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Control Strategies for Inertia Support in VSC HVDC System – A review

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***Abstract*—The last few decades have seen the growing penetration of renewable energy sources (RES) to the power system, which mainly connect to the main grid via VSC-HVDC transmission link. With an increasing number of conventional synchronous generators (SGs) replaced by RES, power system inertia has reduced significantly, and the system response to frequency disturbance is worsened. This paper presents a review of control strategies for VSC-HVDC system to improve inertial response, most of which enable a VSC station to emulate the dynamics of an SG. Based on the potential of VSC-HVDC to participate in inertia support, RES is further considered to provide inertial response with the coordination of VSC-HVDC. The characteristics of some particular strategies are discussed and concluded, offering some suggestions for future work.**

Keywords—VSC-HVDC, renewable energy source, system inertia, phase-locked loop (PLL), frequency control

I. Introduction

In order to reduce CO_2 emissions from electricity generation, exploiting and utilizing renewable energy sources (RES) for generation is a growing trend. Among various types of RES, wind power and photovoltaic power generation have been widely developed and used in many countries. For instance, the United States built the first offshore wind farm with 30MW of generation in 2016 and connected it to the mainland electricity grid [1]. In UK, it is expected that more electricity will be generated from RES than fossil fuels in 2019, accelerating the journey towards the target of zero emission by 2050 [2]. However, unlike conventional thermal power, the randomness and fluctuation of wind farms (WFs) and photovoltaic (PV) stations power output may possibly affect the stability of power system.

VSC-HVDC transmission system was introduced by ABB in the late 1990s [3]. It offers several attractive advantages, for instance, ability to control active and reactive power flow independently, no need for reactive compensation, and black-start capability [4, 5]. Therefore, VSC-HVDC has been an increasingly popular choice to connect WFs and PV stations into the main grid [6]. The first project of wind farm connected with VSC-HVDC was commissioned in Germany in 2010 [7]. In China, some multi-terminal HVDC (MTDC) projects have been put into operation, and ±500kV MTDC grid interconnecting onshore WFs in Zhangbei area is being constructed [8]. Moreover, European Supergrid allows HVDC transmission links to serve as corridors between different countries, which enhances security level of electricity supply as well as the maximum use of renewable generation [9].

However, since VSC-HVDC decouples each connected system, the grid frequency variation cannot be transmitted to the RES side without communication, and thus WFs and PV stations cannot provide any inertial response to the grid [4, 10]. Thus, with conventional synchronous generators (SGs) being replaced by converter-based RES, the effective inertia level of the whole system reduces enormously, causing high rate of change of frequency (ROCOF) and high frequency deviation [11]. To mitigate the impact, the Electricity System Operator of Great Britain has required that a fast frequency response capability be applied to power generator modules without inertia, for which the delay in initial active power frequency response should not be greater than 1 second [12].

As a matter of fact, VSC-HVDC link can provide certain inertia support to the system with specific control strategies. Moreover, RES and energy storage system (ESS) can also participate in inertial response to address the low-inertia issue when coordinated with VSC-HVDC. This review paper focuses on these independent and coordinated control strategies proposed to emulate system inertia and provide inertial response, investigating the role that VSC-HVDC system plays in system frequency regulation.

The organization of the paper is as follows. Section II introduces the concept of system inertia and its relationship with system frequency dynamics. Section III presents control strategies proposed for VSC-HVDC system to improve inertial response, some of which are designed for VSC station only, regardless of the participation of RES and ESS, while the others take it into consideration. The paper is finally discussed and concluded in Section IV and V respectively.

II. Concept of Power System Inertia

In general, inertia is defined as the degree of resistance of a physical object to the changes in its state of motion and is determined by the mass of the object [13]. In conventional power system, the inertia is mainly supported by SGs and turbines connected to the grid because of their heavy rotating masses. From this aspect, the kinetic energy stored in the rotors can be used to quantify the system inertia H_{sys} [14]:

$$H_{sys} = \frac{E_{sys}}{S_{sys}} \quad (1)$$

where H_{sys} is the inertia constant of system, E_{sys} is the total kinetic energy stored in power system, and S_{sys} is the total rating apparent power of the system.

System frequency reflects the power balance. When there is a mismatch between power supply and power demand, the frequency will change from its nominal value f_{nom}. As shown in Fig. 1, the system frequency will start dropping when a sudden loss of generation or an abrupt connection of a large load occurs. To maintain the frequency stability, there are three main kinds of frequency response with different response time, which are: 1) inertial response, 2) primary response, and 3) secondary response [15].

