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Definition and Classification of Power System Stability – Revisited & Extended

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***Abstract*-- Since the publication of the original paper on power system stability definitions in 2004, the dynamic behavior of power systems has gradually changed due to the increasing penetration of converter interfaced generation technologies, loads, and transmission devices. In recognition of this change, a Task Force was established in 2016 to re-examine and extend, where appropriate, the classic definitions and classifications of the basic stability terms to incorporate the effects of fast-response power electronic devices. This paper based on an IEEE PES report summarizes the major results of the work of the Task Force and presents extended definitions and classification of power system stability.**

***Index Terms*—Converter-driven stability, electric resonance stability, frequency stability, power system stability, small-signal stability, transient stability, voltage stability.**

LIST OF ACRONYMS:

BESS	Battery energy storage systems
CIGs	Converter interfaced generation
DDSSO	Device-dependent subsynchronous oscillations
DFIG	Doubly-fed induction generators
FACTS	Flexible ac transmission systems
HVDC	High Voltage Direct Current
IGE	Induction Generator Effect
LCC	Line commutated converters
PLL	Phase locked loop
PMG	Direct-drive permanent-magnet generator
PSS	Power system stabilizers
PV	Photovoltaic
SCR	Short circuit ratios
SSCI	Subsynchronous control interaction
SSR	Subsynchronous resonance
STATCOM	Static synchronous compensator
SVCs	Static Var compensators
VSC	Voltage source converters

I. INTRODUCTION

A. Background

A task force set up jointly by the IEEE Power System Dynamic Performance Committee and the CIGRE Study Committee (SC) 38, currently SC C4 – System Technical Performance, had addressed in [1] the issue of stability definition and classification in power systems from a fundamental viewpoint and had closely examined the practical ramifications. This joint effort involving IEEE PES and CIGRÉ was comprehensive and clearly contrasted the electromechanical phenomena associated with various classes of power system stability behavior in comparison to earlier efforts and limited definitions and classifications provided in various textbooks and papers. At the time this document was published in 2004, the dynamic behavior of power systems was predominantly determined by the dynamic performance of synchronous generators and their controls and the dynamic performance of the loads. Consequently, [1] primarily dealt with fairly slow, electromechanical phenomena, typically present in power systems dominated by synchronous machines, while fast transients related to the network and other fast-response devices were considered out of scope and thus neglected, as they typically decay rapidly [2].

Since the publication of [1], however, electric power systems worldwide have experienced a significant transformation, which has been predominantly characterized by an increased penetration of power electronic converter interfaced technologies. Among these new technologies are wind and photovoltaic generation, various storage technologies, flexible ac transmission systems (FACTS), High Voltage Direct Current (HVDC), lines, and power electronic interfaced loads. With significant integration of converter interfaced generation technologies (CIGs), loads, and transmission devices, the dynamic response of power systems has progressively become more dependent on (complex) fast-response power electronic devices, thus, altering the power system dynamic behavior. Accordingly, the report [3] comprehensively addresses the new stability concerns arisen, which need to be appropriately characterized, classified, and defined.

This paper focuses on classifying and defining power system stability phenomena based on [3], including additional considerations due to the penetration of CIG in bulk power systems. The effects of converter connected loads on stability are also briefly discussed, where relevant.

B. Time Scales of Power System Dynamic Phenomena

Fig. 1 depicts the time scales for various classes of dynamic phenomena in power systems. It can be seen that the time scale related to the controls of CIGs ranges from a few microseconds to several milliseconds, thus encompassing wave and electromagnetic phenomena. Considering the

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proliferation of CIGs, faster dynamics will gain more prominence when analyzing future power system dynamic behavior compared to the phenomena within the time scale of several milliseconds to minutes. Focusing on the time scale of the electromechanical transients enabled several simplifications in power system modeling and representation, which significantly aided the characterization and analysis of the related phenomena. A key aspect of these simplifications is the assumption that voltage and current waveforms are dominated by the fundamental frequency component of the system (50 or 60 Hz). As a consequence, the electrical network could be modeled considering steady-state voltage and current phasors, also known as a quasi-static phasor modeling approach. With this modelling approach, high-frequency dynamics and phenomena, such as the dynamics associated with the switching of power electronic converters, are only represented by either steady-state models or simplified dynamic models, meaning that fast phenomena, like switching, cannot be completely captured. Considering the CIG related time scales of operation mentioned previously, there is a need to extend the bandwidth of the phenomena to be examined and include faster dynamics within electromagnetic time scales when the faster dynamics is of importance and can affect overall system dynamics.

This paper as in [3] focuses on two-time scales, namely, that of "electromagnetic" and "electromechanical" phenomena. Electromechanical phenomena are further divided into "short-term" and "long-term" as introduced in [1]. For short- and long-term dynamics, a phasor representation is usually implied, allowing the use of phasor (or quasi sinusoidal) approximation in time-domain simulations. However, this representation is not directly suitable for the study of electromagnetic phenomena.

