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Forced Oscillation in Power Systems With Converter Controlled-Based Resources–A Survey With Case Studies

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ABSTRACT In future power systems, conventional synchronous generators will be replaced by converter controlled-based generations (CCGs), i.e., wind and solar generations, and battery energy storage systems. Thus, the paradigm shift in power systems will lead to the inferior system strength and inertia scarcity. Therefore, the problems of forced oscillation (FO) will emerge with new features of the CCGs. The state-of-the-art review in this paper emphasizes previous strategies for FO detection, source identification, and mitigation. Moreover, the effect of FO is investigated in a power system with CCGs. In its conclusion, this paper also highlights important findings and provides suggestions for subsequent research in this important topic of future power systems.

INDEX TERMS Converter controlled-based generation, external perturbation, forced oscillation, natural oscillation, renewable generation.

I. INTRODUCTION

In power systems, forced disturbances (FDs) such as unexpected equipment failures, uncertain inputs in turbines, control interactions, and abnormal operating conditions are relatively common [1], [2]. A new oscillation behaviour has been observed in power systems. It has been shown that this new oscillation phenomenon cannot be reproduced by traditional models and methods applied in power systems [3]. The FDs with different ranges of frequency may provoke forced oscillations (FOs) [4]–[6]. If the frequencies of the FDs coincide with the frequencies of electromechanical (EM) modes, i.e., normally in the range of 0.1 Hz to 2.0 Hz, this event will lead to a resonance resulting in a severe FO [4]–[6]. In practical power systems, FOs occur in a number of places in USA, Canada, and China. They normally persist in the system for minutes or even hours. These scenarios may degrade the power system stability, power transfer capability, and they may damage the relevant devices [1], [2], [4]–[6].

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Several techniques have been applied successfully to mitigate FOs. In control and power electronic systems, the voltage source converters connected to long transmission lines may be cause of FOs due to the resonance from a passive property of conductance. A frequency-domain passivity-based voltage source converter control (VSC) [7], and a virtual-impedance-based control for VSC and current-source converter [8], can be used to deal with this problem. Alternatively, this issue can be resolved by shaping both filter impedance and closed-loop control output impedance, and by providing damping in specific frequencies. A review on damping of sub-synchronous torsional interactions by using VSC-based flexible AC transmission systems (FACTSs) and damping controllers can be found in [9]. These challenges will be emerging into the future electronics-based power systems [8]. In power systems, the most common methods to mitigate FOs are: cancelling the FO sources [10], keeping the FD frequency far away from the electromechanical oscillation (EMO) frequency [10], alleviating the FD magnitude [10], and increasing the damping ratio of critical modes by the following methods: i) using power system stabilizers (PSSs) in synchronous generators (SGs) [11]–[13], ii) power oscillation dampers (PODs) in renewable energy sources (RESs) and FACTS devices [14]–[16], and iii) active/reactive power modulations via converters of converter controlled-based generations (CCGs) [17]).

Future power systems will contain a substantial number of CCGs. Consequently, power systems have been transformed significantly over the last few decades. Two new standards have been introduced in terms of power system dynamics and stability, i.e., converter driven stability and resonance stability [18]. Therefore, the CCGs, i.e., renewable energy sources and battery energy storage systems, are expected to play an important role in future power systems [19]. The penetration of CCGs may result in FOs due to the stochastic characteristics associated with them. As a result, the penetration of CCGs in future power systems can contribute to FOs and severe interaction with system modes. For instance, an FO could be caused by the sub-synchronous interaction between voltage source converters and the grids [20]. Previously, the major challenge of substituting SGs with CCGs was not well studied or fully understood [21]. Moreover, the CCGs may create additional oscillation modes associated with their converter controls [22]. Frequency of the new oscillation mode (or FO mode, which is later introduced to the system) may coincide with the EMO frequency resulting in interaction among adjacent EM modes, and a greater complexity to analyze characteristics of FOs and EMOs in power system with CCGs.

The goals of this paper are to consolidate prior works, research consensus on the FO, and provide the researchers a broader picture by:

1) Detailing general backgrounds of the FOs in power systems with and without CCGs, and indicating similarities and distinctions of the FOs, EMOs, and limit cycles;
2) Presenting holistic reviews of actual FO events, as well as FO detection, identification, and mitigation methods in traditional power systems in order to find research gaps, and consequently suggest possible challenges and issues for FOs in future power systems with CCGs;
3) Conducting simulations of various case studies in a future power test system to analyze the effects of FOs caused by CCGs.

II. BACKGROUND

A. FUNDAMENTAL OF FO IN POWER SYSTEM

Power system oscillation can be divided into three major categories, i.e., oscillations from ambient, transient, and forced input as demonstrated in Fig. 1 [23]. Three major types of oscillation are briefly described as follows [24]: i) Ambient is the system response to minor changes. This change is typically characterized by white noise, small random load fluctuations, and stochastic outputs from CCGs. The ambient always occurs in the data obtained by measurements, and it can be handled by using filters; ii) Transient is the response subjected to a change in the power system from an equilibrium or a steady-state operating point such as a fault, outage contingency, line and generator trips, or load rejection. Oscillations in a transient response are naturally characterized by the critical EMO or system modes; iii) Forced is the response in systems associated with an external input, a malfunctioning apparatus, or uncertain inputs such as a malfunction in the on/off cycling of steam valves, furnace induced dynamics, a rapid change in vortex, a malfunction of converter control loop, or poorly designed controllers [3], [25]–[28]. Forced oscillations may include harmonics of the fundamental frequency of the forcing function. Therefore, it may result from the periodicity of the external inputs. The FO is typically undamped and sustained. Moreover, the FO may occur until the FD disappears, or the FD is removed from the system. Specifically, the FO tends to be more severe when frequencies of the FD coincide with critical electromechanical (EM) modes [4], [11], [12].

B. COMPARISON TO EMO

In comparison, the FO is quite distinct from the EMO. The well-known EMO is caused by the dynamic interaction among the groups of synchronous generators, while the FO is excited by an exogenous periodic perturbation with various frequency bands. It means that the form of an EMO or natural response depends on the system operating points, while the form of an FO depends on the driving FD input. This distinction explains why natural responses can be analyzed to estimate the system inter-area and other EM modes [3], [29]. The FO can occur in power systems under a wide variety of circumstances such as failure in equipment, poorly tuned controllers, and abnormal generator operating points [24]. The EMO can be analyzed by the small-signal stability assessment using exact or estimated system parameters and models. The EMO can be suppressed by improving the damping ratios of EM modes. However, the sustained FO can occur after exciting by external perturbations at frequencies close or equal to those of EM modes [5]. The FO is spurious because it is later introduced to the system as external perturbation. Therefore, the FO cannot increase the order of the system or create additional state variables. The FO exhibits an extremely high amplitude due to the resonance effect and it may lead to wide-area blackout, particularly in weak power systems [30]. During that period, the response of the FO comprises two components, i.e., EMO and FO. These may consequently disappear after the ending time of the FO [4]. Normally, the damping of the FO component is around zero, and the frequency of the FO component is the same as that of FD [5]. However, the EM mode may interact with the FO. This scenario may consequently result in alterations to damping and the frequency of the EM mode [11]. Additionally, the mode shapes of the FO and EMO are almost identical. Therefore, conventional EMO detection methods cannot be applied to extract the EMO in the presence of the FO [11].

