1

Power System Stability: Definition, Classification, and Phenomenon

1.1 Introduction

An electrical power system is a fundamental infrastructure of a society. As a large-scale time-varying dynamic system, maintaining its stability is a basic and essential requirement during its operation and planning decision-making process. In general, the stability of a power system refers to its ability to regain a state of operating equilibrium after being subjected to a physical disturbance (such as a short-circuit fault) [1]. In practice, the stability of the power system depends on both its dynamic characteristics, i.e. how the system would behave in response to disturbances, and its steady-state operating conditions, i.e. how the power system is dispatched.

In recent years, modern power systems have started to integrate high shares of renewable energy sources, such as solar photovoltaic and wind power, which are inherently stochastic and intermittent in their power outputs and are interfaced with the power grid through power electronic converters. While these renewable energy-based converter interfaced generators (CIGs) are environmentally beneficial, they significantly complicate the power grid's static and dynamic characteristics. As a result, the dynamic behaviors of the power system become much more complex, which introduces a series of challenges to the control, operation, and planning for maintaining system stability.

In a nutshell, this chapter gives a brief introduction to the modern power system stability, including its definition, classification, and phenomenon.

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1.2 Definition

In this book, the definition of power system stability given in [1] is adopted. Conforming to definitions from system theory, the definition is based in physics, thus easily understood and readily applied by power system engineering practitioners:

> 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.

The definition is applied to interconnected power systems at large while also concerning the stability of a single generator or a group of generators. When a power system is subjected to a disturbance, its stability depends on its initial operating point and the nature of the disturbance. In practice, a power system can suffer from various disturbances regardless of small or large. A small disturbance can be a continuous load change that will not alter the system topologies. A large disturbance is one which may result in structural changes due to the isolation of the faults, such as a short circuit on the transmission line or losses of a large generator. After small or large disturbances, the system must be capable of riding through the disturbances and returning to a viable equilibrium.

It should be noted that, at an initial operating point, a power system may be stable for a given large disturbance but become unstable for another. It is in general not practical or economical to ensure stability against all possible disturbances. It is more reasonable to select contingencies that show a high probability of occurrence and criticality based on historical data and system topology information. Large-disturbance stability is generally validated under a set of specified disturbances. A stable equilibrium has a finite region of attraction; the larger the region, the more robust the system is against large disturbances. However, it should be noted that the region of attraction changes with the operating point of the power system. Though the power system continually fluctuates with small magnitudes, it is usually acceptable to assume that the system is initially in a steady-state operating point when assessing its stability after being subjected to a specific disturbance.

1.3 Classification

Stability is a condition of equilibrium between opposing forces undergoing continuous imbalance, which results in different forms of instability subject to the network topology, system operating point, and the type of disturbance. The different

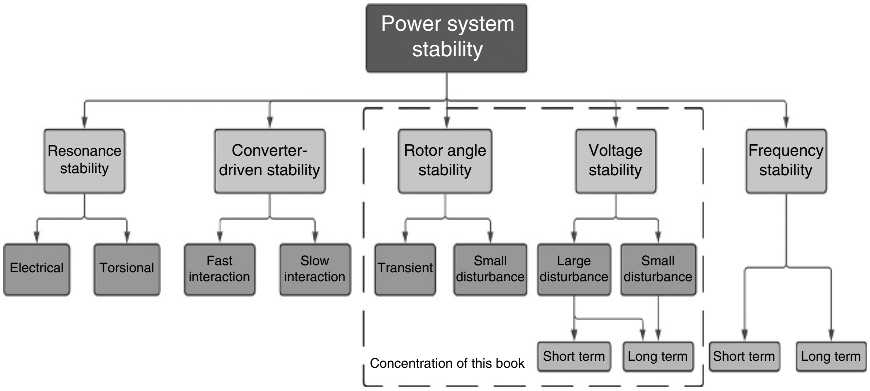

Figure 1.1 Classification of power system stability.

forms of instabilities need to be properly analyzed. To facilitate the analysis of stability problems which are in nature of high dimension and complexity, it is necessary to firstly classify the stability into appropriate categories.