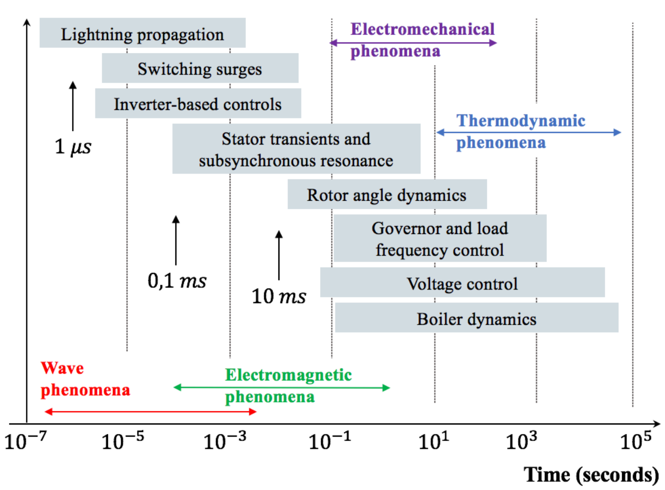

Fig. 1. Power system times scales [3].

C. Scope of this Work

This paper focuses on classifying and defining power system stability phenomena, including additional considerations due to the penetration of CIGs into bulk power systems. The classification is based on the intrinsic dynamics of the phenomena leading to stability problems. The classification into time scales refers to components, phenomena, and controls that need to be modeled to properly reproduce the problem of concern.

The impacts of distributed resources, connected at the distribution level, on the transmission system are addressed in [4] and hence are not dealt with in this document. Furthermore, the paper does not address: i) cases where an incorrect control setting causes a local instability, ii) cases when the instability of a control loop can be directly characterized without modeling the power system, iii) stability issues associated with microgrids (this topic is addressed in [5]), iv) electromechanical and electromagnetic wave propagation phenomena [6]-[10].

II. Characteristics of Converter-Interfaced Generation Technologies

A. Introduction

The increasing share of CIGs in power generation mix leads to new types of power system stability problems. These problems arise due to the different dynamic behavior of CIGs compared to that of the conventional synchronous generators. The stability issues arise due to interactions between CIG controls, reduction in total power system inertia, and limited contribution to short circuit currents from CIG during faults.

B. Characteristics of CIGs and Associated Controllers

The overall performance of CIGs is dominated by the control systems and the strategy used to control the power electronic converter interface between the energy source and the electric grid. The vast majority of large-scale CIGs use voltage-source converters [11], [12], or some derivative thereof, allowing designs that offer full four-quadrant control. In that case, the converter is fully capable of independently controlling active and reactive current that is being exchanged with the grid, as long as the total current remains within the rated capability of the power electronic switches. This allows for fast and accurate control of active and reactive power in most circumstances. Therefore, CIGs present both a challenge and a greater opportunity for hitherto unprecedented flexibility in control of energy sources. For example, with energy sources such as photovoltaic (PV) systems and battery energy storage systems (BESS), very fast and sustained frequency response is technically feasible [13], [14].

The key attributes that need to be considered when evaluating the impact of CIGs on system dynamic behavior are:

1. CIGs can provide limited short-circuit current contributions, often ranging from 0 (converter blocks for close in bolted 3-phase faults) to 1.5 $p.u.$ for a fully converter interfaced resource [15]. Type-3 wind turbine generators [15], i.e., double fed induction generators, can contribute more short circuit current though, as their stator is directly coupled to the grid.
2. The phase locked loop (PLL) and inner-current control loop play a major role in the dynamic recovery after a fault. For connection points with low-short circuit ratio, the response of the inner current-control loop and PLL can become oscillatory. This is due to the PLL not being able to quickly synchronize with the network voltage, and also due to high gains in the inner-current control loop and PLL. This can potentially be mitigated by reducing the gains of these

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controllers. The exact value of the short circuit strength at which this may occur will vary depending on the equipment vendor and network configuration. A typical range of short-circuit ratios below which this may occur is 1.5 to 2.

3. The overall dynamic performance of CIGs is largely determined by the dynamic characteristics of the PLL, the inner-current control loop, and the high-level control loops and their design.

With the switching frequency of the power electronic switches typically in the kilo-hertz range, and the high-level control loops typically in the range of 1 to 10 Hz, similar to most other controllers in power systems, CIGs can impact a wide range of dynamic phenomena, ranging from electromagnetic transients to voltage stability, and across both small- and large-disturbance stability.

In summary, with proper design of both the main circuit and the converter controls, CIGs can contribute to power system control and provide the vast majority of the services traditionally provided by conventional generation such as (i) voltage/reactive power control, (ii) active power control and frequency response, and (iii) ride-through for both voltage and frequency disturbances. In this context, there has been, and continues to be, significant advances and learning of how best to achieve these objectives. Furthermore, due to the significant differences in the physical and electrical characteristics of CIGs compared to synchronous generation, CIGs do not inherently provide short-circuit current nor inertial response, and so these aspects will continue to present some challenges.

III. Definition of Power System Stability

A. General Comments

In this section, the formal definition of power system stability from [1] is presented. The intent in [1] was to provide a physically based definition which, while conforming to definitions from system theory, can be easily understood and readily applied by power system engineering practitioners. For the system transformation resulting from connection of converter interfaced generation and load power-electronics based control devices, described in Section I, the definition in [1] still applies and hence, it remains unchanged.