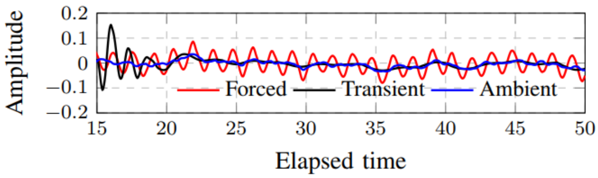

FIGURE 1. Types of oscillation in power systems (the given result is obtained by a simulation in the SE-A power system [36]).

C. COMPARISON TO LIMIT CYCLE

Limit cycles due to the supercritical Hopf bifurcation are another reason for major oscillations in power systems. The limit cycles are nonlinear phenomena occurring in power systems [31], [32]. The instance of limit cycles indicates the loss of power system stability. To restore stability, some operating points may need to be reconstituted [33]. The oscillation behaviours of limit cycles and FOs are identical in time series data. Both of them can result in an unstable system, leading to a difficulty to locate exact causes and apply effective control actions [33]. However, major distinctions between the FOs and limit cycles can be listed as follows:

1) The limit cycles are inherently nonlinear phenomena that can only be described by nonlinear equations while the FOs are excited by external disturbances [33].
2) The characteristic signatures of the power spectrum and auto-covariance of the FOs and limit cycles can be differentiated by analyzing random perturbations [34].
3) The oscillations resulted by limit cycles do not depend on initial conditions. On the other hand, the oscillations resulted by FOs are related to initial conditions and forcing functions [35].
4) To avoid the limit cycles, countermeasures such as generator dispatch, load tap changer blocking, and emergency oscillation controls, are suggested [34]. For the FOs, the countermeasures against forced oscillation are to locate and remove the external oscillation sources [33]. Besides, the FOs can be suppressed by the means of power oscillation damping [11], [12], or modulation from power electronic converters [13], [15].

D. FO IN POWER SYSTEMS WITH CCG

In future power systems, synchronous generators will be replaced by CCGs. Hence, this scenario will lead to system strength and inertia scarcity. Therefore, the problems of FO will emerge with new features of the CCGs. Table 1 summarizes the comparison of characteristics and identification between the FO in power systems with and without CCGs. With the increasing penetration level of CCGs, dynamics of future power systems are more unpredictable due to uncertain CCGs. According to Table 1, scenarios of the FOs will be intensified by CCGs, leading to difficulties in the investigation of oscillation, frequency, and damping characteristics.

E. MODELING OF POWER SYSTEMS WITH FO

A general form of a power system model under the occurrence of the FO can be expressed by a nonlinear equation as $\dot{\mathbf{X}}(t) = f_x\left(\mathbf{X}(t), \mathbf{U}(t), \mathbf{d}(t_f)\right)$, where f_x is the nonlinear function of state variables (X), t is the moving window time, $t_f \in t$ is the FO time, $\frac{\mathrm{d}X}{\mathrm{d}t}$ is the differential of X with respect to t, Y is the output vector, U is the input vector, and $\mathbf{d}$ is the forced disturbance. To evaluate system stability, the nonlinear model is linearized by (1a) and (1b) [11], [12],

$$\frac{\mathrm{d}X(t)}{\mathrm{d}t} = AX(t) + B^c U(t) + B^f d(t_f), \tag{1a}$$

$$Y(t) = CX(t) + DU(t), \tag{1b}$$

A is the state matrix, C is the output matrix, D is the feed-forward matrix, B^c is the input matrix associated with control vector U, and B^f is the input matrix where d is injected.

In power systems with CCGs, $\mathbf{X}(t)$ and B^f can be obtained in the form of conventional SGs and CCGs as,

$$\mathbf{X}(t) = \left[\mathbf{X}^{SG}(t) \;\; \mathbf{X}^{CCG}(t)\right]^{\top}, \tag{2}$$

$$B^f = \left[B^{f,SG} \;\; B^{f,CCG}\right], \tag{3}$$

where $\mathbf{X}^{SG}$ and $\mathbf{X}^{CCG}$ respectively represent the state variables of all SGs and CCGs, and $B^{f,SG}$ and $B^{f,CCG}$ respectively represent the input matrices associated with the FD of SGs and CCGs.

In (2), the state variables $\mathbf{X}^{CCG}$ are used to represent the additional dynamics of CCGs, and these variables significantly affect the power system dynamics and stability. In (3), the input matrices $B^{f,CCG}$ mean the locations of FDs in CCGs such as wind model, solar irradiation, PI controller, high-level control loop, inner-current control loop, and phase locked-loop. By substituting (3) into $B^f\mathbf{d}(t_f)$ yields,

$$B^f\mathbf{d}(t_f) = \left[B^{f,SG}\mathbf{d}(t_f) \;\; B^{f,CCG}\mathbf{d}(t_f)\right] \tag{4a}$$

$$= \sum_{i=1}^{n_d}\left(B_i^f d_i(t_{f,i})\right) \tag{4b}$$

$$= B_1^f d_1(t_{f,1}) + \cdots + B_{n_d}^f d_{n_d}(t_{f,n_d}), \tag{4c}$$

where $\mathbf{d} = \left[d_i, \cdots, d_{n_d}\right]$, $i = 1, \cdots, n_d$ is the counter of FD, and n_d is the total number of FD (for example, a single FD is represented by $i = 1$ and multiple FDs are expressed by $i > 1$).

In (4a) − (4c), it is acceptable that the identification of a single FO source is easier than that of multiple FO sources. Specially, uncertainties from CCGs may result in greater complexities to analyze multiple FO sources. For multiple FO sources, the ranking of FO sources may be applied (please see Section IV-A for a review of FO source identification).

A combination of several sine waves is usually used to model the FD since it can create a severe FO [37]. Other FD models such as square waves, impulses, and random noises can also be considered as the FDs (if they could trigger discernible oscillations with specific frequencies). The FD models in terms of mathematical equations are presented

TABLE 1. Comparison between FO in power systems with and without CCGs.

