PROPOSED TERMS & DEFINITIONS FOR POWER SYSTEM STABILITY

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System Dynamic Performance Subcommittee
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Abstract - This paper presents proposed terms and definitions in pursuit of Electric Utility Industry uniformity and common understanding in the analysis of Power System Stability. Although most of the proposed terms are not new, an attempt has been made to define them precisely. In so doing, the historical usage of the terminology has been taken into account. However, it has been necessary, in certain cases, to deviate from some past practices to be able to resolve differences between the usage of a term in the power systems literature and the usage of that term in related fields.

INTRODUCTION

Power System Stability has been an area of study from the early days of power generation and transmission. This has become an area of concern as power systems over large geographic areas have been interconnected. As the problem has grown, sophisticated control equipment and protection schemes have been added to the power system to enhance stability. As a result the analysis of the problem has become more difficult, but fortunately, better mathematical models and their use in computer simulation have also brought increased understanding.

As the interest in this subject has grown and the technical literature has increased, new terms have been introduced and old terms have been interpreted differently to keep up with the changes in the problem as well as the analytical tools. As a result, there has been some confusion about the precise meaning of certain terms. An attempt has been made in this paper to define the terminology on this subject.

These definitions have resulted from long deliberations of the Task Force set up by the System Dynamic Performance Subcommittee of the Power Systems Engineering Committee for this purpose. The Task Force concluded that there is no one set of definitions on which every worker in this field can agree. Hence, the set of definitions presented here was chosen because they were thought to be consistent within the set, with historical use of the terms; with the present understanding of the subject; with the state of the art in analytical tools; and with the terminology used in related fields, such as Stability of Non-Linear Systems. Compromises were made because of conflicting requirements, but the main purpose of providing a means of uniform usage for common understanding can be served by this set of definitions.

Two sources of definitions influenced this work. One was the IEEE Standard 100 which is the Dictionary of Electrical and Electronics Terms {1}. Many of the terms defined in this paper appear in this dictionary but it was felt that many of the dictionary definitions have not been updated recently to reflect totally the use of control theory and simulation techniques. The definitions given here frequently deviate from the Standard 100.

The other source is the series of CIGRE papers that defines terms in the area of power system stability. This work was published by CIGRE Committee 13 in 1958 {2} and updated in 1966 {3}. The latest update was in 1978 by CIGRE Committee 32 {4} and has directly affected this work. In fact, a conscious effort was made to follow these CIGRE definitions as closely as possible. The deviations were mainly in those terms whose definitions in this paper were made compatible with control theory terminology. Otherwise, the sequence of definitions and the accompanying discussion were inspired by the CIGRE paper.

In the rest of the paper the definitions are presented first with some notes that pertain directly to them. These definitions are arranged such that the terms used in each definition have been defined previously. They are followed by a discussion that presents the thinking behind and some of the implications of the definitions.

DEFINITIONS

1. Power System: A network of one or more electrical generating units, loads, and/or power transmission lines, including the associated equipment electrically or mechanically connected to the network.

2. Operating Quantities of a Power System: Physical quantities, which can be measured or calculated, that can be used to describe the operating conditions of a power system.

   Note: Operating quantities include rms values or corresponding phasors of alternating or oscillating quantities.

3. Steady-State Operating Condition of a Power System: An operating condition of a power system in which all of the operating quantities that characterize it can be considered to be constant for the purpose of analysis.

4. Synchronous Operation:

   4.1 Synchronous Operation of a Machine: A machine is in synchronous operation with a network or another machine to which it is connected if its average electrical speed (product of its rotor angular velocity and the number of pole pairs) is equal to the angular frequency of the ac network voltage or to the electrical speed of the other machine.

   4.2 Synchronous Operation of a Power System: A power system is in synchronous operation if all its connected synchronous machines are in synchronous operation with the ac network and with each other.

5. Asynchronous Operation:

   5.1 Asynchronous Operation of a Machine: A machine is in asynchronous operation with a network or another machine to which it is connected if it is not in synchronous operation.

81 WM 082-7 A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the IEEE PES Winter Meeting, Atlanta, Georgia, February 1-6, 1981. Manuscript submitted September 15, 1980; made available for printing November 18, 1980.

0018-9510/82/0700-1894$00.75 © 1982 IEEE

5.2 Asynchronous Operation of a Power System: A power system is in asynchronous operation if one or more of its connected synchronous machines are in asynchronous operation.

Note: The term 'nonsynchronous' is sometimes used as a synonym for 'asynchronous'.