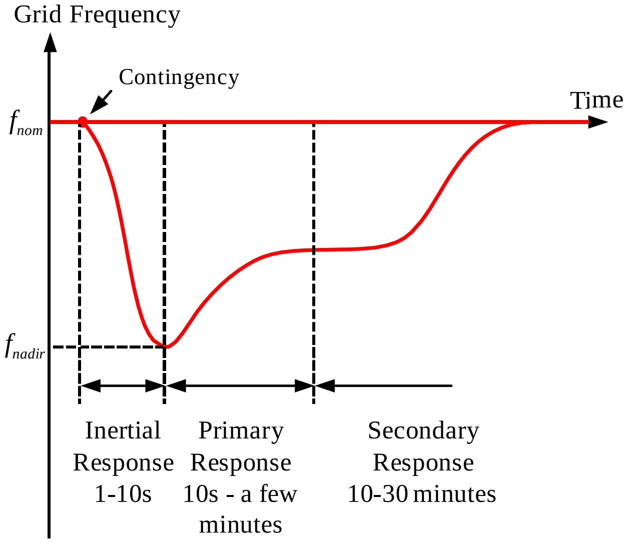

Fig. 1. System frequency response during a contingency [16]

The primary frequency control by turbine governors and the secondary frequency control by automatic generation control (AGC) are generally activated a few seconds or minutes after the contingency. However, the inertial response will participate in frequency regulation almost as soon as the frequency deviation occurs, since the inertia is a natural property of the power system. In this stage, the rotating machinery will regulate the stored kinetic energy to compensate the unbalanced power and stabilize the system frequency, as given by the swing equation [17]:

$$\frac{2H_{sys}}{f_0}\frac{df}{dt} = \Delta P = P_m - P_e \qquad (2)$$

where f_0 is nominal system frequency, df/dt is the ROCOF, and ΔP is the unbalanced power. P_m and P_e are mechanical power and electrical power, which can also be regarded as power generation and load consumption, respectively.

From (2), it is indicated that the system dynamics in the initial stage depend on the system inertia and the amount of unbalanced power. That is to say, as for a low-inertia system, a small degree of imbalance can result in large frequency deviation, which may cause system instability. However, under the same magnitude of imbalance, both the ROCOF and the frequency deviation will be mitigated when large inertia is maintained in the system. With RES connecting to the system via converters and the inertia reduced significantly, many inertia support control strategies based on VSC-HVDC have been proposed to improve the inertial response of the system.

III. Control Strategy Classification

Inertia control strategies will be reviewed and classified in this section, as described in Fig. 2. The strategies are divided into two application scenarios, which are independent VSC-HVDC control and multi-source coordinated control with VSC-HVDC involved, and will be discussed in detail below.

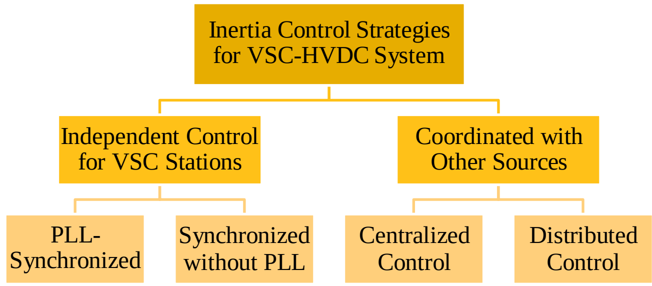

Fig. 2. Classification method of control strategies

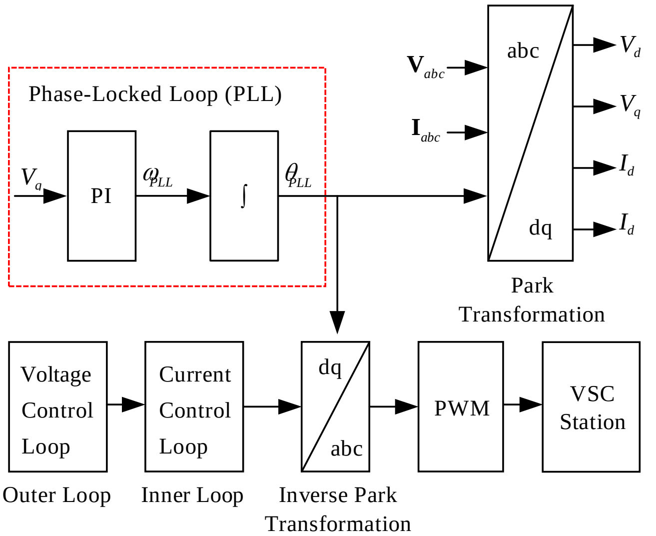

Fig. 3. The structure of PLL and its effect on VSC control [18]

