Research

Active Support of Power System to Energy Transition—Perspective

Addressing Frequency Control Challenges in Future Low-Inertia Power Systems: A Great Britain Perspective

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ABSTRACT

The ambitious global targets on decarbonization present the need for massive integration of renewable generation in power systems, resulting in a significant decrease in the system inertia. In addition to the reduction in system inertia, the transmission system in Great Britain (GB) faces some unique challenges owing to its relatively small capacity, while being decoupled from other transmission systems and with the renewable resources largely non-uniformly distributed across the system. This paper presents opinions and insights on the challenges associated with frequency control in a low-inertia system and the potential solutions from a GB perspective. In this paper, we focus on three main techniques that act over different time scales: synchronous condensers, inertia emulation, and fast frequency response. We evaluate their relative advantages and limitations with learnings from recent research and development projects in GB, along with the opinions on their roles in addressing the frequency control challenges in future low-inertia systems.

1. Introduction

Many power systems are experiencing significant decreases in their system inertia levels owing to the increasing penetration of converter-interfaced renewable generation [1]. In recent years, the challenges of operating low-inertia systems have been widely recognized [2], and comprehensive reviews of potential frequency control solutions have also been reported [3].

However, the transmission system in Great Britain (GB) faces some unique challenges compared with many other countries: The system is relatively small, with a total generation capacity of approximately 110 gigavolt–amperes (GVA) and a demand level of 20–50 gigawatts (GW) in 2019 [4,5]. The system is effectively decoupled from other transmission systems, although there is an ongoing rapid increase in high-voltage direct-current (HVDC) interconnections (from the current 8 links of 8 GVA to over 30 links of more than 30 GVA by 2028) [6]. A further decrease in inertia levels of up to 40% is anticipated by 2025 [7], compared with the current level.

The system has largely non-uniformly distributed renewable resources with relatively large amounts of renewable generation in the north of GB (Scotland), with the majority of the demand in the south. Power is transmitted via transmission corridors with limited capacity, resulting in increasingly obvious short-term regional variations of frequency and relative angles during disturbances.

In this paper, the authors present views and insights on solutions to address the challenges resulting from decreasing system inertia, with a focus on three main techniques that act over different time scales: synchronous condensers (SynCons), inertia emulation (IE), and fast frequency response (FFR). The focus of this paper is primarily on frequency control, with other related operability issues and opportunities in low-inertia systems being discussed in less detail.

2. Key challenges with transitioning to a low-inertia system

Defining "high" or "low" inertia is somewhat subjective—It is only meaningful when referring to a specific set of system conditions (e.g., overall system rating/capacity, largest generating units, loss of infeed/load, and percentage of loads supplied by converter-interfaced resources). Ratnam et al. [3] present several practices currently adopted by network operators, where a quantified matrix is used to indicate the (perhaps somewhat alarming) present and anticipated system-inertia levels.

Fig. 1 summarizes the key challenges related to frequency control in the GB system. The timeline (i.e., from historical high-inertia systems to a future very-low-inertia scenario) is presented, along with the various challenges that may be faced as the system evolves in the future. The figure is for indicative purposes only and is deliberately not concerned with exact specific inertia levels and/or timing details. This section focuses specifically on the first four challenges, which are already becoming apparent in GB.

2.1. Containment of frequency deviation

Many historical disturbances in the GB electrical system have led to under-frequency events (i.e., the initial event is a loss of generation), and there have already been challenges in effectively ensuring that the frequency nadir remains above the statutory lower limit, using conventional primary response from synchronous generators (SGs). With the continued decrease in inertia levels, it may become more difficult to contain the frequency, particularly in an efficient and economic fashion. Studies have shown that the conventional primary response becomes inadequate, and provision of primary response may significantly increase operational costs in the future; thus, different, and possibly faster, responses may be required [8,9].

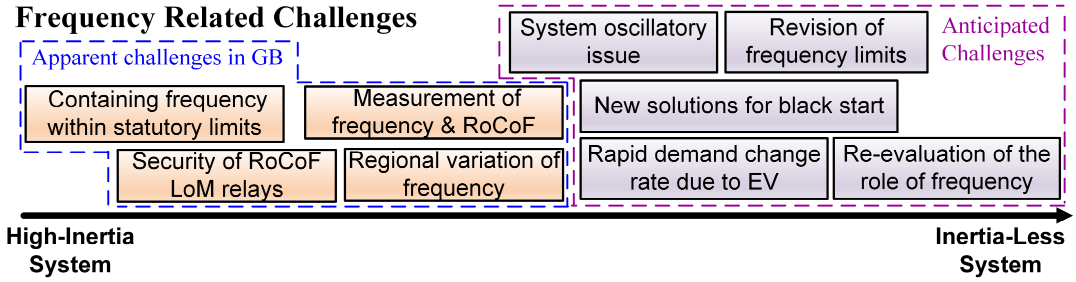

Fig. 1. Timeline of challenges with decreasing system inertia. RoCoF: rate-of-change-of-frequency; LoM: loss of main; EV: electric vehicle.

2.2. Security of rate-of-change-of-frequency (RoCoF)-based loss of main (LoM) relays

RoCoF relays are widely used in GB to detect and react to LoM conditions. They operate by disconnecting distributed-energy resources (DERs) when the measured RoCoF breaches the predefined RoCoF and time-delay thresholds [10]. Historically, the settings used in GB were 0.125 $\mathrm{Hz\cdot s^{-1}}$ with no time delay. This was in the context of high-inertia systems dominated by large SGs. With decreasing inertia, it has become increasingly challenging to operate the system within the 0.125 $\mathrm{Hz\cdot s^{-1}}$ threshold, as the amount of instantaneous "imbalance" power that will result in a RoCoF breach has been decreasing continually as the system weakens.