6. Hunting of a Machine: A machine is hunting if any of its operating quantities experience sustained oscillations.

7. Disturbance in a Power System: A disturbance in a power system is a sudden change or a sequence of changes in one or more of the parameters of the system, or in one or more of the operating quantities.

7.1 Small Disturbance in a Power System: A small disturbance is a disturbance for which the equations that describe the dynamics of the power system may be linearized for the purpose of analysis.

7.2 Large Disturbance in a Power System: A large disturbance is a disturbance for which the equations that describe the dynamics of the power system cannot be linearized for the purpose of analysis.

8. Steady-State Stability of a Power System: A power system is steady-state stable for a particular steady-state operating condition if, following any small disturbance, it reaches a steady-state operating condition which is identical or close to the pre-disturbance operating condition. This is also known as Small Disturbance Stability of a Power System.

9. Transient Stability of a Power System: A power system is transiently stable for a particular steady-state operating condition and for a particular disturbance if, following that disturbance, it reaches an acceptable steady-state operating condition.

10. Power System Stability Limits

10.1 Steady-State Stability Limit: The steady-state stability limit is a steady-state operating condition for which the power system is steady-state stable but for which an arbitrarily small change in any of the operating quantities in an unfavorable direction causes the power system to lose stability. This is also known as the Small Disturbance Stability Limit.

10.2 Transient Stability Limit: The transient stability limit for a particular disturbance is the steady-state operating condition for which the power system is transiently stable but for which an arbitrarily small change in any of the operating quantities in an unfavorable direction causes the power system to lose stability for that disturbance.

11. Critical Clearing Time: If a particular disturbance includes the initiation and isolation of a fault on a power system, the critical clearing time is the maximum time between the initiation and the isolation such that the power system is transiently stable.

12. Monotonic Instability: A power system is monotonically unstable for a particular steady-state operating condition if following a disturbance its instability is caused by insufficient synchronizing torque.

Note: The trajectory for monotonic instability may not be strictly monotonic or have less than one oscillation. The main criterion is insufficient synchronizing torque and the nomenclature is derived historically from the fact that in most cases for such instability the trajectories are monotonic.

13. Oscillatory Instability: A power system is oscillatorily unstable for a particular steady-state operating condition if following a disturbance its instability is caused by insufficient damping torque.

DISCUSSION

This discussion is an elaboration of the thinking behind the definitions presented above. It also presents the reasoning behind the deviations in these definitions from the IEEE Standard 100 or the CIGRE definitions. The discussion of the terms is presented in the same order as the definitions above.

It should be pointed out that the expression "dynamic stability" is carefully excluded from this document. Much confusion has been created by the usage of this expression in English to describe several different phenomena, not to mention its application in translation to other languages. Further use of this expression is discouraged.

Power System

A power system is defined here for the purpose of engineering analysis and does not take into account political, geographical or other jurisdictional boundaries. Although the IEEE Standard {1} defines a power system as being under a common management, engineering studies routinely include equipment that may belong to several different companies; from an analytical viewpoint the total representation is one system and not several. It should be stressed here that a power system not only includes the generators and transmission lines but also the associated equipment such as the remainder of the power plants or all the control mechanisms. Whether all this equipment is represented in the model being studied depends on the effects of individual components and their importance to the phenomena being studied. For instance, in the study of transient stability, the controls on the turbine-generators may not have significant influence on the results and may not be modelled as a part of the power system. But whether they are modelled or not, they are an integral part of a power system.

Steady-State Operating Condition

A power system is continually experiencing fluctuations which may be of small or large magnitudes. However, the tools of analysis usually require that a state with no fluctuations be defined. The assumption is that, even though a power system is seldom in a steady-state, it can be considered to be approximately so for the purpose of analysis.

Synchronous Operation

The synchronous and asynchronous operation are defined here because of the traditional connection between these concepts and stability. The loss of synchronism (i.e., the transition of the power system from synchronous to asynchronous operation) is the usual symptom of loss of stability. However, this is only true for a purely ac system with only synchronous generators. With the increased use of asynchronous generators and dc transmission, not all the machines on a power system may be in synchronism with each other and the relationship of synchronism to stability is made more complex. The definitions of stability given here are suitable for both synchronous and asynchronous operation.

The synchronous operation of a machine is defined by using its average electrical speed because the instantaneous electrical speed may experience some deviations from synchronous speed without losing synchronism. During or after a disturbance such deviations occur as the machine rotors "swing" from their steady state positions but their average electrical speeds over several seconds should be the same as synchronous speed if synchronism is not lost.

