power Research Institute).

Publisher’s note

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