Ensuring the security and stability of RoCoF relays for non-LoM disturbances represents a major constraint for maintaining the required minimum inertia in the GB system [7]. Generally, there are three potential solutions to the problem: ① limit the RoCoF during power-imbalance events, ② update the settings to new values, and ③ seek new LoM protection methods. Option 1 has been adopted in GB by maintaining the required inertia level or containing the output of the largest generating unit to limit the RoCoF; however, it is clearly only a temporary solution. The annual cost of achieving this was 60 million GBP in 2017/2018, and it dramatically increased to 150 million GBP in 2018/2019 [11].

Presently, Option 2 is being adopted, with settings being updated to 1 $\mathrm{Hz \cdot s^{-1}}$ with a delay of 0.5 s. The new setting may ease the RoCoF security issue for the near future; however, it is not an ultimate solution, as some countries have already started planning for system conditions with RoCoFs over 1 $\mathrm{Hz \cdot s^{-1}}$ [12]. Further relaxing the RoCoF setting will compromise the dependability in detecting LoM events, thereby rendering the main function of the protection ineffective. Therefore, either Option 3, or more economic methods of limiting the RoCoF/boosting inertia (Option 1) must be considered.

2.3. Accuracy of frequency and RoCoF measurement

Faster system dynamics due to low inertia result in a requirement for faster measurements (i.e., less group delay in the measurement algorithm); however, this is usually accompanied by an associated significant error in the frequency and RoCoF measurements, particularly in the time period immediately following transients. This is clearly undesirable and affects the performance of monitoring and control systems that rely on measurements for decision making [2].

While filtering can be used to alleviate some measurement errors, it might also delay the decision-making process. Ultimately, there will always be a compromise between measurement accuracy and the consequent speed of operation. In a low-inertia system with higher RoCoF levels, the situation is exacerbated by the fact that less time is available to provide any mitigating reaction before the frequency limits are breached. This could lead to cascade tripping of generation units, under-frequency load shedding, and perhaps local or complete blackouts.

2.4. Regional variation of frequency and RoCoF

Frequency and RoCoF are never truly uniform values across a system during transient periods. However, reductions in system inertia mean that regional variations of these quantities will increase (this has been witnessed), which has led to concerns and possible requirements for locational consideration of post-event frequency management and response [9,13–15].

In the future, with further decommissioning of SGs and their power system stabilizers (PSSs), the system is expected to be more oscillatory in nature, during and following disturbances [16]. The uptake of electric vehicles (EVs) could lead to rapid demand changes, which also presents requirements for faster frequency response [17]. A revision of existing frequency thresholds may be required, especially low-frequency demand disconnection (LFDD) (load shedding) thresholds.

As reported in Ref. [18], existing LFDD limits could lead to unnecessary and excessive disconnections of demands during low-inertia conditions. The risk of an initial under-frequency event could lead to a subsequent over-frequency event with a consequent tripping of over-frequency protection, which could lead to further cascading events and ultimately a total blackout.

With the decommissioning of thermal plants, new solutions will be required to enable system restoration following full or partial system outages [16]. If the system is operating with very few or, in an extreme case, no SGs, the system dynamics will no longer be governed by the swing equation [19]. The role of frequency must be redefined/reassessed and the fact that swing equation–based dynamics in the system no longer apply must be considered. However, it is commonly accepted that a large-scale system may never operate with truly zero inertia, at least in the foreseeable future [2].

In addition to the frequency challenges presented in Fig. 1, the GB system also faces issues with a significant reduction in fault levels [20], with power-quality issues becoming a growing area of concern. The uptake of renewable generation also introduces voltage control challenges. The reliability of protection systems may also be affected by reduced fault levels. This is not only due to reduced and significantly variable fault levels, but also may be exacerbated by the diverse range of fault characteristics that are defined by converters' controller strategies and the energy sources "behind" the converters [21].

3. Addressing the challenges in low-inertia systems

As shown in Fig. 2, frequency disturbances are often initiated by faults, which are typically required to be cleared by the protection system within 140 ms [5] at the transmission level. This might lead to a loss of generation/demand, resulting in an overall power imbalance following the fault clearance. Subject to the settings of the LoM RoCoF relays and the magnitude of any power imbalance, there could be a subsequent loss of DERs.

Conventionally, the primary response from SGs, acting in the range of a few seconds, has been used to contain frequency deviations, followed by secondary and tertiary responses to return the frequency to normal levels and resume an economically optimized system dispatch. If the primary response fails to contain a frequency deviation, an LFDD could be instigated, possibly accompanied by other cascading problems; in the worst-case scenario, this could lead to blackouts.

It is clear that in many cases, multiple events (many of which are causally related) may occur in a timeframe prior to any primary-response impact, so future reactive solutions in a low-inertia context will be required to act before the conventional primary response. Furthermore, enhanced pre-event system monitoring and assessment functions may be required to continually supervise and report on the system status and resiliency, including instructions to enhance resiliency and responses to any future disturbance. This represents an area of emerging and ongoing research.