Figure 1.1 shows the overall picture of the power system stability classification with its categories and subcategories. Traditionally, the power system stability was classified into three categories: rotor angle stability, voltage stability, and frequency stability [1]. The power system stability primarily dealt with fairly slow electromechanical phenomena, which are typically caused by synchronous machines and induction machines. Given the increased penetration of CIGs in modern power systems and their substantial impacts on system dynamic behavior, two new stability categories have been added [2], i.e. resonance stability and converter-driven stability, to deal with faster dynamics within electromagnetic time scales.

The focus of this book is on the rotor angle stability and voltage stability, which are the two most stringent stability requirements for the power system operation and planning. Rotor angle stability and voltage stability can be approached by optimization-based operating point dispatches and network reinforcement (dynamic reactive power device deployment).

1.4 Rotor Angle Stability

Rotor angle stability is the ability of synchronous generators to remain in synchronism after being subjected to a disturbance. It depends on the ability of each synchronous generator to maintain equilibrium between electromagnetic torque and mechanical torque. Instability will occur when the rotor angles of some generators increase continuously with regard to other generators. Namely, the generators lose synchronism with others. The loss of synchronism can occur between one machine and the rest of the system, or between groups of machines, with synchronism maintained within each group after separating from each other. The possible outcome of the instability is generator tripping and/or separation of the power systems.

As presented in Figure 1.1, the rotor angle stability can be divided into large-disturbance rotor angle stability (also called transient stability) and small-disturbance rotor angle stability, based on the severity of the disturbance.

1.4.1 Large-Disturbance Rotor Angle Stability

For transient stability, it is always relative to a severe disturbance, such as a short circuit on a transmission line, which will result in large excursions of rotor angles and is involved by the nonlinear power–angle relationship. Transient stability depends on both the initial operating point and the severity of the disturbance. Instability is usually in the form of aperiodic angular separation due to insufficient synchronizing torque, indicating *first-swing instability*. Figures 1.2 and 1.3 indicate

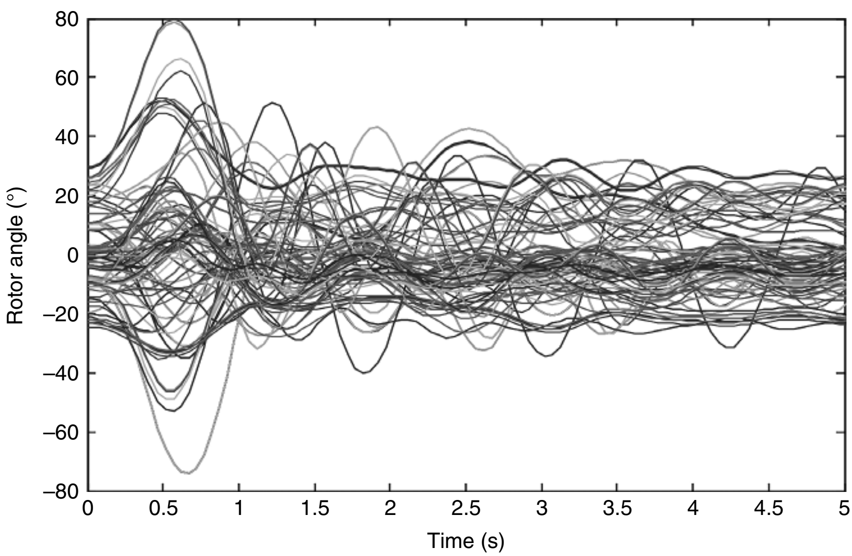

Figure 1.2 Simulated rotor angles of a transient stable case. *Source:* Xu [3].