B. Formal Definition

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

C. Discussion and Elaboration

As in [1], the discussion here (derived from [3]) applies to all aspects of the dynamic performance of interconnected power systems, including synchronous machines and conventional individual components. Of particular interest, though, is the application of the definition proposed in [1] in characterizing stability performance related to CIGs. Akin to the case of a single remote synchronous machine losing synchronism without causing cascading instability of the main system, the stability behavior of a single remote CIG interconnected to the system has identical stability implications. As long as the dynamic response to a disturbance only affects the individual CIG without causing the cascading instability of the main system, the definition provided in [1] still applies.

Section V of reference [1] provides details of the system-theoretic foundation of power system stability. It provides an introduction to differential-algebraic equations forming mathematical models of power systems. This is then followed by specific definitions from system theory. With the inclusion of power electronic inverters and the possible need to model protection systems, however, there is also a need to provide similar definitions for hybrid systems as presented in [3].

D. Stability Definition Hybrid Systems

Hybrid dynamical systems are characterized by interactions between continuous dynamics and discrete events [16]. As with continuous systems, the concept of stability of hybrid dynamical systems should capture the notion that if the continuous state x starts close to an equilibrium point then it should remain close or converge to the equilibrium point. Lyapunov stability for hybrid dynamical systems is also conceptually similar to the requirements for continuous systems. However, hybrid systems require the additional condition that the Lyapunov function must exhibit non-increasing behavior at events.

To illustrate potential complications that can arise from switching, consider the model for a non-windup lag block. It is shown in [17] that this model can encounter situations where upon switching, the model must immediately switch back, *ad infinitum*. This infinite switching sequence prevents the trajectory from progressing beyond that troublesome switching event. Such situations are referred to as *deadlock* or *infinite Zeno*. They are a modeling artifact and cannot occur in real systems, in contrast to chattering, which is an actual phenomenon. This highlights the need for extra care in developing models that involve interactions between continuous dynamics and discrete events.

An actual event that was driven by hybrid dynamics is analyzed in [18]. The event began with an unplanned outage that weakened a section of sub-transmission network, resulting in voltage oscillations. The oscillations arose due to interactions between transformer tapping and capacitor switching, both of which caused discrete changes to the network. Furthermore, the voltage regulating controls of both the transformer and capacitor incorporated switching in the form of voltage deadbands and timers. Hence, hybrid dynamics played multiple roles in this event.

IV. Classification of Power System Stability

A. Need for Classification

Figure 2 shows the classification of the various types of power system stability. With respect to the original classification presented in [1], two new stability classes have been introduced, namely "Converter-driven stability" and "Resonance stability". Adding these two new classes was motivated by the increased use of CIGs. The traditional sub-synchronous resonance class was not included in [1] because such phenomena were outside of the time scale originally considered in [1] (see Fig. 1). Due to the addition of the power electronic dynamics, however, the time scale of interest for

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power system stability extended down to electromagnetic transients.

Note that all dynamic phenomena considered in the original classification presented in [1], are properly modeled using the "phasor (or quasi-sinusoidal) approximation". Most often though, this simplified modeling approach is not applicable to the converter-driven and electric resonance stability classes, with the possible exception of the "slow-interaction of converter-driven stability" (see Fig. 2).

The following table summarizes the categories of stability presented in the next sections.

Table. 1. Categories of power system stability.

Categories of Power System Stability	Additional considerations with respect to Ref. [1]
Rotor Angle Stability • Transient • Small Disturbance	• Definition unaffected. • Effect of CIGs in both subcategories highlighted.
Voltage Stability • Short-term • Long-term	• Definition unaffected. • Effects of HVDC links in short-term voltage stability
Frequency Stability • Short-term • Long-term	• Definition unaffected. • Effects of CIGs in changing and the potential of controlling system frequency.
Resonance Stability • Electrical • Torsional	• New category added. • Effect of HVDC and FACTs on torsional and of DFIG controls on electrical resonance stability
Converter-driven Stability • Fast interaction • Slow interaction	• New category added. • Fast dynamic interactions of the control systems of power electronic-based systems with fast-response components of the power system and other power electronic-based devices. • Slow dynamic interactions of the control systems of power electronic-based devices with slow-response components of the power system.

In the following sub sections, different categories of system stability are presented. The discussion starts with describing the effects of CIGs on the existing stability categories, i.e., those defined in [1] and finishes by describing the two new stability classes.

B. Categories of Stability

B1. Rotor Angle Stability

B1.1. Definition and Description of Phenomena

Rotor angle stability is concerned with the ability of the interconnected synchronous machines in a power system to remain in synchronism under normal operating conditions and to regain synchronism after being subjected to a small or large disturbance [1]. A machine keeps synchronism if the electromagnetic torque is equal and opposite to the mechanical torque delivered by the prime mover. Accordingly, this type of stability depends on the ability of the synchronous machines to maintain or restore the equilibrium between these two opposing torques.