The terms asynchronous and nonsynchronous, which are used synonymously here, are defined differently from the CIGRE version. However, the definitions here reflect the traditional usage of the terms. The definition of the synchronous operation of a machine reflects the same meaning as the IEEE Standard but differs in that the machine here is considered to be a part of a network; this definition is more system oriented. A power system is considered to be in asynchronous operation even if only one machine within it is not in synchronism with all the other machines. However, this may be the desired mode of operation if that machine is designed for asynchronous operation or is connected to the rest of the system with only dc transmission.

Hunting

Hunting is a special operating condition in which certain quantities oscillate with finite and constant magnitude. According to the definitions, this must be considered a steady-state operating condition since the rms values of the oscillating quantities are constant. This phenomenon coincides with the standard control theory concept of a limit cycle being a steady-state condition. Whether this operating condition is stable or unstable depends on whether it meets the various definitions for stability and instability. It should also be noted that hunting can either be forced or spontaneous.

Disturbance

The concept of disturbance is intimately connected to the concept of stability as the initiator of the change of the operating quantities. In control theory, the concept of disturbance is conveniently replaced by the concept of initial state or starting state relative to the post-disturbance steady-state condition. In fact, stability concepts are usually defined in relation to the initial state and the post-disturbance steady-state condition or equilibrium that may or may not be reached. However, in the case of a power system, both the initial state and the post-disturbance steady-state operating quantities are dependent on the pre-disturbance, steady-state operating condition and the disturbance itself, and are not readily available without lengthy calculation. Although such calculation is necessary for analysis, it is more convenient to define the stability concepts of a power system in terms of the known pre-disturbance steady-state operating condition and the disturbance.

It should be noted that a disturbance can be made up of a sequence of sudden changes. For example, the initiation of a fault, the breaker openings to isolate the fault, reclosure on the fault, and breaker openings and lock-out can be considered to be one disturbance. Since such a logical sequence of changes is common in a power system and are often studied together, it was considered more convenient to define stability terms according to such a sequence of changes rather than to each change.

A differentiation is made between small and large disturbances according to whether a linear approximation of the system model is valid for analysis. Obviously, linearization makes it possible to use many more analytical tools than those available for non-linear analysis. However, any linearization requires certain assumptions that limit the range of validity of the analysis. It should also be noted that small disturbances can be analyzed with the same tools as the large disturbances to obtain the same results; consequently none of the definitions were restricted to only large disturbances.

Classes of Stability

In the definitions, stabilities of two different types are identified according to the size of the disturbance. The stability of any non-linear system may or may not depend on the size and type of the disturbance. If it does not, then it is considered "stable in the large". Power systems are not stable in the large and are dependent on the extent of the disturbance. Thus, a steady-state operating condition may be stable for a small disturbance but not for a large one. Hence, two separate questions are of interest:

(i) Is the steady-state operating condition stable for an infinitesimally small disturbance, or, in control theoretic terms, is the equilibrium stable? This concept is the one of steady-state or small disturbance stability. Since the size of the disturbance for this is pre-defined, steady-state stability is the property only of the power system and its steady-state operating condition. Also, since a method to determine the steady-state stability is to linearize the power system equations about the steady-state operating quantities and to use any of the several criteria for stability of linear systems (e.g. no eigenvalues on the positive half of the complex plane), the concept of a small disturbance is linked to the assumption of linearity. However, a solution of the non-linear equations using a small but finite disturbance should provide the same results. Since the disturbance is small, the post-disturbance steady-state operating condition can be expected to be the same or very close to the pre-disturbance steady-state operating condition. The term "small disturbance stability" may be used as an alternate for "steady-state stability" as it is closer to the definition and coincides with similar terminology in control theory. Also, an alternative definition that is more mathematical can be formulated:

   Steady-state stability or small disturbance stability implies that the power system described by the set of differential equations linearized about the steady-state operating condition is stable.