A. *Inertia Control for VSC-HVDC Only*

It is important for VSC stations to maintain synchronism with the grid, and how to estimate the system phase angle is of great importance. Generally, there are two approaches which are: 1) to use a phase-locked loop (PLL), and 2) to emulate the natural synchronization process as an SG.

1) *With PLL-synchronization loop*

PLL is a traditional method for realizing synchronism with the system. The most attractive feature is that it can measure the voltage phase angle and system frequency directly and accurately in strong power grid, which can be used for VSC vector control, as depicted in Fig. 3. In [19], the inverter will control DC voltage based on system frequency. Since capacitor dynamics (3) resemble the SG swing equation, the energy stored in DC capacitors can be delivered to provide inertia support to the system.

$$CV_{DC}\frac{dV_{DC}}{dt} = P_i - P_o \qquad (3)$$

where C is the total capacitance volume of the capacitor, V_{DC} is the DC voltage, P_i and P_o are the power injected into the capacitor and power output from the capacitor, respectively.

This method is initially for point-to-point VSC-HVDC configuration, and its application has further been extended to MTDC and MMC-based systems in [20-22]. Moreover, on the basis of it, an implementation of generalized voltage droop control (GVD) is proposed in [23], which makes VSC stations more flexible during normal operation and contingencies.

Another control method for PLL-synchronized VSC-HVDC has been presented in [24] to develop the phase motion equation concept that can improve the frequency dynamic behaviors of the VSC with embedded inertia control loop. The authors have established a small-signal model of the proposed VSC and analyze the effects of PLL controller parameters on the stability of a single-VSC infinite-bus system. Reference [8] has further investigated this strategy, which can maintain frequency stability in an islanded system. In [10, 25], the concept of virtual synchronous generator (VSG) is proposed to mimic the rotor swing equation in VSC with external control loop introduced.

Basically, all these strategies have utilized PLL to estimate system phase angle and synchronize with the grid. Although PLL has been widely used in VSC control, it has been reported that the dynamics of PLL may be distorted in the transient process when connected to weak system [26, 27]. In other words, PLL cannot trace the system frequency accurately in weak grid and increase the risk of control system malfunction.

2) Other synchronization methods

To overcome the aforementioned issue in weak system, it is feasible to enable VSC to emulate the behavior of an SG to maintain synchronization with the grid. There are three main methods: a) converter power synchronization control, b) synchronverter, and c) DC-link virtual synchronous control.

a) Converter Power Synchronization Control (PSC). PSC is first proposed in [26], controlling VSC active power output directly by power control loop based on swing equation (4), realizing inertia support and estimation of system phase angle.

$$P_m - P_e - D(\omega - \omega_s) = J\omega_s \frac{d\omega}{dt} \quad (4)$$

where D is the damping coefficient, J is the inertia constant, ω_s is the grid synchronous angular frequency, and ω is the virtual rotor angular frequency.

PSC can be used as an alternative to PLL during normal operation, but may not work when the VSC is blocked or AC system faults occur. Therefore, virtual admittance has been introduced in [28] to emulate the output impedance of SG, as shown in Fig. 4(a), by which a backup PLL is not necessary for start-up or severe fault conditions [29-31]. Some authors have also proposed an improved controller, in which a droop branch is added for a good grid interactive performance [32], or a new scheme, which has adopted the concept of alternating inertia constant for fast damping of oscillations [33].

b) Synchronverter. The concept of synchronverter is established in [34] for inverters, which is equivalent to an SG covering all the dynamics, while PSC only emulates the SG rotor dynamics. From the part in red box in Fig. 4(b), it can be seen that the synchronverter emulates the swing equation (5), expressed in terms of mechanical quantities.

$$T_m - T_e - D\omega = J\frac{d\omega}{dt} \quad (5)$$

where T_m and T_e are the mechanical torque and electrical torque, respectively.