Insufficient or negative synchronizing torque results in aperiodic or non-oscillatory *transient* instability. This kind of instability involves large excursions of the rotor angles of the synchronous machines that is typically analyzed using numerical integration methods. The lack of negative damping torque, on the other hand, will lead to *small-disturbance* oscillatory stability [1]. This kind of instability is characterized by a complex conjugate pair of relatively poorly damped eigenvalues of the linearized system state matrix moving from the left-half plane (stable) to the right half-plane (unstable) of the complex plane following a system disturbance or a change in the system topology [19].

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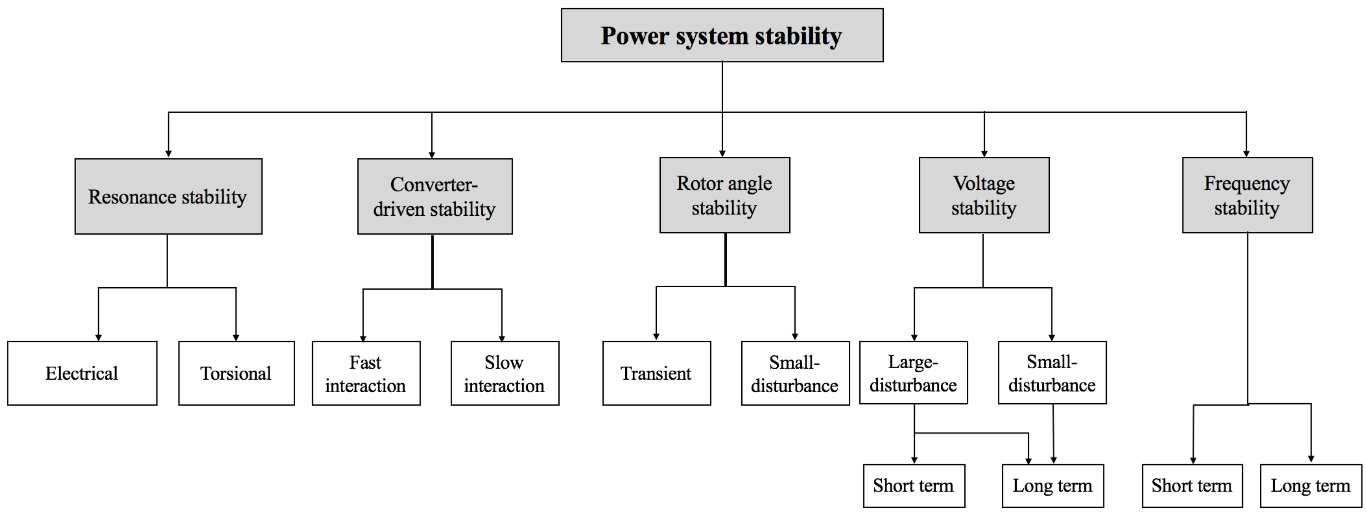

Fig. 2. Classification of power system stability [3].

B1.2. Effects of CIG

The integration of CIGs does not change the fundamental definition of rotor angle stability presented in [1]. Still, as conventional synchronous generators are displaced by CIGs, the total inertia of the system will be reduced. This in turn has an impact on rotor angle stability and also on the electromechanical modes of the system [20]. The displacement of synchronous generation by CIGs, affects the rotor-angle stability of the remaining synchronous generators in the system by:

1. Changing the flows on major tie-lines, which may in turn affect damping of inter-area modes and transient stability margins [21], [22].
2. Displacing large synchronous generators, which may in turn affect the mode shape, modal frequency, and damping of electromechanical modes of rotor oscillations [21].
3. Influencing/affecting the damping torque of nearby synchronous generators, similar to the manner in which FACTS devices influence damping [23], [24]. This is reflected in changes in the damping of modes that involve those synchronous generators.
4. Displacing synchronous generators that have crucial power system stabilizers.

Given item 3 above, there may be future potential for designing supplemental controls for CIGs to help mitigate power oscillations, similar to the concept of power oscillation dampers on FACTS devices [23], [24].

Significant effort has already been devoted to understanding and describing the effects of CIGs on small-disturbance stability. However, results and conclusions obtained are to a large extent influenced by the test power systems used and their operating conditions [25]. Accordingly, there is no general consensus regarding the effects of increased penetration of CIGs on electromechanical modes and on the small disturbance rotor angle stability [20]. The effects can be both small and large, and the presence of CIGs beneficial or detrimental [21], [25]. The type of impact will depend on several factors, including the number of CIGs in the system, the type of controls applied, network topology and strength, the loading conditions in the system, and other similar factors.

In terms of transient rotor angle stability, lowering the total system inertia may result in larger and faster rotor swings thus making the system more prone to stability problems [20]. As before, studies have shown that increased penetration of CIGs can have both beneficial and detrimental effects on transient rotor angle stability depending on the grid layout, and the location, and control of CIGs [20], [21]. The effects of CIGs on transient rotor angle stability are also impacted by other factors such as the type of disturbance and its location with respect to the CIGs and the large power plants [26]. The control of the converters during and after the fault and their ride-through capability can also significantly influence transient rotor angle stability, as pointed out in, e.g.,[26], [27].