Characteristic	FO in traditional power systems	FO in power systems with CCGs
Oscillation mode	Difficult to be analyzed by oscillation mode since it is later introduced to the systems	More difficult to be analyzed than the **FO in traditional power systems** since the systems are more complex and uncertain due to characteristics of CCGs
Frequency	The severity of FO depends on the closeness of FD frequencies to those of the EMO modes	The severity of FO depends on the closeness of FD frequencies to 1) those of the EMO modes 2) those of additional oscillation modes caused by CCGs
Damping	Normally close to zero due to external persistent inputs, and may not be sensitive to typical damping controllers	Same as the **FO in traditional power systems**. However, the damping during the FO associated with the CCGs has not been well reported and studied
Identification	Several research works have well established for the identifications (Please see Section III and IV.A)	The identifications of the **FO in power systems with CCGs** have not been thoroughly realized and analyzed in previous research works

in [11], [12], [37]. For example, Fig. 2 shows the FD models. Fig. 2(a) is the pure sine wave analyzed by [12], while Fig. 2(b) is the combination of sine waves as reported in [11], [12]. Multiple FDs are also considered in [11]. The periodic FD in Fig. 2(c) is investigated and modeled by [37]. Fig. 2(d) is the non-stationary FD. It is believed that this type of FD leads to the non-stationary FO [38]. However, the impacts of the non-stationary FD on the power system stability are yet to be fully analyzed and understood.

Several practical causes of the FD models in actual power systems are given as follows:

1) In 2012, the Midcontinent Independent System Operator (known as MISO) performed base-lining analysis to set inter-area oscillation monitoring thresholds. However, the base-lining analysis identified an instance of the FO with 0.285 Hz for two minutes and a half [28]. In this event, the cause of FO was malfunctioning of the turbine controller after a routine valve testing. An investigation by the plant's personnel confirmed that the FO was driven by a single FD, such as Fig. 2 (a), with frequency around 0.285 Hz;
2) The Electric Reliability Council of Texas (ERCOT) observed several examples of oscillations driven by controllers of wind generators under high wind output conditions. The ERCOT and its consultants conducted pre- and post-disturbance spectral analysis of the PMU data following significant wind events on 3 November 2010. They found that several FO frequencies consisting of 3.2, 5.0, 5.4, and 5.5 Hz, were prominent in wind generation areas [28]. Accordingly, the wind generators could create a FD with a combination of multiple frequencies, as depicted in Fig. 2 (b);
3) In November 2016, a periodic FO was detected in the American Electric Power (known as AEP) footprint from a PMU [28]. This PMU was used to monitor a solar power plant. The FO was caused by a periodic solar irradiation during daytime. In this case, the periodic solar irradiation can be assumed to be a forced disturbance, as in Fig. 2 (c);
4) An FO driven by a non-stationary FD in Fig. 2 (d) probably occurred on 3 October 2017 in the ISO New England (ISO-NE) power system when multiple frequencies with growing magnitudes were caused by a large generator located outside of the ISO-NE power system [39]. In this event, the fundamental of FD frequency was linearly increased from 0.1 Hz to 0.3 Hz in 100 s, covering the inter-area oscillation frequency bands. The obtained results indicated that the non-stationary FO can significantly excite all the system modes.

When the mentioned FDs are injected into the system, the closed-loop state equation can be obtained by the following form $\dot{\mathbf{X}}_{cl}(t, t_f) = A_{cl}(t_f)\mathbf{X}_{cl}(t_f)$, where $\mathbf{X}_{cl}$ and A_{cl} are the closed-loop of $\mathbf{X}$ and A including $\mathbf{d}$, respectively. The measured outputs with FO ($\mathbf{Y}_{cl}$) can be written by a closed-loop system as in (5a) and (5b),

$$Y_{cl}(t, t_f) = C_{cl}\mathbf{X}_{cl}(t, t_f) = \sum_{emo=1}^{N_{emo}} \left[\alpha_{emo}S_{emo}(t)\cos\left(2\pi F_{emo}(t)t\right)e^{-\zeta_{emo}t}\right] \quad (5a)$$

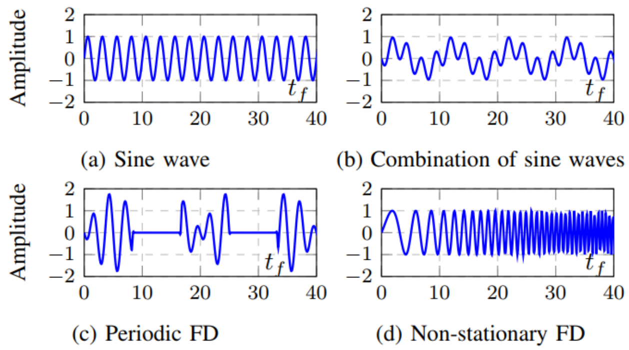

FIGURE 2. Various FD models.

$$+\sum_{d=1}^{N_d}\left[\alpha_d S_d(t_f)\cos\left(2\pi F_d(t_f)t_f+\phi_d(t_f)\right)e^{-\zeta_d t_f}\right], \tag{5b}$$

where e is the exponential constant, C_{cl} is the closed-loop state matrix, $emo = 1, \cdots, N_{emo}$ is the number of EM modes, F_{emo} is the frequency of corresponding emo^{th} modes, N_{emo} is the total number of EM modes, S_{emo} and S_d are the amplitudes of corresponding emo^{th} EMO and d^{th} FO modes, α_{emo} and α_d are the coefficients of corresponding emo^{th} EMO and d^{th} FO modes, and ζ_{emo} and ζ_{emo} are the damping coefficients of corresponding emo^{th} EMO and d^{th} FO modes.

During the FO, the signal Y_{cl} contains both EMO and FO. This signal is measured by a phasor measurement unit (PMU) with a time stamp in the range of 40 to 100 ms [40]. The signal Y_{cl} can be used to analyze the FO components, i.e., F_{emo}, ζ_{emo}, F_d, and ζ_d. Let us consider (5b): the FD creates twin components, i.e., EMO (first term) and FO (second term). The first term is dominated by ζ_{emo}. The higher the value of ζ_{emo}, the lower the value of $\alpha_{emo}S_{emo}$. Similarly, the second term is dominated by ζ_d. The higher the value of ζ_d, the lower the value of $\alpha_d S_d$. After getting the A_{cl}, stability indices, i.e., the eigenvalues (λ_{cl}) and damping ratio (ζ_{cl}), can be estimated. Let λ_{emo} and λ_d be the eigenvalues of the EMO and FO modes, when $\{\lambda_{emo}, \lambda_d\} \in \lambda_{cl}$, frequency of EMO ($F_{emo}$) and FO ($F_d$) modes in Hz can be obtained by: $F_{emo} = \frac{\omega_{emo}}{2\pi}$, $F_d = \frac{\omega_d}{2\pi}$, and $\Delta F = |F_{emo} - F_d|$.