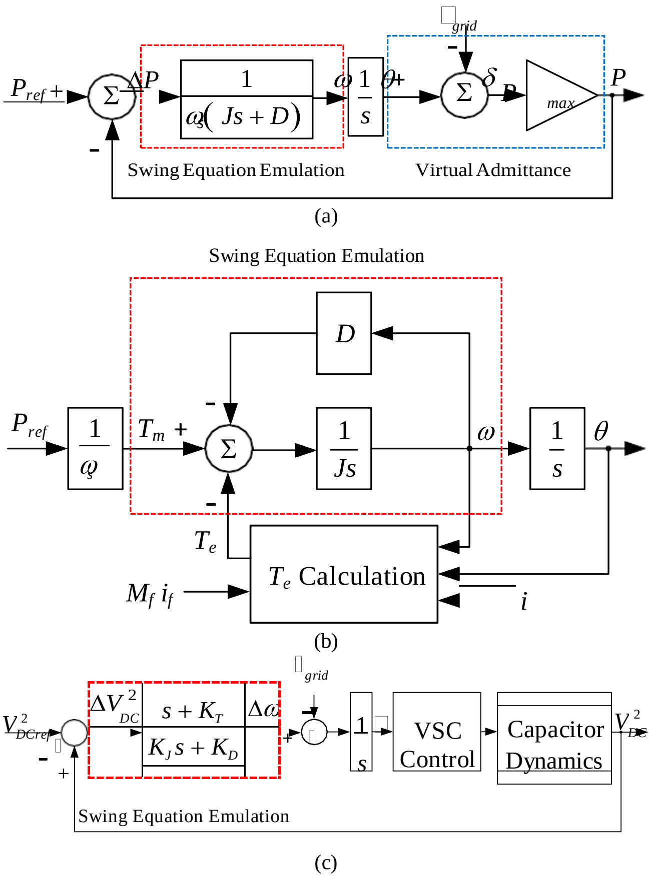

Fig. 4. Control structures of three non-PLL synchronization loops: (a) Power synchronization control [30]; (b) Synchronverter [34]; (c) Virtual synchronous control utilizing DC capacitor [35]

The synchronverter is improved to obtain the capability of self-synchronization in [36]. Two significant changes have been made, one is to introduce virtual admittance and virtual current to be fed into controller, and the other is to add a PI controller to compensate the frequency reference. Meanwhile, three switches are also added to change the operation mode, increasing the flexibility of the synchronverter.

c) DC-Link Virtual Synchronous Control. This strategy aims to control DC voltage and utilize capacitor dynamics (3) for self-synchronization [35]. Its basic idea is derived from [19]. The main difference between them is that, the previous strategy requires PLL to provide system phase angle, while the proposed one can estimate the angle by a DC voltage-frequency control loop designed in Fig. 4(c). Thus, the power-frequency characteristics of VSC can be expressed as (6).

$$P_i - P_o - \frac{K_D C}{2}(\omega - \omega_{grid}) = \frac{K_J C}{2}\frac{d\omega}{dt} \quad (6)$$

where K_D, K_J, and K_T in the diagram are the damping coefficient, inertia emulation coefficient, and DC voltage tracking coefficient, respectively. It can be found that (6) is similar to (4), where $K_D C/2$ and $K_J C/2$ are equivalent to D and J in (4), respectively. ω_{grid} represents frequency setting value, obtained by PLL or Frequency-Locked Loop (FLL). It should be noted that they are only used to measure grid frequency at steady state but not for synchronization.

Moreover, considering the DC grid dynamics, a unified virtual synchronous control is proposed in [37] that can be applied to MTDC system. It not only inherits the original control scheme, but also implements droop relationship so that each VSC can participate in DC voltage regulation equally.

It is worth mentioning that, comparing the basic equations (4)-(6), all the three methods are essentially the same in the perspective of implementing SG swing equation into the VSC control loop and providing system inertia support, but different in the form of expression. Therefore, their control structures can be generalized as a common one in Fig. 5.

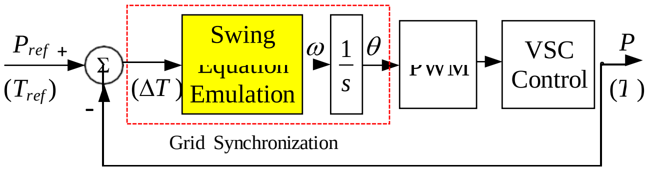

Fig. 5. A general control structure for three non-PLL synchronization schemes

B. *Coordinated Inertia Control with Other Sources*

Due to the decoupling property of HVDC link, when frequency disturbance occurs in the main grid, the sources at other sides cannot track the frequency and provide support simultaneously. To solve the issue, there are two general control modes: 1) centralized control, requiring a control center to collect and manage the information and then dispatch the signals, or 2) distributed control, delivering frequency signals to other grids via either communication or artificial coupling of the frequencies of the grids without control center.