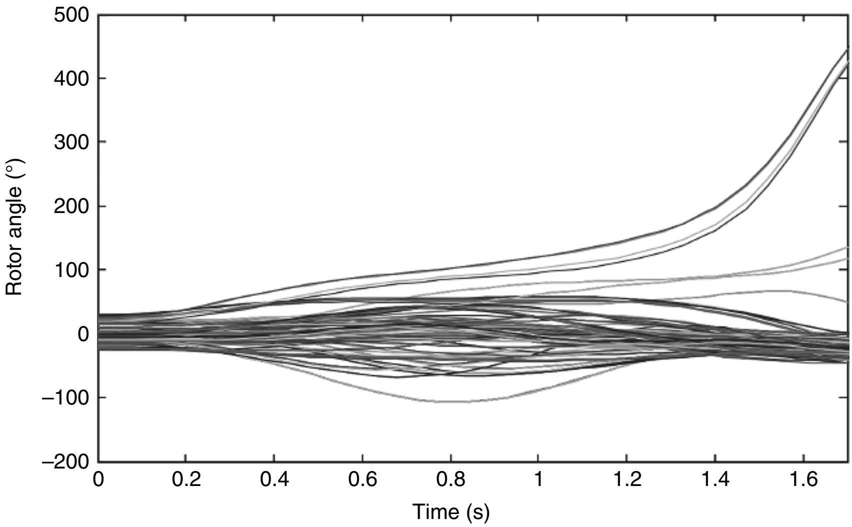

Figure 1.3 Simulated rotor angles of a transient unstable case. *Source:* Xu [3].

the simulated post-disturbance rotor angle trajectories of a real large power grid for a stable case and an unstable case, respectively. From the two figures, the stable case corresponds to keeping the synchronism of all the generators, while the unstable case corresponds to the loss of synchronism of some generators after the disturbance.

1.4.2 Small-Disturbance Rotor Angle Stability

Small-disturbance rotor angle stability refers to the ability of the power system to maintain synchronism under small disturbances. The disturbances are considered to be sufficiently small that linearization of system equations is permissible for purposes of analysis, e.g. the sudden variation of the load demands and/or the change of generation output. Small-disturbance rotor angle stability usually depends on the initial operating point. Instability is often in two forms: (i) non-oscillatory increment of rotor angle due to lack of synchronizing torque; or (ii) rotor oscillations of amplitude due to lack of damping torque. For modern power systems, small-disturbance rotor angle stability is usually associated with insufficient damping torque. The illustration of the small-disturbance stability problem due to the lack of damping torque is presented in Figure 1.4.

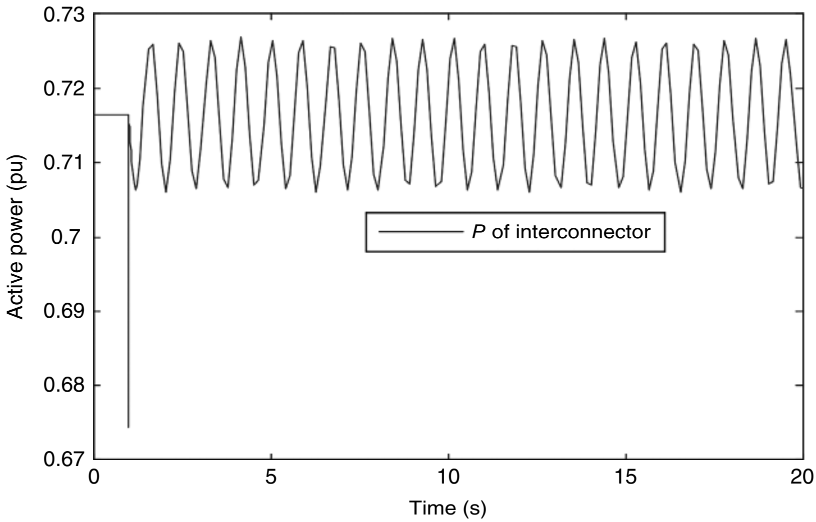

Figure 1.4 Active power oscillation due to the small-disturbance instability. *Source:* Xu [3].