(ii) Is the steady-state operating condition stable for a particular disturbance, or in control theoretic terms, does a particular disturbance cause the trajectories of the operating quantities to stay within the "domain of attraction" of the post-disturbance equilibrium? This concept is the one of transient stability. Obviously, transient stability is the property of the power system, its steady-state operating condition <u>and</u> the disturbance itself. Since the disturbance may <u>be</u> large, protective relaying may change the power system configuration and the post-disturbance steady-state operating condition, if reached, may be quite different from the pre-disturbance steady-state operating condition. In some extreme cases, the post-disturbance steady-state may be reached after losses of many lines, generators and loads, and it may not be an acceptable mode of operation. Thus, a power system can be considered to be transiently stable only if it reaches an acceptable steady-state. The loss of synchronism or the slipping of a pole by a particular machine may or may not be acceptable depending on the circumstances and operating criteria. Again, an alternative definition that is more mathematical can be formulated:

   Transient stability implies that an acceptable post-disturbance steady-state operating condition of the power system is asymptotically stable and the response to the given disturbance is such that the trajectories of the operating quantities tend to this operating condition as time increases.

Two other classifications of power system stability should be mentioned. One such classification is according to whether control action is necessary for stability:

(i) Natural or Inherent Stability: A power system is naturally or inherently stable for a particular steady-state operating condition and a particular disturbance if no automatic control action is required to maintain stability.

(ii) Conditional Stability: A power system is conditionally stable for a particular steady-state operating condition and a particular disturbance if some particular control action(s) is(are) required to maintain stability.

The last two decades have seen a steady introduction of new automatic control schemes to enhance the stability of power systems. It was found that a particular manifestation of instability may be made stable by the use of some control scheme. Thus, the concept of stability that is conditional on particular controls became important. However, the reverse concept of natural or inherent stability seems to have become redundant at this time with many automatic controls being considered inherent parts of the system. Since many cases of stability are conditioned on some control action, this classification is not included in the definitions but is mentioned here as its usage continues to some extent.

The other classification of stability is according to the time period that is under study:

(i) Short Term Stability: A power system is stable in the short term if it is found to be stable when the study of its behavior is limited to several seconds.

(ii) Long Term Stability: A power system is stable in the long term if it is found to be stable when the study of its behavior is extended beyond several seconds.

The usage of this classification is so new that the concept is not well defined and the above descriptions should not be considered to be strict definitions. The main difference between the terms is that for short term stability the electromechanical transients associated with interconnected machines, including the effects of excitation control and speed governing systems, are considered in the analysis but for long term stability the slower control actions such as load frequency controls, boiler controls, load shedding and many others also have to be considered. The exact time period that differentiates between short term and long term is not very definite and the phrase 'mid-term' has also been used in connection with certain computational tools. For this reason, better classification may be possible according to the representation of the power system (e.g. whether slow controls are modelled or not) than the time period.

Classes of Instability

In the case of unstable power systems, another classification is according to the nature of the cause of instability. Instability can be caused by insufficient synchronizing torque as well as by insufficient damping torque, and the corresponding concepts of monotonic and oscillatory instability are used. Mathematically, these correspond to cases where the linearized equations have at least one positive real root, or one pair of complex roots with positive real parts, respectively. In practice, of course, instability may be caused by the lack of a combination of synchronizing and damping torque. This classification can be easily determined for a small disturbance by analyzing the roots of the linearized system, but for a large disturbance, because of the nonlinearities, the difference between synchronizing and damping torque can only be estimated from the nature of the trajectories. Synchronizing torque, which is in phase with the rotor angular deviation, and damping torque, which is in phase with the rotor speed deviation, are components of the net torque acting on a generator but conceptually separating them as causes of instability provides valuable indication about the most effective ways to stabilize the system.

Instability can also be caused by insufficient reactive support, resulting in a voltage collapse even when sufficient synchronizing and damping torques are available. The term "voltage instability" has been used to describe this and it has become important because of cases where all, or nearly all, of the generation is remote from the load. The extreme example is a single generator at maximum excitation supplying a purely resistive load. As load is increased, a limit is reached when the resistance equals the reactance in the system such that the power delivered does not increase any further but voltage collapses. This steady state limit occurs at the limiting rotor angle of 45° and the concept of a 90° limit does not appear as there is no voltage support. Many practical cases of instability are blends of both "angle" and "voltage" instability. However, these terms are not yet widely used and are only mentioned in this section because recent voltage problems on many systems may make them important in the near future.

CONCLUSIONS

A set of definitions is presented to foster a common understanding of the terms used in the area of power system stability. The definitions reflect the state of the art and consistency of usage without deviating from the traditional understanding of the terms in any significant way. The relationships between power systems phenomena and control theoretic or mathematical study tools are taken into consideration. A discussion explains the rationale behind the definitions.

ACKNOWLEDGEMENTS

The Task Force on Terms & Definitions has the following members:

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In addition, P.M. Anderson, D.D. Robb and J.W. Lamont actively participated in the Task Force deliberations.