1) *Centralized Inertia Control*

Centralized control scheme has a great dependence on communication. A simplified schematic of signal transfer for a two-area system is depicted in Fig. 6. The areas are connected via parallel HVAC and HVDC links with ESS. Each area consists of several generation units and a load center which are not shown in detail. AGC is part of the control center. During operation, frequency and power flow are measured and sent to the control center via communication link, shown as dotted and solid arrows in black, respectively. After processing, the center communicates command signals to the HVDC and area controllers, which then dispatch the orders to each VSC station and generation unit. The two steps are represented as solid and dotted arrows in red, respectively.

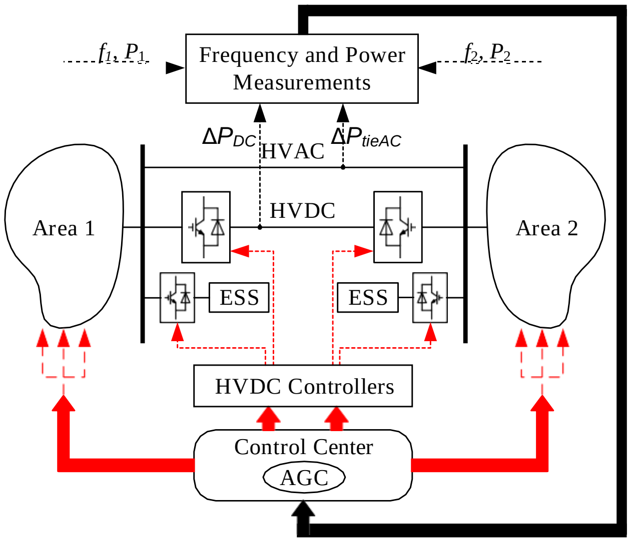

Fig. 6. The simplified schematic of communication transmission for a two-area interconnected system [38]

A derivative control strategy in multi-area AGC interconnected system is proposed in [38]. The objective of the strategy is to enable the control center to calculate the ROCOF during contingencies and generate HVDC set-points. The ROCOF determines the power for emulating virtual inertia, provided by an installed ESS or neighboring areas. Besides, a supplementary modulation controller (SPMC), which is essentially a damping controller, is implemented to coordinate the operation of AGC and improve the system performance. Since the calculation of ROCOF is sensitive to the noise in frequency measurement, such effects have been taken into account in [39], and a robust control strategy to minimize the undesirable influence of PLL is presented in [40]. Specifically, if battery is adopted, it can be operated according to its state-of-charge (SOC) for quick inertia support [41].

Furthermore, the application of PSC-based HVDC link in multi-area AGC system is studied in [42], whereas non-synchronous unit has not been considered. Thus, authors in [43] have integrated converter-interfaced generators (CIG) and battery storage with the original system. Once there is power imbalance, the signal will be transmitted to control center, and it will then send power commands to each CIG to modify its power output, which depends on how much the CIG participates in total power production. Authors in [44] have considered electric vehicles (EVs) as energy storage for frequency regulation through vehicle-to-grid (V2G) network. Through bi-directional converter, EVs can be regarded as mobile storage and the charging and discharging can be monitored smartly. The V2G algorithm of battery SOC controller is optimized in [45, 46], considering the driving behaviors of EV owners and SOC level. It is also verified that the combination of EVs with such controller and PSC-based VSCs can effectively damp oscillations and peak deviations.

2) *Distributed Inertia Control*

Opposed to centralized control, distributed control does not need a control center. In this subsection, we mainly take VSC-HVDC system connected with offshore WF into consideration, since a number of distributed control strategies for it to provide inertia support have been reported.

It is a traditional method to send grid frequency signal to WF via communication line and modulate the active power output. Reference [47] has proposed a novel frequency controller for WF, including under-frequency controller and over-frequency is within corresponding ranges. Authors in [48] have demonstrated a cascading control strategy that can ensure better harvest of wind energy while supporting system frequency effectively. In both strategies, ancillary frequency control for VSC station is implemented to speed up the response to frequency excursion. As for MTDC applications, an approach is presented in [49] where the offshore frequency depends on the weighted sum of the frequencies of onshore systems, with the aid of the fiber optic link embedded within sub-sea DC cables for communication.