1.5 Voltage Stability

Voltage stability is the ability of the power system to maintain steady voltages at all buses after being subjected to a disturbance. It depends on the ability to maintain equilibrium between load demand and load supply from the power system. Instability will occur in the form of a successive fall or rise of voltage in some buses. A possible outcome of instability is loss of load in an area or transmission lines and other elements tripping by their protective systems, leading to cascading outages. It should be noted that a progressive drop in bus voltage may be associated with rotor angle instability.

The driving force for voltage instability is usually the loads. A run-down situation causing voltage instability occurs when load dynamics attempt to restore power consumption beyond the capability of the transmission network and the connected generation.

As in the case of rotor angle stability, classifying voltage stability into large-disturbance voltage stability and small-disturbance voltage stability is applicable.

1.5.1 Large-Disturbance Voltage Stability

Large-disturbance voltage stability refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. This ability is determined by the system and load characteristics, and the interactions of both continuous and discrete controls and protections.

The simulated post-disturbance voltage trajectories of the New England 10-machine 39-bus system are indicated in Figures 1.5 and 1.6 for a stable and unstable case, respectively. In the stable case, all voltage trajectories fluctuate and return

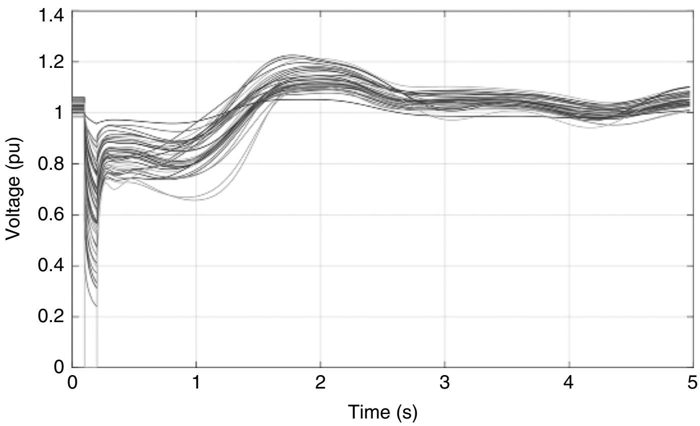

Figure 1.5 Simulated voltage trajectories of the large-disturbance voltage stable case.

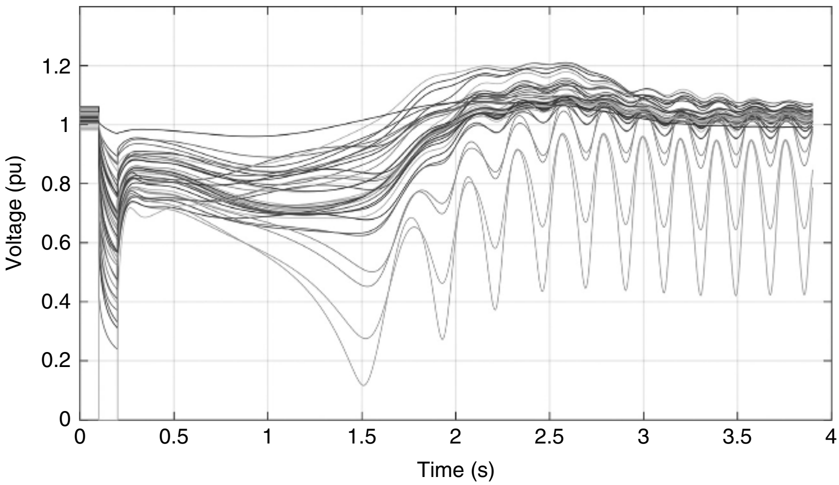

Figure 1.6 Simulated voltage trajectories of the large-disturbance voltage unstable case.