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Discussions

J. D. Hurley and **F. W. Keay** (Westinghouse Electric Corp., East Pittsburgh, PA): In deprecating the expression "dynamic stability", the working group has endeavored to eliminate one source of confusion in discussions pertaining to Power System Stability. Another source of confusion exists among terms which have been used in the literature to describe different modes of oscillatory instability.

Reference 1 identifies two separate but related modes of oscillatory instability. The expression "inter-area oscillations" is used to describe oscillations (characterized by a frequency $\leqslant$ 0.3 Hz) between interconnected power systems. The expression "local-mode oscillations" is used to describe oscillations (characterized by a frequency 1 to 2 Hz) between a machine or group of machines and the remainder of the power system.[1] Some investigators have used the expressions "inter-tie" or "tie-line oscillations" to describe oscillations in the frequency range of 1-2 Hz and have used the expression local-mode oscillations to describe oscillations between generators within a power plant.[2]

In the interest of uniformity and common understanding, it would be desirable to have a consistent set of terms for classifying modes of oscillatory instability. Did the working group consider proposing any such classification?

In defining the term "transient stability", the working group has lumped together the characteristics of the "first swing" response with the damping characteristics of the response under the post-disturbance operating conditions. This broad use of the term is good in that it stresses the importance of considering more than the first swing in assessing stability following a disturbance. However, some confusion may occur in differentiating between transient stability which is strongly affected by the severity and duration of the disturbance itself and that which is affected only by the post-disturbance system conditions. Does the working group suggest any means of distinguishing between these two types of phenomena?

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Manuscript received February 23, 1981.

R. P. Schulz (General Electric Company, Schenectady, NY): In the work of the Task Force, it was recognized that the classifications of stability are in advance of the growth of a common, accepted usage, to lead the development of common usage. Among these secondary definitions, the term "Long Term Stability" is discussed. The Task Force has adopted this term from the prior CIGRE papers. I feel that this term "Long Term Stability" should be deprecated and should be replaced by the term "long term dynamics", with the corresponding use of "short term dynamics" to encompass the forms of stability in definitions 8 through 13. The use of the word stability implies that there is a corresponding mode of instability to which the user has reference (perhaps by implication). The experience of work we have done [References A, B, C] and those of other investigators indicates that there is no single common instability mode associated with the longer term operation of power systems (where longer term implies consideration of events after the "stability" time frame, i.e., after approximately 5, 10, or even 20 seconds after an upset). Generally, the longer term failure modes may be characterized by an inadequacy of either response, or of resources, or of both. These are questions of survival; Zaborszky has titled these questions "viability crises" [D]. There is yet a limited body of literature in the longer term studies of power system operation following major disturbances. The discussor suggests that the most common term for the study is "Long Term Dynamics" rather than "Long Term Stability", recommends that the proposed terms and definitions reflect these considerations and recommends that the term long term dynamics be continued to be used in this context.

This comment is not a minority report but is one of several directions in which the Task Force should go; since the paper has been prepared several additional topics have been suggested which the Task Force intends to pursue.

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Manuscript received March 2, 1981.

Anjan Bose, Chairman, Task Force on Terms and Definitions: We thank the discussors for their comments which generally point at some of the limitations of the set of definitions presented in this paper. We share some of Mr. Schulz's concern about the term "Long Term Stability" and it is because of similar uncertainties in the present understanding of this area that the term was only discussed but not proposed as a definition. The proposed set of defined terms only included those that are in common usage and that described phenomena that are well understood. Whether the task force should propose definitions to facilitate the growth of common usage of terminology in relatively new areas of study is now under consideration.

Messrs. Hurley and Keay point out a similar limitation in the definition of "Oscillatory Instability" which does not differentiate between the different modes of oscillations. The study of the different oscillation modes, apart from being relatively new, is also of a special area of power system dynamics. Many special areas (e.g. subsynchronous resonance) have developed the common usage of terminology and this set of definitions did not attempt to address all of these areas. However, this discussion points to the interrelationship of terminology used in the study of the different aspects of power system phenomena and the need to coordinate between them.

The problem of differentiating between transient stability that is strongly affected by the severity and duration of the disturbance and that which is affected only by the post-disturbance system conditions was considered by the Task Force. Since the post-disturbance operating condition is a result of the severity and duration of the disturbance (for a particular pre-disturbance operating condition), it was felt that the two should not be considered separate factors influencing transient stability.

Manuscript received May 4, 1981.