As reported in [4], a smaller ΔF means a higher interaction. However, when $\Delta F = 0$ (i.e., $F_{emo} = F_d$), strong resonance between the EMO and FO modes may occur [4]. This could lead to the maximum value of $\alpha_{emo}S_{emo}$ and $\alpha_d S_d$ [4], [5], [11], [12]. Both cases may jeopardize the oscillatory stability of the power system. In the latter case, the FO and EM modes are merged. Under this scenario, it is difficult to distinguish the EMO from FO modes [6], [41], [42]. The damping and frequency of such a scenario can be estimated. These estimated modes are referred to as resonance modes [6], [11], [12], [41]. The severity of the FO also depends on the FD model, amplitude, and phase [4], [5], [11], [12]. These analyses can be further used for making control decisions to mitigate the FO [11], [12].

F. MAJOR FO EVENTS IN POWER SYSTEMS

There have been 14 major FO events recorded since 2005 by the North American Electric Reliability Corporation (known as NAERC) [24] and the North American Synchrophasor Initiative (known as NASPI) [28]. The FOs in these events were measured and analyzed by data from PMU or supervisory control and data acquisition (SCADA). To observe the oscillation in power systems, it was reported that PMU is more suitable than SCADA due to a lower time stamp [3], [28]. The FOs in these events were analyzed by Oscillation Detection Module, Mode Meter Module, Oscillation Monitoring System (including Event Analysis Offline and Damping Monitor Offline), and Pattern-mining Algorithm. As can be summarized in Fig. 3, significant observations of these events are highlighted as follows:

1) The FO frequency could vary between 0.01 and 14 Hz, and the FO duration could be in the range of seconds to several hours. However, the oscillation magnitude is higher in a lower frequency range (approximately $100 - 200$ MW);
2) Active power, reactive powers, voltage, and current can be used to observe and analyze the FO phenomenon;
3) Most of these FO events were resolved by the network solutions, i.e., reducing the FO source output, and repairing and tripping the FO source [24], [28]. Some events were resolved by the control actions, i.e., switching of control mode and re-tuning of control parameters;
4) Suitable control actions were not applied for at least 11 events due to limitations of measurement, and the lack of fast FO analysis, detection, and source identification algorithms [24], [28]. Besides, these analyses (FO analysis, detection, and identification algorithms) were conducted offline;
5) Most of the FOs occurred due to the malfunction and/or interaction of among controllers, especially the FOs caused by CCGs, i.e., wind and solar generations. As can be observed, the resonance with the EM modes can be caused by the FOs at various locations in power systems. Besides, suitable algorithms for FO analysis, detection, and source identification are highly required;
6) In actual power systems, the steps for mitigating the FOs are implemented by the following steps: implementation of the FO analysis and detection, identification of the location of the FO source, and elimination of the FO by using the network solutions. Nevertheless, the network solutions require system reconfiguration. Thus, the presented methods may further affect power system stability. Therefore, investigations of the FO phenomenon with respect to the power system stability are sought.

III. ANALYSIS AND DETECTION

Significant works have been conducted on this after the major event on 29 November 2005 (see the first event in Fig. 3). In Western interconnection, a 20 MW FO with 0.25 Hz

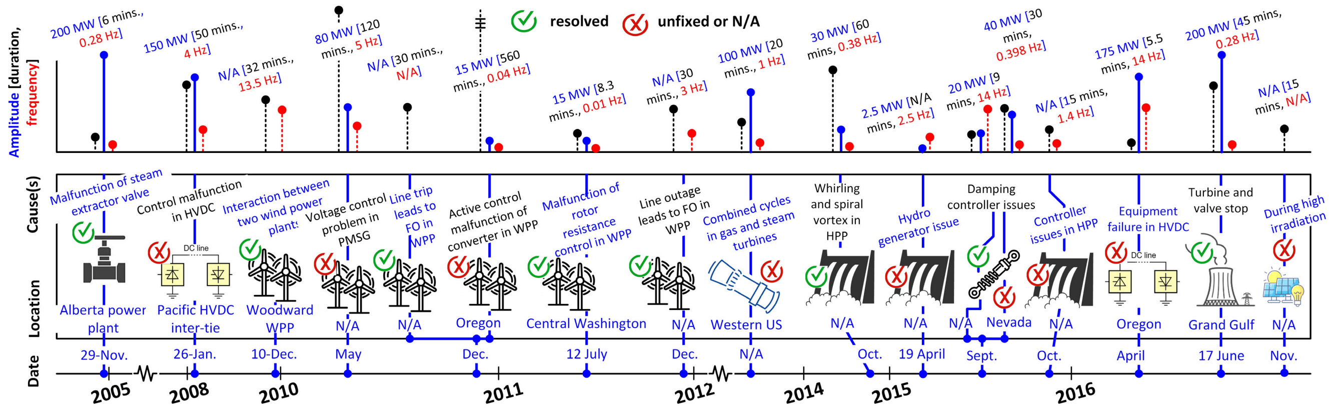

FIGURE 3. Summary of major FO events.

occurred at Nova Joffre co-generating plant in Alberta. This FO excited the 0.27 Hz North-south inter-area mode, leading to 200 MW oscillations on the California – Oregon intertie lines. In this event, some of the synchrophasor measurement units (SMUs) were out of service near the FO source in Alberta. To analyze the FO, a Fast Frequency-Domain Decomposition (FFDD) and Stochastic Subspace Identification (SSI) were applied [30]. It was concluded that the SSI provided a better estimation result than that of the FFDD. In addition, the SSI can simultaneously estimate the EMO and FO modes (also demonstrated by the same authors in [4]). The performance of the stochastic SSI was also evaluated in [43].