B2. Voltage Stability

B2.1 Definition and Description of Phenomena

Voltage stability refers to the ability of a power system to maintain steady voltages close to nominal value at all buses in the system after being subjected to a disturbance [1]. It depends on the ability of the combined generation and transmission systems to provide the power requested by loads [28]. This ability is constrained by the maximum power transfer to a specific set of buses and linked to the voltage drop that occurs when active and/or reactive power flows through inductive reactances of the transmission network. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other network components, by their protective systems, leading to cascading outages. Loss of synchronism of some generators may also result from these outages or from operating under field current limitation [3].

The above definition applies to both short-term and long-term voltage stability that are introduced below.

B2.2 Short-term Voltage Stability

Short-term voltage stability involves dynamics of fast acting load components such as induction motors, electronically

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controlled loads, HVDC links and inverter-based generators. The study period of interest is in the order of several seconds, similar to rotor angle stability or converter-driven stability (slow interaction type). Accordingly, models with the same degree of detail as for the above stability classes must be used. In addition, for short-term voltage stability, the dynamic modeling of loads is essential, and short circuit faults near loads are the main concern.

- *Instability Driven by Induction Machines*

The most typical case of short-term voltage instability is the stalling of induction motors following a large disturbance by either loss of equilibrium (between electromagnetic and mechanical torques) or by lack of attraction to the stable equilibrium due to delayed fault clearing. During a fault, induction motors decelerate (due to decreased electromagnetic torque) which makes them draw a higher current and reactive power, causing further voltage depression. After fault clearing, electromagnetic torque recovers. If the motor has not decelerated below a critical speed, it reaccelerates towards a normal operating point. Otherwise, it cannot reaccelerate and stalls. Stalled motors can either be disconnected by undervoltage protection or remain connected, drawing a large (starting) current until they are disconnected by thermal overcurrent protection. In the latter case, voltage remains depressed for longer time, possibly inducing a cascade of similar events on nearby motors [29].

- *Instability Driven by HVDC Links*

Voltage stability problems may also be experienced at the terminals of HVDC links with line commutated converters (LCC). They are usually associated with HVDC links connected to weak AC systems and may occur at rectifier or inverter stations, due to the unfavorable reactive power “load” characteristics of the converters. The associated phenomenon is relatively fast with the time frame of interest being on the order of one second or less. On the other hand, the voltage instability may also be associated with converter transformer tap-changer controls, which is a considerably slower phenomenon.

The use of voltage source converters (VSC) in HVDC converter stations has significantly increased the stable operation limits of HVDC links in weak systems compared to LCC based HVDC links.

B2.3 Long-term Voltage Stability

Long-term voltage stability involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. It usually occurs in the form of a progressive reduction of voltages at some network buses. The maximum power transfer and voltage support are further limited when some of the generators hit their field and/or armature current time-overload capability limits.

The study period of interest may extend to several minutes, and long-term simulations are required for analysis of system dynamic performance.

This type of stability is usually not determined by an initiating fault, but by the resulting outage of transmission and/or generation equipment after fault clearing.

Long-term instability is usually due to loss of long-term equilibrium, when load dynamics attempt to restore power consumption beyond the maximum power transfer limit. Instability may also result when a remedial action restores a stable post-disturbance equilibrium, but too late, so that attraction to the equilibrium does not take place.

Alternatively, the disturbance leading to instability could also be a sustained load buildup (e.g., morning load increase).

Long-term voltage stability is usually assessed by estimating a stability margin expressed in terms of load power increase from an operating point to the maximum power transfer (onset of instability). For this purpose, the direction of system stress has to be defined, including the load increase pattern and generation participation. As stated in [1], linear and nonlinear analyses are used in a complementary manner. Linear analysis can be used to assess the stability of an operating point (i.e. eigenvalues of an appropriate Jacobian matrix) to identify the point of maximum power transfer and to provide sensitivity information for identifying factors influencing stability. Nonlinear models, however, are required to account for nonlinear effects such as limits, deadbands, discrete tap changer steps, and (constant or variable) time delays. In this respect, the distinction between both, small- and large-disturbance must be considered for long-term voltage stability assessment.

While the most common form of voltage instability is the progressive drop of bus voltages, the risk of overvoltage instability also exists and has been experienced in a few cases [30], [31]. It is caused by a capacitive behavior of the network (e.g. EHV/HV transmission lines operating below surge impedance loading, shunt capacitors and filter banks from HVDC stations), as well as by under-excitation limiters preventing generators and/or synchronous compensators from absorbing the excess reactive power. In this case, the instability is associated with the inability of the combined generation and transmission system to operate below a minimum load consumption level.

B3. Frequency Stability

Figure 3 depicts the three distinct periods during an event that causes decline in frequency, frequency, in a system dominated by synchronous generators, and the related controls: (i) the initial inertial response of synchronous generators, (ii) the primary frequency response of generators and load damping, and (iii) automatic generation controls bringing the frequency back to its nominal value.

CIGs do not inherently provide inertial response. Furthermore, since CIGs are typically associated with renewable resources, there are considerable economic consequences associated with the “spilling” of the incident resource in order to maintain a margin for reserve and thus provide primary-frequency response. These economic factors aside, it has been demonstrated that CIGs can contribute quite well and decisively to frequency response [13], [14], [33]-[40]. Thus, as CIGs penetration increases, it is technically feasible for them to contribute decisively to controlling system frequency, particularly in the case of battery-energy storage.