Relying on communication may lead to reliability issues such as time latency and signal loss, especially when interconnecting remote areas. Reference [50] has proposed a communication-free control scheme for a VSC-HVDC link connecting offshore WF with the onshore main grid. Fig. 7 illustrates the configuration of the studied system and the overall strategy. DC voltage is regulated depending on the grid frequency deviation and then WF frequency changes according to DC voltage variation, both of which apply droop control. With DC voltage used for transmitting frequency signal, the frequency deviations of the two-side systems can be controlled proportionally, namely artificial coupling of the frequencies of the grids, which means wind turbines in WF only need to detect local frequency instead of receiving grid frequency signal by communication. Such strategy has been further optimized and adopted not only in two-terminal systems [51-53] but also in multi-terminal systems [54-56]. It is noticeable that non-PLL synchronization schemes, such as PSC, are also feasible in these applications to provide inertia support and enhance system robust [57, 58].

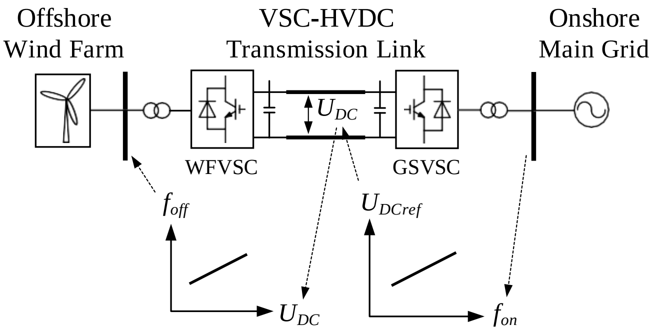

Fig. 7. The overall control strategy without communication [52]

IV. Discussion

PLL is commonly used for converters to synchronize with the grid. It can be easily implemented since it has been modularized. However, its dynamics may be worse in weak grids, unable to get the correct phase-locked. Three non-PLL synchronization control loops have been proposed to overcome the drawback of PLL, which share the same design idea of emulating SG swing equation. Besides, each strategy has its own features: 1) PSC is implemented with adjustable virtual admittance, making VSC more flexible during operation; 2) Synchronverter replicates an SG faithfully, which may introduce undesirable oscillatory response and increase the complexity of the controller; 3) DC-link virtual synchronous control is specifically designed for VSCs that control DC voltage and reactive power output, with potential to be further applied in RES scenarios.

Centralized control is on the basis of fast communication system. Control signals are generated by the control center and sent to each area. In this way, the control center can set the power references for each controller with the capability of global planning, ensuring reasonable distribution of power output and enhancing the effectiveness of control. However, it needs a large amount of computation, and system reliability may decrease due to complicated communication. On the contrary, distributed control enables VSCs and generation units to adjust power output and provide inertia support by themselves. Frequency signal can be transmitted via long-distance communication and artificial coupling of the frequencies, and the latter can utilize DC voltage for fast frequency information transmission.

According to the reviewed literature, there are several suggestions for future work:

- The satisfactory performance of non-PLL strategies when interfacing weak grid or isolated system has been verified in many references. The follow-up work should focus on the operation under unbalanced and distorted grid voltages.
- Grid code for RES to support system frequency has been announced in many countries. Corresponding rules for VSC stations can also be established to reduce the requirement for RES to provide frequency response.
- In UK, there has long-term planning that SGs in thermal plants will be completely replaced by RES by 2050. Since these SGs contribute to the stability of the main grid greatly at present, strategies to maintain system frequency and AC voltage without the support of SGs should be studied in the following future.

V. Conclusion

Power system inertia has been gradually decreased by the increasing penetration of RES. To overcome this problem, it is of significant importance to study how to obtain a better system inertial response by the inertial emulation technology of VSC-HVDC. A literature review on the inertia support control strategies is presented, considering VSC-HVDC transmission system with RES, which effectively improves system frequency dynamics. It can be seen that VSC-HVDC can not only emulate the behavior of SG to provide inertia support, but also transmit system frequency signals to RES and coordinate them to participate in inertial response. The advantages and disadvantages of the proposed strategies are discussed in the paper, with the hope that more modified schemes will be designed to enhance the stability and reliability of system in the future.

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