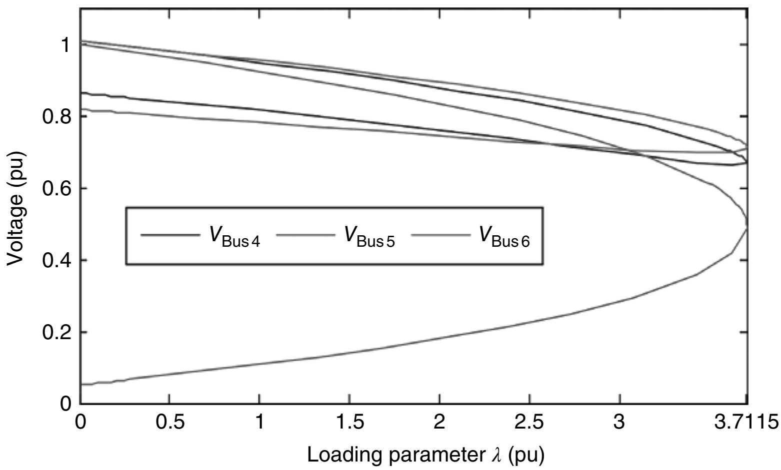

Figure 1.7 Simulated power–voltage (PV) curve. *Source:* Xu [3].

to the nominal level finally, while in the unstable case, the voltage trajectories fluctuated dramatically without recovery.

1.5.2 Small-Disturbance Voltage Stability

Small-disturbance voltage stability refers to the system's ability to maintain steady voltages when subjected to small perturbations, such as incremental changes in system load. Under this case, the system voltage will drop continuously with the load increment until a critical point is reached. After the critical point, the system voltage will drop dramatically and finally collapse.

A simulated power–voltage curve is presented in Figure 1.7, where the loading parameter means the load-increasing rate. When it increases to 3.7115 times the initial operating point, voltage instability will occur.

1.6 Frequency Stability

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to maintain/restore equilibrium between system generation and load, with minimum unintentional loss of load. The instability that may result occurs in the form of sustained frequency swings, leading to the tripping of generating units and/or loads.

Figures 1.8 and 1.9 indicate the simulated post-disturbance frequency trajectory for a stable and unstable case.

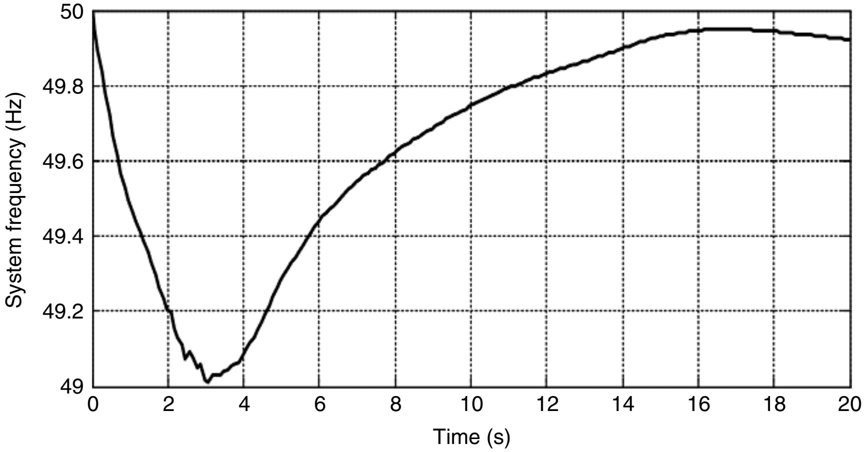

Figure 1.8 Simulated post-disturbance frequency trajectory of a frequency stable case. *Source:* Xu [3].