Coherence-based techniques such as the state-space model and AutoRegressive Moving Average eXogenous model, for distinguishing FOs from natural oscillations have been reported in [29]. These methods can be applied to the signals obtained from measurements [29]. However, FOs observed in various frequency bands are difficult to identify using such methods. The detection of FOs in power systems with multi-channel methods was proposed by [44]. In this research project, the performance of FO detection algorithms can be improved by simultaneously analyzing data from multiple PMUs. As a result, a high reliability in detecting small oscillations and faster detection of large oscillations can be achieved. However, this method contains some drawbacks, e.g., its dependence on estimates of the ambient noise spectra, and generalization of the Magnitude-Squared Coherence spectrum. To focus on an interaction of the FO and EM modes, the same attempt was conducted in the two-area four-machine interconnected power system (Kundur) [4]. The result demonstrated that a 10-MW FO can eventually lead to 477 MW of oscillation amplitude in the tie-lines. In addition, an analysis of sensitivities to different FO locations and amplitudes was conducted. The results showed that the FO effects on local modes were relatively small as compared to those of inter-area modes. In [5], the component-analysis-based FO was mathematically investigated. The words "beat" and "resonance" were described. An envelope of oscillation signal was also applied to detect the FO. It was demonstrated that the component-analysis-based FO detection method showed a better capability to detect the FO with multiple FDs, and the mixture of FOs and EMs compared to the envelope shape method. The proposed method in [5] was also verified in the Shandong power system (China) on 18 June 2012. Switching the digital electro-hydraulic governing system was utilized to handle the FO. By using the component properties and envelope shapes, five components (i.e., 0.9824, 0.9984, 1.3184, 1.4356, and 2.4255 Hz) were also detected from the measured active power flow in the tie-line. Twin components from the FO created the resonance of 0.9824 and 0.9984 Hz. However, the FO source was obscured due to the large time stamp of measurement (around 0.2 s or 200 ms), and the non-occurrence of an oscillation event during the field tests. The simultaneous estimation of the EMO and FO was presented in [6]. In this work, an Autoregressive Moving Average (ARMA) model was applied with FD input signals, resulting in the ARMA+S. Additionally, a two-stage least-squares algorithm from the ARMA was derived to incorporate the FO. Thus, this enables the proposed algorithm to estimate characteristics of the EMOs and FOs simultaneously. The EMO estimation under the periodic FO was proposed in [37]. It was reported that the estimated EM modes can be altered and rely on characteristics of the FDs. The modified Yule–Walker method with estimated autoregressive coefficients of an ARMA was applied to examine the EM modes under the periodic FOs. Moreover, the effects of miscalculation of FO frequency on the ARMA+S was reported in [45]. In this work, the FO frequency estimated by ARMA+S was unable to specify acceptable accuracy in certain cases. The authors suggested an adaptive frequency estimation method to overcome this problem. However, the simulation environment in this study assumed that the EM mode was not changed during the FO. Moreover, it was supposed that the frequency and amplitude of the FO were constant.

However, as reported by [38], this may not be a valid assumption since the FO is non-stationary in actual power systems. Therefore, the EM modes may be changed by the system operating points. Consequently, the FO frequency and amplitude may vary according to moving window time. The periodic FO detection was proposed by [41]. In [41], the proposed method used a threshold that is varied by dominant frequency. This was employed to characterize the nature of Synchrophasor measurement unit (SMU). Analysis data were reported in multiple segments to improve the detection performance in the real-time environment. Although the FO components were too small, the proposed method regarding the probability of detection motivated the use of multiple detection segments. The periodic FO detection was enhanced by incorporating a multi-taper approach [42]. In [42], the Thomson's multi-taper spectral estimation and harmonic analysis technique were proposed. This approach is a measurement-based method that requires only the measured data from SMUs for 10 s. By testing on simulated and real SMU data, the proposed algorithms in [41], [42] were applicable for the periodic FOs in practical power systems. In [46], the interaction of the FO with other system modes was analyzed. The forecasting-residual spectrum analysis was applied to discriminate between FOs and natural oscillations [47]. In [48], the wavelet ridge technique was used to track the oscillation patterns and classify modal or FO modes by using different characteristics of noises. A contrastive analysis was applied to differentiate general and special FOs [49]. All of these methods have low-computational demands for utility application. With the small computational time, these methods are claimed to be suitable for reporting the FO analysis and detection results. However, the method proposed in [46]–[49] are suitable only for offline FO analysis. Therefore, such methods may not be suitable to measure the interaction of the FO and EM modes in moving window or real time. In [38], the non-stationary FO was analyzed by using Fourier synchrosqueezing transform. This FO can be caused by the FD containing multiple frequency bands (see Fig. 2 (b)), which also varies in time domain. The dissipating energy flow method was applied to extract the oscillation components and locate sources of the non-stationary FOs. As reported, this type of FO is more realistic in actual power systems. However, the interaction of the non-stationary FO and EM modes was not well reported.

IV. IDENTIFICATION AND MITIGATION

A. IDENTIFICATION OF FO SOURCE

As reported in Fig. 3, the FO mitigation methods were mostly conducted by using network solutions. Therefore, the exact locations of FO sources need to be found in order to apply effective actions. Various approaches as reported in [33], [50]–[66], were presented to examine and locate sources of the FO. Table 2 summarizes the methods for the source identification. The major conclusions of this review can be drawn as follows:

1) Most of the identification methods were used to detect FO sources in SG and load. Only two works have proposed the methods for locating the FO in a high-voltage direct current and doubly-fed induction generator, respectively. Thus, locating the FO caused by CCGs in future power systems is sought;
2) To mitigate the FO, an effective way is to locate the source identification before disconnecting it from service. Hence, the FO source identification is a prerequisite for making control decisions. Failing to identify the FO source may result in a false alarm. Thus, the computational time and accuracy of the identification should be small and accurate so that the control action can be performed on time. Nevertheless, locating the FO source remains a challenging task since the FO is sporadic in nature, and it is difficult to be predicted [51], [52];
3) As proposed by [62], the online management system is quite possible for the detection, source identification, and mitigation of the FO by using PMU data. It also provides an actionable information. However, the computational time (or processing time) for each process should be taken into account so that the control action can be appropriately conducted.

B. FO MITIGATION

In addition to the network solutions summarized in Section II-F, a review of FO mitigation methods by control solutions is given in this section. The control solution can be used to modulate controllable devices (i.e., CCGs, SG, and FACTS) to cancel the effects of FOs without locating the FO source automatically [13]. Table 3 summarizes recent control solutions for FO mitigation. The salient observations can be highlighted as follows:

1) Only seven works so far have focused on this area, when the first attempt for FO mitigation using a control solution was established in 2017 [16]. It is evident that most of the stabilizing devices, i.e., PSS, and controllers in CCGs, HVDC, STATCOM, and UPFC, can be used to suppress the FO. However, these studies were conducted in a simulation platform. Besides, FO mitigation in future power systems with high penetration of CCGs is only assessed in [17];
2) Only [11], [12] considered the damping of FO mode. Early investigators were not sure about the damping benefits. Therefore, the damping control design for the FO will be introduced later;
3) In actual power systems, the FO source is durable. Although the control solution can mitigate the effect of FO (up to 90% as reported by [13]) without conducting any source identification method, the sustained FO may appear in the system. To manage the FO effectively, the FO mitigation framework with control solutions can be incorporated with the network solutions as discussed in Fig. 3. To avoid propagation of the FO, the effect of the FO can be initially mitigated by the control

TABLE 2. Summary of FO source identification methods.