3.1. Pre-event solutions

For the pre-event period, a wide-area monitoring system was deployed in GB, as part of the Visualization of Real-Time System Dynamics Using Enhanced Monitoring (VISOR) Project to enhance real-time system awareness [22]. The VISOR system allows for enhanced frequency, voltage, and angle monitoring to identify potential operational risks (e.g., inter-area oscillations). An assessment of the reliability of protection systems, with the increasing prevalence of converter-interfaced sources, has also been a key topic of investigation in GB, including examining the validity of settings [23], evaluating the impact of increasing converter-interfaced generation on protection performance, and investigating mitigating actions [21,24,25].

3.2. Post-event solutions

This section will focus on three techniques, acting in various time scales following the initiating event (i.e., SynCons providing instantaneous and inherent inertial support; IE schemes with near-instantaneous (less than 20 ms) responses, and FFR), deemed as acting in the range of hundreds of milliseconds. For the post-event action in the case of a blackout, GB is also testing the DERs' capability to provide a black start [16]; however, this is outside the scope of this paper.

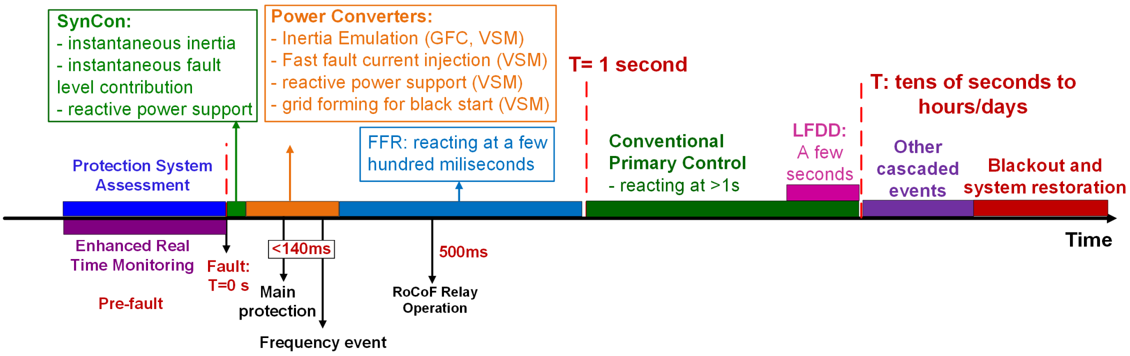

Fig. 2. Timeline of individual events potentially experienced during and following a disturbance. GFC: grid-following control; VSM: virtual synchronous machine; *T*: time.

3.2.1. Synchronous compensation

SynCons are essentially unloaded synchronous machines (SMs) (normally operating in motoring mode, but able to transfer instantaneously to generation mode if the frequency drops). This is a mature technology that has been in use for decades, typically for reactive power support [26]. SynCons inherently provide inertia to the system, responding instantaneously to power imbalances and contributing to the limitations of RoCoF [27,28].

In addition to inertia, SynCons are capable of providing a wide range of other services to address challenges, along with frequency control, as specified in Section 2. They contribute to the short-circuit level (SCL) to enhance system strength [29,30] and provide support for power system protection [31], reactive power support for dynamic voltage regulation with strong overloading and fault ride-through capability [32,33], and oscillation damping [34]. These are the main reasons that this technology is being “resurrected” and has attracted significant interest globally (e.g., GB [29], Denmark [35], and the United States [36]).

Specifically in GB, the Phoenix project was undertaken to design and demonstrate a hybrid SynCon and static-condenser (STATCOM) system, which is referred to as a hybrid synchronous condenser (H-SC). An outline of the H-SC arrangement is presented in Fig. 3, where the SynCon and STATCOM units are connected to a high-voltage (HV) bus through a three-winding transformer and coordinated via a master controller. The 140 megavolt–amperes (MVA) H-SC unit has been installed in the Neilston substation in Scotland [37]. The location was chosen strategically and was based on extensive studies considering the challenges discussed in Section 2.

The design of the H-SC and a coordinated control scheme aims to complement the relative strengths of the SynCon and STATCOM; thus, it optimizes the overall performance and maximizes the benefits. Within the H-SC arrangement, the SynCon is the main contributor to the system inertia and SCL, as these cannot be effectively provided by the STATCOM. Compared to power-electronics devices, the strong overload capability is advantageous for providing effective voltage support during severe depressions.

The STATCOM is used as the main provider of “fast” reactive power for voltage regulation. During fault and switching phenomena, it can quickly exchange reactive power to assist in maintaining voltages within limits. The STATCOM is also relatively more suitable for mitigating power quality issues, as it has faster response capability (typically in the order of milliseconds). When implemented with advanced control schemes, it can ① act as an active harmonic filter (i.e., suppress harmonics over a wide range of frequency spectra), ② prevent transient currents and voltages, ③ balance phase currents (caused by unbalanced operation of non-linear loads), and ④ mitigate voltage fluctuations that can produce flicker effects in industrial and domestic systems.