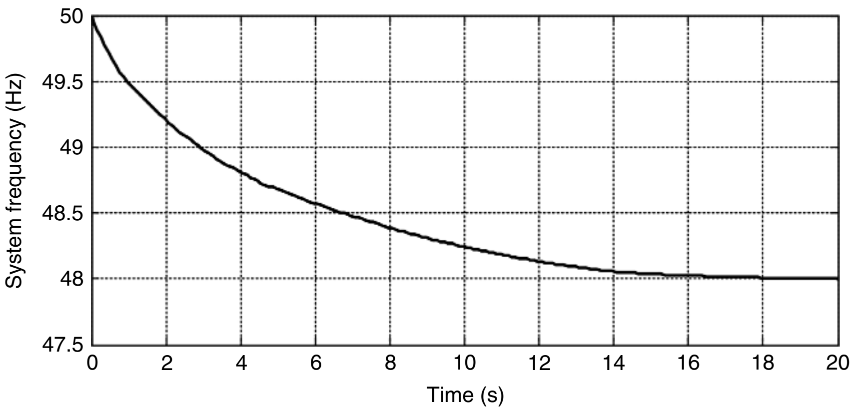

Figure 1.9 Simulated post-disturbance frequency trajectory of a frequency unstable case. *Source:* Xu [3].

1.7 Resonance Stability

Generally, resonance instability may occur when the oscillatory magnitude of voltage/current/torque exceeds specified thresholds due to insufficient dissipation of energy in the flow path. The term resonance stability encompasses subsynchronous resonance (SSR) and can be indicated in two forms: (i) due to a resonance between series compensation and the mechanical torsional frequencies of the turbine-generator shaft; (ii) due to a resonance between series compensation and the electrical characteristics of the generator. Thus, the resonance stability has been divided into two categories shown in Figure 1.1.

1.7.1 Torsional Resonance

Torsional resonance is the SSR due to torsional interactions between the series compensated line(s) and a turbine-generator mechanical shaft, particularly as it pertains to conventional synchronous generation.

Figure 1.10a indicates the torsional torque in low-pressure turbine B to generator 1 (LPB-G1) shaft section with 70% and 30% compensation levels. The dark blue shade shows the torsional torque with a 70% compensation level, and the gray shade shows the torque with a 30% compensation level. From the figure, the torque is growing slowly for the dark blue shade, which means that the 70% compensation level leads the system unstable. While for the gray shade, the torque is decaying. It represents the system becomes stable with the 30% compensation level. It can be found that the higher the compensation level, the weaker the damping.

1.7.2 Electrical Resonance

As the variable-speed DFIG generator is an induction generator connected to the grid, the electrical resonance between the generator and series compensation may exist, which would be highly susceptible to IGE-self-excitation type SSR. In this case, the self-excitation type SSR occurs when the series capacitor forms a resonant circuit, at subsynchronous frequencies, with the effective inductance of the induction generator.

The phenomena can be realized by the IGE simulation performed with the torsional system disabled. Figure 1.10b indicates the dynamic responses with various wind speeds and a constant 75% compensation level. From the figure, it can be found that the higher the wind speed, the better the SSR damping for the doubly-fed induction generator (DFIG) system.