Method no.	Reference no.	Proposed framework	FO source	Advantage(s)	Disadvantage(s)/gap(s)
1	[50]	Developed a mapping approach to locate the FO source in the low-frequency oscillation range	SG	did not require the global synchronization for locating the FO	1. require a long computation time when the test system consists of multiple subsystems 2. mathematical equations of the system models and proposed method were not completely analyzed
2	[51]	Used an energy-based method to locate the FO sources based on WAMS data	SG	1. did not require a full system model to locate the FO 2. practical to actual power systems with online application	1. lack of conditions for applicability and strict mathematical foundation 2. did not verify the result in multiple FO modes
3	[52]	Used a Bayesian framework for locating the FO source under uncertain generator parameters	SG	1. provide high performance under presence of multiple FO sources 2. locate the FO source accurately	did not guarantee the outcomes for FO oscillation caused by loads and FACTS devices
4	[53]	Proposed a two-layer FOs source location method incorporating phasor and energy analysis	SG	1. accurately locate the FO source in control device inside SG 2. locate the FO source under multiple FDs and various modes	1. test on only common type of FO (see Fig. 2 (a)) 2. may not be suitable to other types of FD
5	[33]	1. Used statistical signatures of different oscillation mechanisms to evaluate the FO 2. used the Kurtosis to discern the weakly damped oscillation 3. applied the PSD to distinguish the limited cycle and the FO	Load	precisely analyze the exact mechanism of the FO by using data from PMU	1. failed to locate the FO source accurately in some cases 2. applying control actions after identifying the exact oscillation was not considered
6	[54]	Utilized an effective generator impedance and Frequency Response Function to locate the FO source	SG	1. did not rely on strong system modeling assumptions 2. provided a signature qualitative difference between source and non-source of the FO	the result was not verified with multiple FOs
7	[55]	Used Dissipating Energy Flow (DEF) incorporating Tellegan's theorem and passivity concept to locate the FO sources	SG	resolved failures of previous DEF methods for locating the FO	1. required full system model and parameters 2. required multiple PMUs to observe the FO signals accurately
8	[56]	Used Distributed Cooperative Scheme to locate the FO source	SG	1. robust to FO source identification with multiple FO sources and change in system topology 2. evaluate the problem with small computational time by using a phasor data concentrator (PDC) instead of central monitoring system	did not verify the results with communication failure or data quality of PMUs or PDCs
9	[57]	Used Energy Flow Method (EFM) and Incremental Energy (IM) to locate the FO sources with a wide range of forced oscillation frequencies	SG	locate the FO sources under different damping levels of EMO modes, and loading conditions	did not guarantee the outcomes of the proposed method in large-scale power systems with CCGs (only verified the result in two-area four-machine (Kundur) system)
10	[58]	Applied a Luenberger observer to differentiate the outputs of the observer and FO sources	SG	1. accurately classify and calculate the amplitude when the system is subjected to multiple forced oscillation sources 2. robust to generator model uncertainties	1. not applicable to large power systems 2. required full system model
11	[59]	Used a synchrophasor data-driven method to locate the FO sources	SG	1. pinpointed the FO sources during real-time operation 2. did not require any exact system parameters or grid topology	did not verify the result in the presence of multiple FOs

TABLE 2. *(Continued.)* **Summary of FO source identification methods.**

Method no.	Reference no.	Proposed framework	FO source	Advantage(s)	Disadvantage(s)/gap(s)
12	[60]	Used a dissipating energy-based technique to locate the FO sources	SG	1. implemented by using SCADA signal 2. robust to presence of multiple sources of oscillation, uncertain loads, and systems with varying system damping	The proposed method may not be suitable for large-scale power systems with multiple CCGs
13	[61]	Used a frequency-domain approach to locate the FO sources in mechanical and control parts of SG	SG	accurately locate the FO sources in mechanical parts in SG, and control parts in excitation systems	the result was not verified in a power system with multiple FOs
14	[62]	Used a DEF to locate the FO online	SG HVDC	1. accurately locate the FO sources online even with limited system observability by PMU 2. notify an actionable information for FO mitigation	1. failed to guarantee the result with bad data or PMU measurement errors 2. unable to locate the FO sources in an area with large wind power plants
15	[63]	Proposed a two-stage scheme to locate the FO sources	SG	distinguish an FO from a poorly damped oscillation	1. the result was verified with multiple FOs 2. did not test the result in large-scale power systems with CCGs
16	[64]	Developed a time-series classification-based machine learning method to locate the FO source	SG	1. required small computational time 2. provided high accuracy for the FO location 3. robust to data quality issues	failed to guarantee accurate outcomes when the FO sources exhibit closely-correlated dynamic responses to loads
17	[65]	1. Used energy structure of DFIG converter to locate the FO source caused by DFIG 2. Applied port-controlled Hamiltonian method to analyze the influence of FDs to the potential energy of DFIG	DFIG	1. locate the FO sources accurately 2. can define the participation of DFIG in the FO event	failed to ensure accurate outcomes when the FOs are generated by multiple FO sources

solutions. Therefore, the source identification can be implemented to find the FO sources. Consequently, the network solutions can be decided for further FO mitigation.

V. FO ANALYSIS WITH CCGs

Fig. 4 shows the future 14-machine SE-A power system with CCGs. This system has been modified from an original model that has been reported in [36].[1] The modification and development of this system are conducted based on the Australian Energy Market Operator's Inertia Requirements, Shortfalls Report with Integrated System Plan [67], and the report from Clean Energy Australia [68]. The system in Fig. 4 has been developed and modified by using MATLAB & Simulink version 2018a. Accordingly, more than 24% of electricity is expected to be generated by the CCGs (i.e., wind and solar generations) at the end of 2020 [68]. With the integration of CCGs, the future Australian power system may suffer from the system strength and inertia scarcity. The WG is represented by the doubly-fed induction generator (DFIG) with the sixth-order model. The dynamics of DFIG comprise the rotor speed, d-q axis currents of grid and rotor side converters, flux linkage of rotor, and the DC link voltage. The solar photovoltaic (SPV) is modeled by the sixth-order model including the dynamics associated with the current of photovoltaic arrays, voltage of SPV, induce current of DC-DC converter, d-q axis currents of DC-AC converter, and DC link voltage. In this system, there are three dominant modes with frequencies around 0.215, 0.385, and 0.442 Hz, respectively. The damping ratios of these modes are less than 3%. To monitor the FO, the mean frequency deviation ($\Delta\bar{F}$) is measured because of high observability. Moreover, $\Delta\bar{F}$ contains all crucial characteristics of the dominant modes [11], [12], [66]. In order to measure the data of $\Delta\bar{F}$, the time stamp of an individual PMU is 100 ms [5]. The subspace-based state-space system identification (4*SID*) proposed in the previous work [11] has been applied to analyze characteristics of the FO, i.e., damping and frequency. In this paper, the 4*SID* is implemented by Signal Processing Toolbox [69] and System Identification Toolbox [70].