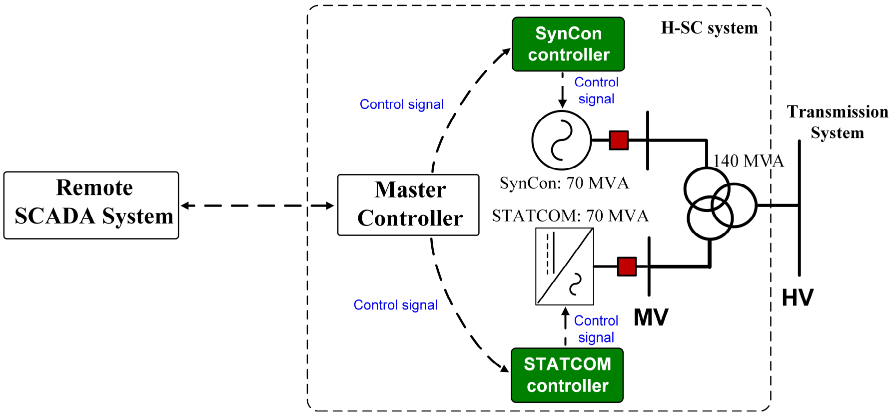

Fig. 3. Outline of H-SC arrangement in the Phoenix project. SCADA: supervisory control and data acquisition; MVA: megavolt–ampere; MV: medium-voltage; HV: high-voltage.

3.2.2. IE from power converters

Emulated (also commonly referred to as "synthetic") inertia from converters is well documented, and several control topologies have been proposed, with varying degrees of functionality and complexity [38]. Grid-following control (GFC) appears to be the most common approach for grid-connected converters and can provide inertial responses via an extra control loop [39,40]. GFC requires the measurement of the grid frequency, typically via a phase-locked loop (PLL). However, PLLs may not be viable in low-inertia systems because of increased frequency variations (making it difficult to reliably follow the frequency/angle continuously) and their susceptibility to signal noise. With any form of emulated inertia, a very fast and reliable response is required, or the controller could actually have a detrimental (as opposed to supportive) impact on the overall system [2]. It has also been reported that PLL tuning can compromise overall system stability [41].

An alternative to GFC for IE is the virtual synchronous machine (VSM), which is a family of grid-forming converter technologies that has gained significant interest in GB, and other locations where decreasing inertia is causing concern [42–44]. A trial of a 69 megawatts (MW) grid-connected wind park operating in VSM mode was conducted in 2019 [45]. In addition to providing inertia, VSMs can also increase system support by mimicking SG behavior during grid disturbances (e.g., reactive power/voltage support) [46]. Visma [47], a VSM, and synchronverters [48] represent the first generation of VSMs and reproduce the behavior of a SM in great detail, including all behaviors defined in the classic SM electrical and mechanical equations. Several studies on these controllers have been carried out, considering different energy sources [49–51]. Simpler structures have also been investigated to recreate the behavior of an SM, based solely on the swing equation [52], delivering similar results.

For both GFC and VSMs, it is likely that additional energy will be required to provide sustained and useful levels of emulated inertia. Some methods operate generating resources non-optimally (outside the "maximum power point") to provide headroom for the provision of additional active power when an inertial response is required. However, this is not a cost-effective option. Battery-energy storage solutions (BESSs) represent one of the most popular sources of additional active power, with ongoing studies and tests investigating optimal sizing, location, and so forth. [53].

3.2.3 Fast frequency response

Generally, FFR refers to frequency-control schemes that provide faster responses than the primary response, which has been traditionally provided by SGs. The required response times for conventional primary response vary across countries; in GB, it is typically required to activate within 2 s, with full delivery of the required power within 10 s of the initiating event [54]. Presently, there are no commonly accepted criteria for FFR. In this study, FFR is considered to have an activation time of no longer than 500 ms after the schemes that event initiation, and full delivery time within

1 s. With these criteria in mind, FFR should really be provided primarily by converter-interfaced resources (e.g., HVDC, BESS, etc.) [17,55].

FFR can be categorized into two main types, according to the activation mechanism (i.e., droop and direct step changes in the power reference). Droop-type FFR is similar to conventional governors incorporating droop control, with converters having an advantage in that they do not exhibit delays due to turbine dynamics, and thus can provide relatively faster responses than SGs.

In GB, the enhanced frequency response (EFR) service is a droop-type response adopted to address decreased inertia. The EFR is mainly provided by BESS, with a required activation time of within 500 ms and a full delivery time of less than 1 s [49]. Droop control is a type of distributed control, which is advantageous because no communication is required for coordinating with other droop-controlled units. However, the output power reference in droop control changes proportionally with the magnitude of the frequency deviation. Therefore, for large disturbances, the frequency could deviate significantly in order for the power reference to be adjusted by the droop characteristic to meet the required power imbalance.

The direct-power-reference change method is typically triggered by the frequency magnitude and/or RoCoF. Thresholds are used, where a fixed amount of power is injected to/retracted from the system when the thresholds are violated. Compared with droop controllers, the advantage of this type of control is that, once activated, it will react to the targeted amount of power at the fastest rate. However, this type of control can only play a facilitating role in frequency control, as it is only capable of reducing the power imbalance. It cannot regulate the frequency to the desirable level, as the response is not proportionate to the deviation (as is the case with droop, which also has drawbacks, as explained earlier). Coordination may be required across all participating resources to achieve optimal performance.

For example, wind farms can provide fast power injection even while operating at the maximum power point, but only for a short period of time. Hence, another resource will be required to coordinate with the response from wind to avoid a second frequency dip that could be caused by the drop in wind power to re-accelerate the turbine. This could potentially bring about the need for communication and relatively complex wide-area coordination and aggregation controllers.