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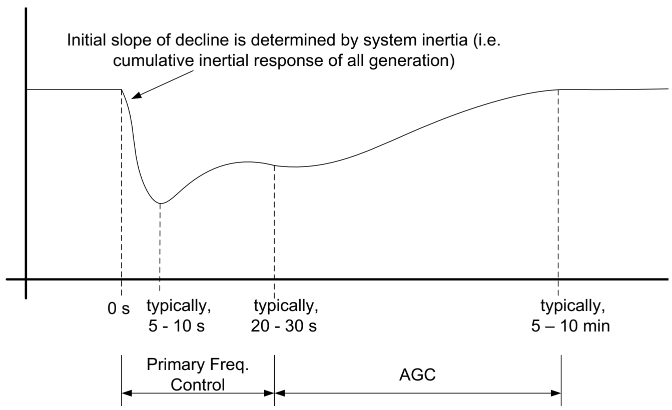

Fig. 3. An illustration of power system frequency response to a major loss of generation. (IEEE © 2013, reproduced from [32])

CIGs can provide primary frequency response faster and can have smaller droop settings (large response), since the limiting factor in many cases (e.g., solar PV and battery energy storage), is the response time of electronics/electrical equipment and not mechanical systems (e.g. boilers and turbines) [14], [32].

As the penetration of CIGs increases in power systems around the world, it is likely that the frequency response of power systems will tend towards the response of smaller systems, which places a greater emphasis on the need for, and tuning of the controls associated with primary-frequency response. It should be noted that in the case of wind turbine generators, a form of inertial-based fast-frequency response is possible and provided by many vendors [13].

Due to the decreasing grid inertia resulting from the displacement of synchronous generators, frequency excursions become faster and therefore the likelihood of instability occurring earlier is increasing. This puts more emphasis on the need to design appropriate fast acting controllers to arrest frequency drops as soon as detected. High penetration of CIGs may not always result in a notable reduction of system inertia if the synchronous generators remain connected but de-loaded. For example, the Western Wind and Solar Integration Study [41] recommends a 2/3 de-commitment and 1/3 re-dispatch approach to balance a reduction in load, i.e., 2/3 to the reduction in load is balanced by disconnecting synchronous generators and 1/3 of the reduction is balanced by de-loading synchronous generators. In this case the effect on frequency response could be positive as more spinning reserve becomes available while the drop in system inertia may not be significant. The recent studies [42] and [43] have shown that the frequency response of systems with CIGs is a complex phenomenon which requires further investigation.

B4. Resonance Stability

The resonance, in general, occurs when energy exchange takes place periodically in an oscillatory manner. These oscillations grow in case of insufficient dissipation of energy in the flow path and are manifested (in electrical power systems) in magnification of voltage/current/torque magnitudes. When these magnitudes exceed specified thresholds, it is said that a resonance instability has occurred. The term resonance stability encompasses subsynchronous resonance (SSR), whether it be associated with an electromechanical resonance or an entirely electrical resonance. The term SSR, as defined in the original publications related to this phenomenon [44], can manifest in two possible forms: (i) due to a resonance between series compensation and the mechanical torsional frequencies of the turbine-generator shaft, and (ii) due to a resonance between series compensation and the electrical characteristics of the generator. The first of these occurs between the series compensated electrical network and the mechanical modes of torsional oscillations on the turbine-generator shaft, while the second is a purely electrical resonance and termed Induction Generator Effect (IGE) [45], [46]. Hence, in Fig. 2 the resonance stability has been split into these two categories.

B4.1 Torsional resonance

The SSR due to torsional interactions between the series compensated line(s) and the turbine-generator mechanical shaft are well documented in the literature, particularly as it pertains to conventional synchronous generation [44]-[48]. According to the IEEE working group [47], subsynchronous oscillations are mainly classified into SSR and device-dependent subsynchronous oscillations (DDSSO). SSR involves an electric power system condition where the network exchanges significant energy with a turbine-generator at one or more of the natural sub-synchronous torsional modes of oscillation of the combined turbine-generator mechanical shaft [44], [47]. The oscillations can be poorly damped, undamped, or even negatively damped and growing [44], thus threatening the mechanical integrity of the turbine-generator shaft. DDSSO arise due to the interaction of fast acting control devices, such as HVDC lines, static Var compensators (SVCs), static synchronous compensators (STATCOM), and power system stabilizers (PSS) with the torsional mechanical modes of nearby turbine-generators [44], [47]-[51]. It should be noted, however, that DDSSO are not always detrimental, in some cases the interaction can be beneficial and in fact improve torsional damping [52]. For this reason, in many cases devices such as SVCs may in fact be used as a means of providing a solution for SSR by improving torsional damping.