To analyze effects of the FO in a power system with CCGs, four different case studies are given as follows:

[1]The SE-A power system with examples of FO is available at https://doi.org/10.5281/zenodo.5533383

TABLE 3. Summary of FO mitigation methods (control solutions).

Method no.	Reference no.	Proposed framework	FO control device	Advantage(s)	Disadvantage(s)/gap(s)
1	[12]	Used an event-triggered forced oscillation damping controller (FODC) to damp the FO	FODC	1. keep the damping of FO mode in stable region at all operating conditions 2. the FODC is activated separately to avoid the interaction with conventional PSSs in SGs	1. designed by using pole placement to improve damping ratio of FO mode; thus it may not guarantee the robustness of the system against system uncertainties 2. required additional FODCs in control loops
2	[16]	Used active and reactive power modulations of static synchronous compensator with energy storage (E-STATCOM) to suppress the FO	A resonant controller in E-STATCOM	1. effectively eliminate the FO 2. provide robustness even when the resonant frequency was not calculated accurately	1. did not consider characteristics of the FO mode 2. required an additional controller in E-STATCOM 3. cannot guarantee the result with multiple FDs and in large-scale power systems
3	[14]	Used a unified power flow controller (UPFC) to mitigate the FO by shifting the frequency of FD	UPFC	same as method no.2	1. same as method no.2 2. use of UPFC is limited in practical power systems
4	[15]	Used an additional damping controller in voltage source converter of high voltage direct current (VSC-HVDC) to suppress the FO	SDC in VSC-HVDC	effectively mitigate the FO when the FO frequency is close to or far away from the frequency of inter-area modes	1. did not consider impact of delay in SDC 2. did not verify the result in large-power systems with CCGs and multiple FDs
5	[13]	Used "*Supervisor*" to adjust feedback controllers in CCGs in order to suppress the FO	Feedback controllers in CCGs	1. automatically adapt control parameters to suppress the FO 2. ability to suppress 90% of the FO 3. practical to implement in actual power systems	1. control parameters were not optimized 2. only effective in a range of $\pm 10\%$ FO frequency estimation error
6	[11]	Used adaptive PSSs in SGs to simultaneously damp the inter-area and forced oscillations	Adaptive PSS	1. robust to various system operating points and FO models 2. able to simultaneously damp the FO and inter-area oscillation without installation of additional controllers	the result was not verified in power systems with CCGs
7	[17]	Isolate and suppress the FO by using wind farms under grid-forming and grid-following controls	Modulation in grid-side converter of wind farms	1. release or absorb active and reactive powers opposite to the oscillation 2. can prevent the propagation of FO to other areas	did not coordinate the proposed method with other devices such as HVDC, FACTS, etc.

Case Study 1: The FDs with 0.215, 0.385, and 0.442 Hz sine components are injected into the converter control loop of either WG-41, WG-31, or SPV-52. Thus, these CCGs behave as the FO sources. The penetration level of CCGs (defined as *PLV* in Fig. 5) is adjusted by two levels, i.e., 24% and 36%. Fig. 5 shows the maximum tie-line amplitude (P_{tie}^{max}) resulted by such scenarios. As can be observed, P_{tie}^{max} tends to increase when the FO frequency (F_d) is close to 0.215, 0.385, and 0.442 Hz (dominant modes). Besides, the scenario is intensified by the increased penetration level of CCGs (or high *PLV*).

Case Study 2: The FDs with 0.215, 0.385, and 0.442 Hz sine components are injected into different CCGs, while the FD amplitude (P_d) varies from small to large values. From the results in Fig. 6, it is evident that the FOs caused by different types of CCGs can lead to high oscillation amplitude, especially when P_d is increased. At P_d = 0.3 pu, the system severely oscillates and eventually becomes unstable.

Case Study 3: The same FDs in *Case Study 2* with fixed 0.1 pu P_d are applied at WG-52 (Area-5). Besides, the total inertia of Area-5 is assumed to decrease from 100% to 60% with 20% step. Fig. 7 demonstrates the system responses for this case. Although P_d is small as 0.1 pu, the system can become unstable when the total inertia is reduced. Moreover, the conventional SG replacement by CCGs can result in the decreasing of total system inertia. This scenario could happen in future power systems with high penetration of CCGs.

Case Study 4: To verify the result in a wide range of system operating conditions and various uncertainties, the probabilistic analysis is applied to analyze the impact of FO by randomly and simultaneously changing possible system conditions, i.e., location and duration of the FD, size of the CCGs, penetration levels of CCGs, and total inertia of the system. As a result, by such random conditions, the probability of damping ratios under 1,000 different operating points is depicted in Fig. 8. It can be observed that the FO caused by RESs exhibits both critical and negative damping, especially

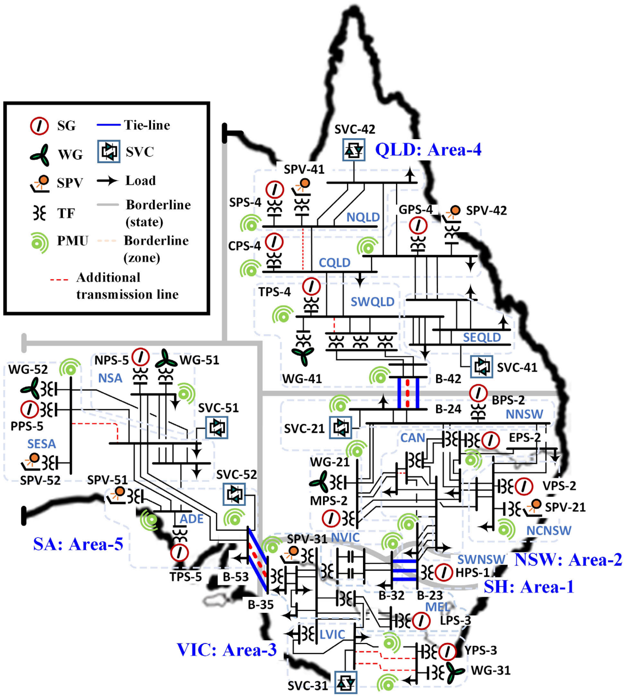

FIGURE 4. Future 14-machine SE-A power system with CCGs (base 100MW, 50Hz).