3.2.4 Comparison of the solutions for future frequency control

Table 1 presents a comparison of the strengths (using admittedly subjective metrics) of the various techniques in addressing frequency-control challenges, as discussed in previous sections (i.e., SynCon, IEs with GFC and VSM, and FFR). Unless specifically highlighted, comparisons are made, based on the effectiveness of these solutions with the assumption that they have the same capacity.

Table 1

Comparison of the frequency control capability of SynCon, IEs with GFC and VSM, and FFR in low-inertia systems.

Solution	Cost	TRL	Frequency control challenges					
			Limit RoCoF	Frequency nadir	Regional behavior	System oscillation	Rapid Demand change	Black start
SynCon	High	9	Strong	Weak	Medium	Medium	Medium	Supporting
IE with GFC	Low	7[a]	Strong	Medium	Medium	Medium	Strong	Supporting
IE with VSM	Low	7	Strong	Medium	Medium	Medium	Strong	Grid forming sources
FFR	Low	8–9	Medium	Strong	Weak	Weak	Strong	Supporting

TRL: technology readiness level.

[a] GFC is a mature technique by itself, but the use of GFC for IE is still during trialing stage and has not yet been widely adopted.

From a cost perspective, IE and FFR can be achieved relatively economically by deploying dedicated control algorithms on existing converter-interfaced resources. The deployment of SynCons requires either the installation of dedicated new units or the conversion of retired SGs, which would be relatively costly. Furthermore, for these solutions to play an effective role in frequency regulation, sufficient aggregate capacity is required. As a rapidly increasing amount of converter-based resources is expected to be installed in the system for integrating renewables, it is anticipated that a significant amount of converter-based resources could potentially be enabled with IE and FFR to support future frequency control, whereas for SynCon, a significant dedicated capacity (either via existing plant conversion or new installations) would be required. However, as mentioned in Section 3.2.1, the key attribute of a SynCon unit is its similarity to an SG, so it is capable of delivering a range of extra services, in addition to frequency control.

SynCon is a mature technology that has been used in power systems for decades, while IE and FFR have been introduced in the past decade. Active trials have been conducted for IE for both GFC and VSMs [45,56,57]; therefore, the technology readiness levels have been increasing with recent large-scale trials. Accordingly, IE with both GFC and VSM is expected to play a more active role in frequency regulation in the near future. In comparison, FFR is relatively more mature, as it has been used/rolled out as an ancillary service in various countries (e.g., the EFR service in GB) [58].

Limiting the system's RoCoF is critical for both frequency control and ensuring the stability of RoCoF relays, thereby avoiding unnecessary and unwanted tripping of distributed generation. As SynCon can provide instantaneous inertia to constrain the RoCoF during power imbalances, it is particularly valuable in enhancing the security of RoCoF relays, with no intentional delay settings applied, which is still the case for a certain percentage of relays in GB.

The process of updating the settings represents a major and ongoing activity. It remains difficult to effectively mitigate the risk of RoCoF-relay maloperations with no delays applied using IE and FFR, owing to inherent measurement delays impacting the IE/FFR functions. However, with the introduction of certain changes in the recommended settings for RoCoF relays (e.g., a 0.5 s delay in GB), IE is expected to react sufficiently fast to limit the RoCoF to mitigate maloperation risks in the future.

SynCons do not have connected prime movers, so their inertia is relatively low (typically 2–3 s [28]), although the addition of flywheels can increase their inertia (but also increase the accelerating power requirements, which could be disadvantageous). In contrast, for IE, the inertia constant can be relatively easily tuned to provide a flexible level of emulated inertia. FFR is mainly designed to assist in the re-balance of supply and demand; however, it could also act to indirectly limit the RoCoF, especially if it can react within the time-delay setting of RoCoF relays. Accordingly, it could also provide support to reduce the risk of RoCoF-relay maloperation.

To effectively manage the frequency nadir challenge, limiting the RoCoF and rapid injection of sustained additional power to the system (or a reduction in power, in the case of over-frequency events) are the main assisting factors. FFR is specifically designed to meet such requirements; thus, it is effective in containing the frequency within the required limits, thereby enhancing system robustness in the face of rapid demand/generation changes.

Both SynCon and IE, which either provide “true” or emulated inertia, can only provide short-term support to the system and cannot provide sustained additional power inputs. Hence, their efficacy in limiting the prospective frequency nadir is relatively low (although they do “buy time” for other resources to be deployed to provide a degree of low-nadir mitigation). IE can be tuned to emulate a larger inertia than a SynCon with similar capacity, owing to its ability to flexibly adjust the emulated inertia constant; thus, it offers relatively higher effectiveness in this respect, when compared to a SynCon.

With reference to the regional behavior of the frequency and RoCoF, a key contributor is the non-uniform geographic distribution of renewable generation and synchronous generation throughout the system [14,15]. Accordingly, if SynCons are properly located and sized, they can effectively mitigate regional behavior in large systems. IE can also theoretically mitigate non-uniform regional behavior; however, this has not yet been fully proven [13]. FFR is mainly designed to react to the frequency and RoCoF in the system, so it does not inherently address the regional-behavior issue. However, if controlled appropriately, it can account for regional behavior within the system and deploy locational responses that could potentially mitigate regional behavior in the system.

In GB, the enhanced frequency control capability (EFCC) project used wide-area monitoring data from synchrophasors to enable a fast and coordinated response, considering the locational impact of events [9]. The main challenge associated with such systems is that communication of real-time data is required across a wide area. This may require a significant investment to achieve the required performance levels. However, this investment in communications infrastructure may be justified in the future, owing to the many requirements for such a provision.