B4.2 Electrical resonance

In the case of power systems with conventional turbine-generators only, the issue related to SSR is one of torsional interactions and resonance. The IGE [45] (or self-excitation [53]) has never been observed in real power systems with conventional synchronous generation. However, it was predicted as early as 2003 that variable speed induction generators used in doubly-fed induction generators (DFIG) would be highly susceptible to IGE self-excitation type SSR [54]. This is due to the fact that a variable speed DFIG generator is an induction generator directly connected to the grid, which makes such an electrical resonance between the generator and series compensation possible [53]. In this case, the self-excitation type SSR occurs when the series capacitor forms a resonant circuit, at sub-synchronous frequencies, with the effective inductance of the induction generator, and at these frequencies, the net apparent resistance of the circuit is

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negative.

The net negative resistance occurs due to the inherent negative resistance of the induction generator rotor, as seen on the stator side, and much more so because of the action of the DFIG controls governing the converter connected between the stator and rotor circuits. Thus, if the total negative resistance resulting from these sources exceeds the positive resistance of the circuit at or near the resonant frequencies, self-excitation SSR occurs. The resultant resonance primarily leads to large current and voltage oscillations that can damage the electrical equipment both, within the generators and on the transmission system. It may also be possible that large perturbations in electrical torque, could result in mechanical damage to the turbine-generator assembly (e.g. gear box). This phenomenon was observed for the first time in the field in the Electric Reliability Council of Texas (ERCOT) in 2009 [49], [55]-[57]. Similar events, also including DFIGs and series compensation, have been observed in the Xcel Energy network in Minnesota [58].

The phenomenon leading to the subsynchronous oscillations in both incidents was termed subsynchronous control interaction (SSCI) in the literature [55], [59], [60]because the dominant factor in producing negative damping at the electrical resonant frequencies is the control action of the DFIG converter controls. This has been widely investigated and documented during the last ten years, [61]-[68], determining that the major cause of SSCI stability problems is the IGE [62]. The term SSCI should not be misunderstood by thinking that the resonance is only due to control interactions with the series capacitor. It should be remembered that the underlying phenomenon is the purely electrical resonance between the series capacitor and the effective reactance of the direct connected induction generator (i.e. self-excitation [45], [53]) which becomes unstable once the apparent resistance in the circuit becomes largely negative due to the additional effect of the converter controls. It has been shown that supplemental controllers added to the DFIG converter controls can help to mitigate and damp the resonant oscillations [69].

B5. Converter-driven Stability

The dynamic behavior of CIG is clearly different from conventional synchronous generators, due to the predominant VSC interface with the grid [70]. As described in Section II, a typical CIG relies on control loops and algorithms with fast response times, such as the PLL and the inner-current control loops. In this regard, the wide timescale related to the controls of CIGs can result in cross couplings with both the electromechanical dynamics of machines and the electromagnetic transients of the network, which may lead to unstable power system oscillations over a wide frequency range [71]. Consequently, slow- and fast-interactions are differentiated as shown in Fig. 2, based on the frequencies of the observed phenomena. Instability phenomena showing relatively low frequencies are classified as Slow-Interaction Converter-driven Stability (typically, less than 10 Hz), while phenomena with relatively high frequencies are classified as Fast-Interaction Converter-driven Stability (typically, tens to hundreds of Hz, and possibly into kHz), as discussed in more detail next, providing several examples of both types.

B5.1 Fast-Interaction Converter-driven Stability

These types of instabilities involve system-wide stability problems driven by fast dynamic interactions of the control systems of power electronic-based systems, such as CIGs, HVDC, and FACTS with fast-response components of the power system such as the transmission network, the stator dynamics of synchronous generators, or other power electronic-based devices. Instabilities in power systems due to fast converter interactions may arise in a number of different ways. For instance, interactions of the fast inner-current loops of CIG with passive system components may cause high frequency oscillations, typically in the range of hundreds of hertz to several kilohertz [72], [73]. This phenomenon has been referred to as harmonic instability in the power electronics community. It is a general term used for a wide range of phenomena resulting in high frequency oscillations, including resonance and multi-resonance issues, which can be prevented and/or mitigated by active damping strategies [73].

Several inverters in close proximity to each other may also generate interactions leading to multi-resonance peaks [74]. They can also be caused by high-frequency switching of CIGs that may trigger parallel and series resonances associated with LCL power filters or parasitic feeder capacitors [72], [75]. The resonance of an inverter filter can also be triggered by the control of the inverter itself or by interactions with nearby controllers [76]. The mutual interaction between the control loops of grid-connected converters may also lead to high frequency oscillations [77], [78].

Due to the very fast controls of the power converter in CIGs, interactions induced by the coupling between the converters and the grid are also possible [79]. High and very high frequency oscillations have been reported in the case of large-scale wind power plants connected to VSC-HVDC [80], [81] (i.e. between 500 Hz to 2 kHz). In another paper [82], it is argued that synthetic inertia controllers that sought to replicate swing equation inertial response, under high CIG penetration, may trigger super-synchronous stability problems due to converter control interactions. However, it is shown in [83] and [84] that a properly tuned virtual synchronous machine controller is less likely to induce these types of fast oscillations, in part due to their slower control response. These remain areas of active research.

Recently, some fast oscillation phenomena including sub- and super-synchronous interactions between STATCOM and weak AC/DC grids have been detected in the China Southern Grid. The observed oscillations have frequencies of 2.5 Hz and 97.5 Hz [49], [85].