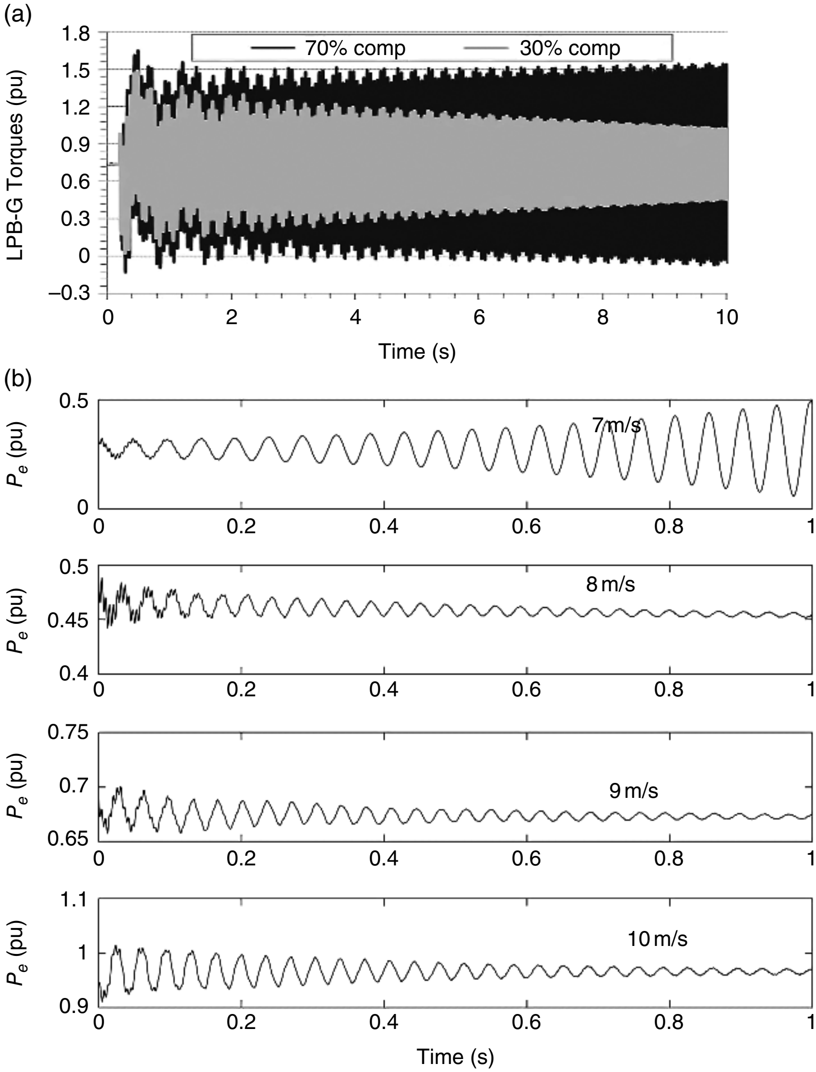

Figure 1.10 Phenomenon of resonance stability. (a) Torsional torque in LPB-G shaft section. *Source:* Adrees and Milanović [4]/(© [2014] IEEE. (b) Dynamic response of Pe under different wind speeds. Compensation level: 75%. *Source:* Fan et al. [5]/© [2010] IEEE.

1.8 Converter-Driven Stability

Since the timescale referring to the controls of CIGs is wide, the cross-coupling occurs with both the electromechanical dynamics of machines and the electromagnetic transients of the network, which may lead to unstable power system oscillations within a wide frequency range. Hence, slow-interaction converter-driven stability (less than 10 Hz) and fast-interaction converter-driven stability (tens to hundreds of Hz to kHz) are categorized.

1.8.1 Fast-Interaction Converter-Driven Stability

Fast-interaction converter-driven stability is driven by fast dynamic interactions of power electronic-based control systems, such as CIGs, HVDC, and FACTS, which are fast response elements. Instabilities produced by fast converter interactions may indicate various forms. For example, interactions of the fast inner-current loops of CIG with passive system components may cause high-frequency oscillations.

Figure 1.11a shows the harmonic instability phenomenon due to the interactions between the inner alternative current control (ACC) loops of the three paralleled VSCs. The bandwidth of the ACC loop is increased from $f_s/20$ to $f_s/15$ at the time instant of T_i. It is obvious to see that the three paralleled VSCs become unstable with the bandwidth of $f_s/15$.

1.8.2 Slow-Interaction Converter-Driven Stability

Slow-interaction converter-driven stability is driven by slow dynamic interactions of power electronic-based devices' control systems, such as the electromechanical dynamics of synchronous generators. Like voltage stability, a weak system can be the primary cause of instability. However, these two types of stability are fundamentally different since voltage instability is driven by loads, while converter-driven instability is involved by power electronic converters.

Figure 1.11b shows low-frequency oscillation and subsynchronous frequency oscillation phenomena for four phase-locked loop (PLL) parameters. For PLL1, there is a 4.5 Hz undamped oscillation, which is defined as low-frequency oscillation. For PLL2, 30 Hz oscillations are dominant. The low-frequency mode can also be found in the initial few cycles. For PLL3, both modes can be damped. For PLL4, the 40 Hz oscillation mode is dominant and the system becomes unstable.