For the increasingly oscillatory behavior of the system, SynCon could contribute to the oscillation damping with a conventional PSS (similar to the PSSs used in SGs [34]). According to Refs. [59,60], SynCons with conventional PSSs are not considered to be effective for damping; however, the damping performance can be improved with enhanced control of the SynCon's automatic voltage regulator (AVR). Damping system oscillation can be relatively easily altered via controller design and parameter tuning in power converters. The damping provided by a power converter may differ significantly from that of an SM with a similar inertia constant [46], adding flexibility to the system operation. FFR does not inherently provide oscillatory damping, as its control algorithms are typically designed to rebalance the system. There is normally no built-in mechanism for evaluating oscillation modes and responding to them.

With respect to the anticipated rapid demand changes, owing to the proliferation of EVs, SynCons may only play a facilitating role. While they can assist in limiting the RoCoF via the provision of short-term inertial power, they clearly cannot provide continuous additional power to meet increases in demand. For IE, because of the growing and significant overall capacity of converters in many power systems, the total emulated inertia from the converter could provide effective support for frequency containment and limit the RoCoF. Limiting the RoCoF using fast-acting IE also provides more time to initiate other sources of reserve power; thus, it would generally enhance stability to a rapid change in demand (or generation output). FFR is designed to act rapidly when a power imbalance occurs and is expected to possess the capability of both fast and sustained power provision to address any power imbalance.

Frequency control during a black start presents particular challenges because, during the restoration process (particularly in the early stages), the system is relatively small, and sensitive to any disturbance. Furthermore, with the ongoing decommissioning of large thermal plants, DERs will play a critical role in supporting black starts, and these DERs generally have less inertia than large thermal generators. SynCons could play a supporting role in stabilizing newly established networks (or islanded sub-networks) via the provision of inertia. Similarly, IE and FFR can provide support for black starts by reacting to any power imbalance during the restoration process. In particular, VSMs have grid-forming capabilities and could potentially act as energy sources for restoring future systems (converter-interfaced sources generally cannot start an islanded system, at present).

4. Summary

It is clear that decreasing the system inertia of a power system certainly introduces significant system frequency control and other operational challenges. From the frequency control perspective, if purely relying on SynCons, a significant introduction of SynCons will be required to fully manage and mitigate the impact of decommissioning SGs. Power converters can be controlled to provide IE and FFR, which offer promising capabilities that can assist in resolving many of the frequency control challenges; these technologies are considered to be relatively cost-effective.

However, in the future, frequency control will no longer be able to be considered as a relatively independent function and must be considered alongside other system operability parameters (e.g., fault levels and reactive power characteristics). Accordingly, the selection of frequency control solutions in the future must consider the wider system architecture and the mix of active control technologies and devices that are used within the system.

In scenarios where SGs are extremely limited, SynCons will undoubtedly play a critical role because of their capability to provide a range of desirable properties to the system. Power converters will also play a more active role in addressing operational challenges in future systems, owing to their proliferation and their inherent high degrees of controllability and flexibility. The exact nature and portfolio of solutions to be deployed will be market driven, and will be heavily influenced by the properties of individual power systems. In all cases, the coordination of the various and different techniques will be critical in achieving an optimal solution for the continued provision of reliable, robust, and resilient power systems that have been available in developed countries for many decades.

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Compliance with ethics guidelines

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References

[1] Zhu J, Booth CD, Adam GP, Roscoe AJ, Bright CG. Inertia emulation control strategy for VSC-HVDC transmission systems. IEEE Trans Power Syst 2013;28(2):1277–87.

[2] Milano F, Dörfler F, Hug G, Hill DJ, Verbič G. Foundations and challenges of low-inertia systems (invited paper). In: Proceedings of 2018 Power Systems Computation Conference (PSCC); 2018 Jun 11–15; Dublin, Ireland. New York: IEEE; 2018. p. 1–25.

[3] Ratnam KS, Palanisamy K, Yang G. Future low-inertia power systems: requirements, issues, and solutions—a review. Renew Sustain Energy Rev 2020;124:109773.

[4] Future energy scenario. Report. Warwick: National Grid ESO; 2020 Jul.

[5] System operability framework 2016. Report. Warwick: National Grid; 2016 Nov.

[6] Interconnector register by 30 July 2020 [Internet]. Warwick: National Grid ESO; c2021 [cited 2020 Aug 26]. Available from: https://data.nationalgrideso.com/data-groups/connection-registers.

[7] Operating a low inertia system—a system operability framework document. Report. Warwick: National Grid ESO; 2020 Feb [cited 2020 Aug 26]. Available from: https://www.nationalgrideso.com/document/164586/download.

[8] Hong Q, Nedd M, Norris S, Abdulhadi I, Karimi M, Terzija V, et al. Fast frequency response for effective frequency control in power systems with low inertia. J Eng 2019; 16: 1696–702.

[9] Hong Q, Karimi M, Sun M, Norris S, Bagleybter O, Wilson D, et al. Design and validation of a wide area monitoring and control system for fast frequency response. IEEE Trans Smart Grid 2020;11(4):3394–404.

[10] Tzelepis D, Dyśko A, Booth C. Performance of loss-of-mains detection in multi-generator power islands. In: Proceedings of 13th International Conference on Development in Power System Protection 2016 (DPSP); 2016 Mar 7–10; Edinburgh, UK. London: IET; 2016. p. 1–6.