B5.2 Slow-interaction Converter-driven Stability

These types of instabilities involve system-wide instabilities driven by slow dynamic interactions of the control systems of power electronic-based devices with slow-response components of the power system such as the electromechanical dynamics of synchronous generators and some generator controllers.

This category of converter-driven instability can be similar to voltage stability, in the sense that maximum power transfer

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between the converter and the rest of the system, i.e., a weak system, can be the root cause of instability. The two mechanisms are different insofar as voltage instability is driven by loads, while converter-driven instability is associated with the power electronic converter controls.

- *Low frequency Oscillations*

Unstable low-frequency oscillations in power systems with CIGs can appear due to a variety of forms of interaction between the controllers of the converters and other system components. The outer (power and voltage) control loops and the PLL of CIGs can, for instance, lead to unstable low frequency oscillations [73]. System strength at the connection point of CIGs has a significant influence on the stability of low-frequency oscillations [86]-[90]. This has been observed in real events in Xinjiang (China), where the interaction between direct-drive permanent-magnet generator (PMG) wind turbines and weak AC grids has resulted in the system experiencing sustained oscillations since 2014. The oscillation frequencies range between 20 Hz and 40 Hz, depending on the system operating conditions [66], [91]. In power systems with low short circuit ratios (SCR), i.e. weak grids with SCR less than 2 [92], [93], the oscillations may become unstable and could lead to growing low-frequency oscillations in the PMG and the local grid.

Other factors affecting low-frequency oscillations in weak grids include the online capacity of CIG and the control strategies and parameters of the converters [86], [87]. Although a higher PLL bandwidth makes the system more stable when the converter is in power control mode, there are practical limitations related to the PLL gains and bandwidth, imposed by the low-pass filters used for eliminating noise and harmonics from the measured signals [87].

Unstable low-frequency oscillations in VSC-HVDC systems with weak grid connection have also been observed [89], [90]. In this case, system stability is mainly affected by the tuning of the outer loop parameters and the response time of the PLL [90], particularly at low SCR [89].

- *Weak System Stability*

The ability of the CIG PLL to synchronize with the grid in the case of nearby faults can be extremely challenging in weak networks [94], [95]. This phenomenon has been shown to be related to the PLL effectively introducing a negative admittance in parallel with the system input admittance [95]. When the PLL attempts to quickly track large changes in the angle during transients in weak networks, this effective admittance may lead to a high-gain PLL providing an erroneous value of angle to the inner current controller. Thus, the resulting current being injected by the CIG may be at the wrong phase, which could result in further voltage magnitude and angle degradation, thus leading to instability [95]. A variety of potential solutions may include tuning the PLL and inner-current control loops to lower their gains, considering other emerging control strategies, introducing other supplemental controls, or adding equipment to improve system strength (e.g. installation of synchronous condensers).

- *Stability Issues related to Power Transfer Limits*

As detailed in [3], power transfer limits imposed on CIGs connected to weak networks may also result in stability problems. This can be caused by the inability of the converter to adjust its phase to export the generated power or when the inverter hits its current limit [97], [98].

C. Analysis tools and contingency selection

In order to study the various stability phenomena and concerns addressed in Section IV.B, power system analysts and modelers have suitably adapted existing tools and models to study various phenomena and their associated timescales. In order to study the impacts of CIGs on electromechanical phenomena, excellent models for study of the impact of CIGs in positive-sequence time-domain simulation software packages have been developed and introduced in commercial transient stability software packages. These models have also been incorporated in commercial small-signal stability analysis tools. For disturbances in which the faster timescale response and phenomena are of interest, the technical community has developed co-simulation tools and techniques which incorporate electromagnetic and electromechanical transient analysis with detailed representation of the fast power electronic components and devices. The various CIGs, storage devices, and power electronics components also need to be appropriately incorporated in the overall study as critical elements while performing contingency selection. Furthermore, based on the timescale considered, appropriate analysis tools need to be utilized to examine the phenomena that are likely to result with the contingency associated with these devices.

V. Summary and Conclusions

This paper revisits the classic power system stability definition and extends the classifications of the basic stability terms detailed in [3], in order to cover the effects of the increasing penetration of fast-acting, CIGs, loads, and transmission devices in modern power systems. This extension was needed in order to incorporate new stability problems arising from CIGs' characteristics, which differ from those of conventional synchronous machines. Factors driving these new problems include potential decrease in system frequency response, notable reduction in total system inertia, and reduced contribution to short circuit currents. The formal definition of power system stability in [1] is shown to apply to the new conditions introduced by CIGs while conforming to definitions from system theory. An expanded classification is proposed in order to cover the effects of fast-response power electronic devices down to electromagnetic transients. The basic categories of "rotor angle", "voltage" and "frequency" stability are described focusing on the presence of CIGs. Next to these classic categories, two new stability classes are introduced, namely "Converter-driven stability" and "Resonance stability", also motivated by the increased presence of CIGs in modern power systems. It should be noted that the classification presented in this paper (as developed and detailed in [3]), is based on the intrinsic system dynamics (time constants associated with actual physical phenomena) and not on the scenario or disturbance initiating the instability.

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