This book mainly focuses on transient stability and large-disturbance voltage stability, as marked in the dashed square in Figure 1.1. Besides, transient stability in this book refers to first-swing stability. Multi-swing stability is not considered.

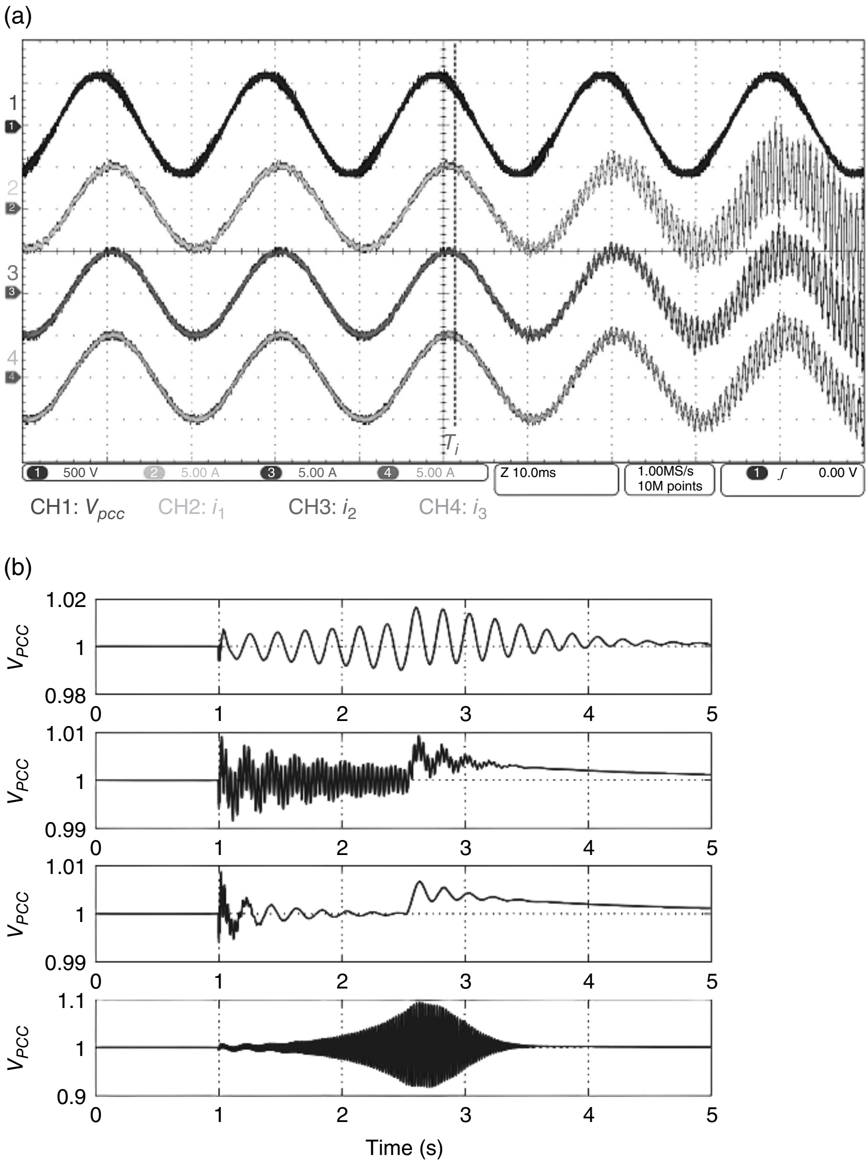

Figure 1.11 Phenomenon of converter-driven stability. (a) Measured waveforms for the harmonics instability. *Source:* Wang and F. Blaabjerg [6]/(© [2019] IEEE. (b) Response of V_{PCC} for four sets of PLL parameters, from upper to bottom: PLL1, PLL2, PLL3, and PLL4. *Source:* Fan and Miao [7]/© [2018] IEEE.

Thus, the transient stability in the subsequent chapters all refers to the first-swing stability.

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