[11] Operability strategy 2019. Report. Warwick: National Grid ESO; 2019.

[12] ENTSO-E System Protection & Dynamics Sub Group. Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe. Report. Brussels: European Network of Transmission System Operators for Electricity (ENTSO-E); 2016 Mar.

[13] Poolla BK, Bolognani S, Dörfler F. Optimal placement of virtual inertia in power grids. IEEE Trans Automat Contr 2017;62(12):6209–20.

[14] Xu T, Jang W, Overbye TJ. Investigation of inertia's locational impacts on primary frequency response using large-scale synthetic network models. In: Proceedings of 2017 IEEE Power and Energy Conference at Illinois (PECI); 2017 Feb 23–24; Champaign, IL, USA. New York: IEEE; 2017. p. 1–7.

[15] Martínez-Sanz I, Chaudhuri B, Junyent-Ferré A, Trovato V, Strbac G. Distributed vs. concentrated rapid frequency response provision in future Great Britain system. In: Proceedings of 2016 IEEE Power and Energy Society General Meeting (PESGM); 2016 Jul 17–21; Boston, MA, USA; New York: IEEE; 2016. p. 1–5.

[16] Brown G. Distributed restart: Ofgem project progress. Report. Warwick: National Grid ESO; 2020 Dec.

[17] Operability impact of distributed storage and electric vehicles—a system operability framework document. Report. Warwick: National Grid ESO; 2020 Apr.

[18] Low frequency demand disconnection. Report. Bristol: Western Power Distribution; 2018 Jun.

[19] Kundur P. Power system stability and control. New York: McGraw-Hill Professional; 1994.

[20] System operability framework - whole system short circuit levels. Report. Warwick: National Grid ESO; 2018 Dec.

[21] Li R, Zhu J, Hong Q, Booth C, Dyśko A, Roscoe A, et al. Impact of low (zero) carbon power systems on power system protection: a new evaluation approach based on a flexible modelling and hardware testing platform. IET Renew Power Gener 2020;14(5):906–13.

[22] Cai D, Wall P, Osborne M, Terzija V. Roadmap for the deployment of WAMPAC in the future GB power system. IET Gener Transm Distrib 2016;10(7):1553–62.

[23] Hong Q, Booth C, Dyśko A, Catterson V. Design of an intelligent system for comprehensive validation of protection settings. In: Proceedings of 13th International Conference on Development in Power System Protection; 2016 Mar 7–10; Edinburgh, UK; London: IET; 2016. p. 1–7.

[24] Fang Y, Jia K, Yang Z, Li Y, Bi T. Impact of inverter-interfaced renewable energy generators on distance protection and an improved scheme. IEEE Trans Ind Electron 2019;66(9):7078–88.

[25] Jia J, Yang G, Nielsen AH, Rønne-Hansen P. Impact of VSC control strategies and incorporation of synchronous condensers on distance protection under unbalanced faults. IEEE Trans Ind Electron 2019;66(2):1108–18.

[26] Oliver JA, Ware BJ, Carruth RC. 345 MVA fully water-cooled synchronous condenser for Dumont station part I. Application considerations. IEEE Trans Power Appar Syst 1971;PAS-90(6):2758–64.

[27] Moeini A, Kamwa I. Analytical concepts for reactive power based primary frequency control in power systems. IEEE Trans Power Syst 2016;31(6):4217–30.

[28] Nguyen HT, Yang G, Nielsen AH, Jensen PH. Combination of synchronous condenser and synthetic inertia for frequency stability enhancement in low-inertia systems. IEEE Trans Sustain Energy 2019;10(3):997–1005.

[29] Tzelepis D, Hong Q, Booth C, Papadopoulos PN, Ramachandran J, Yang G. Enhancing short-circuit level and dynamic reactive power exchange in GB transmission networks under low inertia scenarios. In: Proceedings of 2019 International Conference on Smart Energy Systems and Technologies (SEST); 2019 Sep 9–11; Porto, Portugal. New York: IEEE; 2019. p. 1–6.

[30] Marrazi E, Yang G, Weinreich-Jensen P. Allocation of synchronous condensers for restoration of system short-circuit power. J Mod Power Syst Clean Energy 2018;6(1):17–26.

[31] Tzelepis D, Tsotsopoulou E, Nikolaidis V, Dyśko A, Papaspiliotopoulos V, Hong Q, Booth C. Impact of synchronous condensers on transmission line protection in scenarios with high penetration of renewable energy sources. In: Proceedings of 15th International Conference on Developments in Power System Protection; 2020 Mar 29–Apr 1; Manchester, UK. 2020.

[32] Igbinovia FO, Fandi G, Ahmad I, Muller Z, Tlusty J. Modeling and simulation of the anticipated effects of the synchronous condenser on an electric-power network with participating wind plants. Sustainability 2018;10(12):4834.

[33] Rousis AO, Tzelepis D, Pipelzadeh Y, Strbac G, Booth CD, Green TC. Provision of voltage ancillary services through enhanced TSO-DSO interaction and aggregated distributed energy resources. IEEE Trans Sustain Energy 2021;12(2):897–908.

[34] Katsuya Y, Mitani Y, Tsuji K. Power system stabilization by synchronous condenser with fast excitation control. In: Proceedings of 2000 International Conference on Power System Technology; 2000 Dec 4–7; Perth, WA, Australia; New York: IEEE; 2020. p. 1563–8.