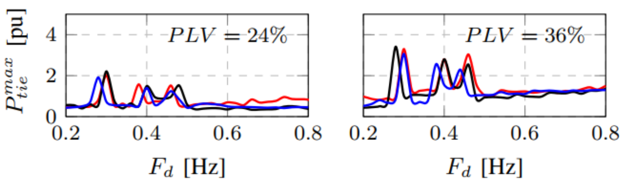

FIGURE 5. Maximum tie-line amplitudes with different penetration levels of CCGs, black line: FD at WG-41, red line: FD at WG-31, blue line: FD at SPV-52.

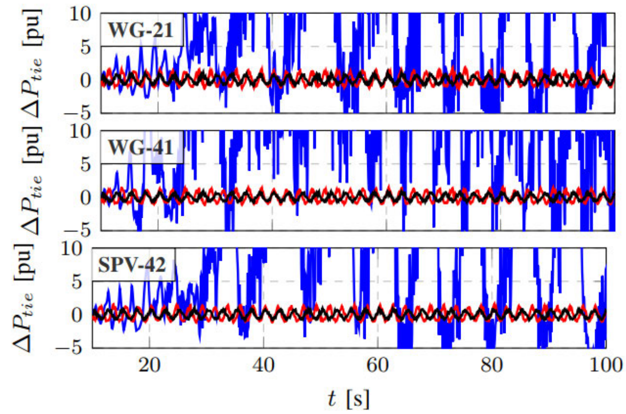

FIGURE 6. System responses with different FD amplitudes, black line: $P_d = 0.1$ pu, red line: $P_d = 0.2$ pu, blue line: $P_d = 0.3$ pu.

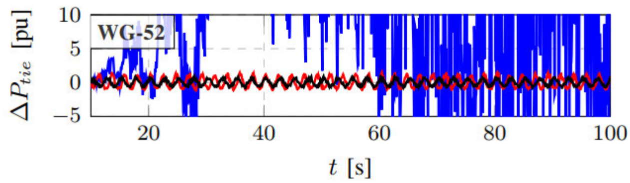

FIGURE 7. System responses with different levels of inertia in Area-5, black line: $H = 100\%$, red line: $H = 80\%$, blue line: $H = 60\%$.

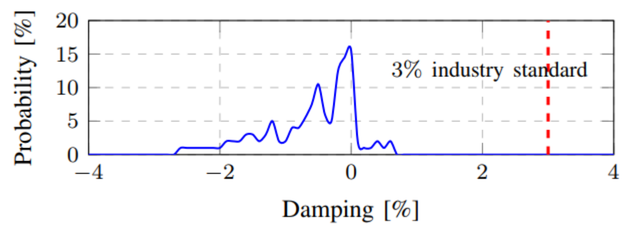

FIGURE 8. Probability of damping of the dominant inter-area mode under 1,000 random uncertainties and system operations.

when the frequency of FD is in the range of inter-area mode. During the FO, damping of the third inter-area mode is below the industry standard (3%). Therefore, it is evident that the FO from RESs significantly degrades the damping of dominant mode. Consequently, it may result in small-signal instability.

When the FD contaminates in wind speed or solar radiation, the CCGs can become the possible FO sources; the severe FO might occur in well-damped power systems. This could degrade the power system stability for certain conditions such as large FD amplitude, adjacent of frequencies of FO and inter-area modes, and FO in systems with low inertia. When the frequency of FD is in the inter-area oscillation frequency band, the resonance occurs, and the damping ratio of the dominant mode is significantly decreased (approximately zero). Conversely, if the frequency of FD is nearly equal to that of the dominant mode, it may result in negative damping and consequently leads the system to the unstable region.

VI. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

An overview of the FO has been given with representative case studies. A thorough review of recent methods of FO analysis, detection, source identification, and mitigation has been discussed in this paper. The problem of FO regarding the penetration of CCGs in future power systems has been introduced. Besides, simulation results demonstrate that the FO caused by CCGs can potentially lead to power system instability. The results also reveal that the system with a high FD amplitude, proximity to inter-area mode frequencies, and low system inertia may be susceptible to the FO. The gaps and future research directions are given as follows:

1) FO analysis, detection, and source identification in power systems with CCGs were not well studied or understood. Most of the literature attempted to analyze the FO, which is originated from SGs. In future power systems, uncertainties of CCGs may affect the accuracy and reliability of such means, and they may result

in false alarms of the FO. Therefore, it is important to consider all possible uncertainties that might cause errors in these processes;

2) Using network solutions to mitigate the FO (i.e., disconnection of FO sources and/or reduction in the output from the FO source) in low-inertia power systems with CCGs may ignite other instability issues. To suppress the FO effectively, CCGs with FO damping controllers and/or coordinated control with PSS in SGs and/or FACTS devices will be an emerging field of future research;
3) As reported by [13], a control solution is an alternative option to mitigate the FO in future power systems effectively without locating the source of the original FO. However, control solutions may not entirely mitigate the sustained FO. Therefore, a coordination of control and network solutions will be an interesting research topic;
4) Control solutions may reduce the FO amplitude in the measured signal. Therefore, the observability of FO could be decreased. Consequently, the accurate source identification could be limited due to the obscured FO source. Hence, the interaction between control and network solutions should be taken into account;
5) With the penetration of CCGs in future power systems, this scenario may lead to greater complexity in locating and ranking the FO sources, difficulty to alleviate the FO. Consequently, the possibility of new control strategies of CCGs and/or SGs will be introduced to mitigate the FO.

Furthermore, the following analyses, enhancements, and modifications are promising:

1) Deep-learning-based artificial intelligence such as cognitive modeling and neural networks, can be applied to enhance the performances of previous FO detection and identification methods, especially in power systems with high penetrations of stochastic CCGs. All previous methods can extend their applications to detect and identify the FO in microgrids with CCGs, e.g., how do the FOs affect the small-signal and transient stability margins of microgrids when they operate in islanded, standalone, or grid-connected mode? Moreover, characteristics of FO caused by CCG controllers have not been thoroughly studied. For instance, the interactions among phase lock loop, high-level control loops, inner control loops, grid parameters, sensor feedback limitations, and controller bandwidths, can become potential sources of the FOs in future power systems and microgrids;
2) The application of previous FO isolation and suppression methods would be extended by incorporating other controllable devices. For example, such applications can be implemented in grid-interfacing converter systems such as solar photovoltaic, wind farms, battery energy storage systems, electric vehicles, FACTS, and controllable loads. Besides, effects of additional FO controllers can be investigated in terms of both power system planning, and power system dynamics and stability.

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