[35] Jia J, Yang G, Nielsen AH, Gevorgian V. Investigation on the combined effect of VSC-based sources and synchronous condensers under grid unbalanced faults. IEEE Trans Power Deliv 2019;34(5):1898–908.

[36] Zhou G, Wang D, Atallah A, McElvain F, Nath R, Jontry J, et al. Synchronous condenser applications: under significant resource portfolio changes. IEEE Power Energy Mag 2019;17(4):35–46.

[37] Hume C. PHOENIX project progress report 2019. Report. Glasgow: SP Energy Networks; 2020 Feb.

[38] D'Arco S, Suul JA. Virtual synchronous machines—classification of implementations and analysis of equivalence to droop controllers for microgrids. In: Proceedings of 2013 IEEE Grenoble Conference; 2013 Jun 16–20; Grenoble, France; New York: IEEE; 2013. p. 1–7.

[39] Morren J, de Haan SWH, Kling WL, Ferreira JA. Wind turbines emulating inertia and supporting primary frequency control. IEEE Trans Power Syst 2006;21(1):433–4.

[40] Bao W, Wu Q, Ding L, Huang S, Terzija V. A hierarchical inertial control scheme for multiple wind farms with BESSs based on ADMM. IEEE Trans Sustain Energy 2021;12(2):751–60.

[41] Wang X, Harnefors L, Blaabjerg F. Unified impedance model of grid-connected voltage-source converters. IEEE Trans Power Electron 2018;33(2):1775–87.

[42] Demonstration of virtual synchronous machine control of a battery system [Internet]. London: Energy Networks Association (ENA); 2019 Jun [cited 2020 Aug 26]. Available from: https://www.smarternetworks.org/project/nia_ngso0026.

[43] Control and protection challenges in future converter dominated power systems [Internet]. London: Energy Networks Association (ENA); 2013 Oct [cited 2020 Aug 26]. Available from: https://www.smarternetworks.org/project/nia_nget0106.

[44] Hybrid grid forming converter [Internet]. London: Energy Networks Association (ENA); 2018 Nov [cited 2020 Aug 26]. Available from: https://www.smarternetworks.org/project/nia_ngso0019.

[45] Roscoe A, Brogan P, Elliott D, Knueppel, Gutierrez I, Campion JCP, et al. Practical experience of operating a grid forming wind park and its response to system events. In: Proceedings of 2019 18th Wind Integration Workshop; 2019 Oct 16–18; Dublin, Ireland; 2019.

[46] ENTSO-E Technical Group on High Penetration of Power Electronic Interfaced Power Sources. High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters. Report. Brussels: European Network of Transmission System Operators for Electricity (ENTSO-E); 2020 Jan.

[47] Beck HP, Hesse R. Virtual synchronous machine. In: Proceedings of 2007 9th International Conference on Electrical Power Quality and Utilisation; 2007 Oct 9–11; Barcelona, Spain; New York: IEEE; 2007. p. 1–6.

[48] Zhong QC, Weiss G. Synchronverters: inverters that mimic synchronous generators. IEEE Trans Ind Electron 2011;58(4):1259–67.

[49] Meng L, Zafar J, Khadem SK, Collinson A, Murchie KC, Coffele F, et al. Fast frequency response from energy storage systems—a review of grid standards, projects and technical issues. IEEE Trans Smart Grid 2020;11(2):1566–81.

[50] Vasudevan KR, Ramachandaramurthy VK, Babu TS, Pouryekta A. Synchronverter: a comprehensive review of modifications, stability assessment, applications and future perspectives. IEEE Access 2020;8:131565–89.

[51] Natarajan V, Weiss G. Synchronverters with better stability due to virtual inductors, virtual capacitors, and anti-windup. IEEE Trans Ind Electron 2017;64(7):5994–6004.

[52] D'Arco S, Suul JA, Fosso OB. A virtual synchronous machine implementation for distributed control of power converters in SmartGrids. Electr Power Syst Res 2015;122:180–97.

[53] Beltran H, Harrison S, Egea-Àlvarez A, Xu L. Techno-economic assessment of energy storage technologies for inertia response and frequency support from wind farms. Energies 2020;13(13):3421.

[54] Firm frequency response (FFR)—interactive guidance. Report. Warwick: National Grid ESO; 2017 Dec.

[55] Li Z, Wei Z, Zhan R, Li Y, Tang Y, Zhang XP. Frequency support control method for interconnected power systems using VSC-MTDC. IEEE Trans Power Syst 2021;36(3):2304–13.

[56] DS3 system services qualification trials process outcomes and learnings. Report. Dublin: EirGrid; 2017 Nov.

[57] Dyśko A, Egea-Àlvarez A, Hong Q, Khan A, Ernst P, Singer R, et al. Testing characteristics of grid forming converters part III : inertial behaviour. In: Proceedings of 2020 19th Wind Integration Workshop; 2020 Nov 11–12; online conference.

[58] System needs and product strategy. Report. Warwick: National Grid ESO; 2017 Jun.

[59] Nguyen HT, Yang G, Nielsen AH, Jensen PG, Pal B. Applying synchronous condenser for damping provision in converter-dominated power system. J Mod Power Syst Clean Energy 2020. In press.

[60] Nguyen HT, Yang G, Nielsen AH, Jensen PG. Hardware- and software-in-the-loop simulation for parameterizing the model and control of synchronous condensers. IEEE Trans Sustain Energy 2019;10(3):1593–602.