Comparative Study of Different Methods of Dynamic Stability Assessment

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Abstract— This review paper present the comparative study between the various methods of dynamic stability assessment and also investigate the various technique used to study dynamic response of power system. In this paper complete mathematical analysis of small signal stability using eigen value and eigen vector method is discussed. At last linearization of power system is discuss through mathematical equations and graphically shows the predictable solution of equation hence according to eigen values various state of power system dynamics also discussed.

Key words: Dynamic Stability Assessment, Dynamic Response, Eigen Values, Linearization, Stability State

I. INTRODUCTION

The highly interconnected character of power systems makes their operation and control a complex process. Thus turbulence in some elements may influence the whole system operation and stability causing poor power quality or even disruption of power supply. Since the development of interconnection of large electric power systems, there have been spontaneous system oscillations at very low frequencies in order of 0.2 to 100 Hz. Dynamic phenomena in power systems are usually classified as

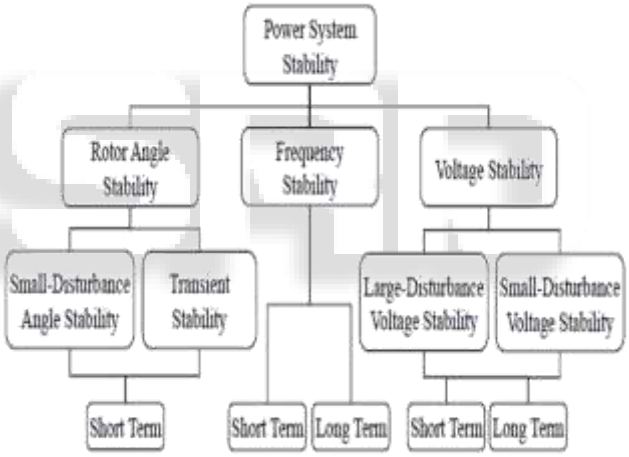
1) Electro-magnetic transients (100 Hz –1 MHz)
2) Electro-mechanical swings (rotor swings in synchronous machines) (0.1 –3 Hz)
3) Non-electric dynamics, e.g. mechanical phenomena and thermodynamics (up to tens of Hz)

Once started, they would persist for a long period of time. In some cases, they continue to grow, causing system separation if no sufficient damping is available. To enhance system damping, the generators are equipped with power system stabilizers (PSSs) that provide supplementary feedback stabilizing signals in the excitation systems. PSSs augment the power system stability limit and extend the power-transfer capability by enhancing the system damping of low-frequency oscillations.

A. Power System Stability

Power system stability defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. Stability phenomenon is a single problem associated with various forms of instabilities affected on power system due to the high dimensionality and complexity of power system constructions and behaviours. For properly understood of stability, the classification is essential for significant power system stability analysis. Stability classified based on the nature of resulting system instability (voltage instability, frequency instability…), the size of the disturbance (small disturbance, large disturbance) and timeframe of stability (short term, long term). In the other hand, stability broadly classified as steady state stability and dynamic stability. Steady state stability is the ability of the system to transit from one operating point to another under the condition of small load changes. Whereas Dynamic stability is the stability which deals with continuous small disturbances occurring in the system broadly it is small signal stability. A System is said to be dynamically stable, if the oscillations do not acquire certain amplitude and die out quickly. Dynamic stability is concerned with small disturbances lasting for a long time. Low frequency oscillations are observed when large power systems are interconnected by relatively weak tie lines. These oscillations may sustain and grow to cause system separation if no adequate damping is available.

According to IEEE/CIGRE Power system stability is broadly classified as



The following literature review describes the important result regarding the dynamics of power systems;

A paper[4] published in IEEE, revealed that Bifurcation theories are widely applied in the analysis of both static and dynamic characteristics of power systems for they can be of tremendous value for our understanding of the instability issues of a power system. In his paper, the dynamic characteristics of a power system with HVDC transmission system has been studied with nonlinear bifurcation theory, in addition, eigenvalues analysis and time-domain simulation are also used to study this problem. First, the dynamic. Second, bifurcation theory is applied to the analysis of an AC/DC interacting power system. With the single-parameter and multi-parameter bifurcation analysis, it's been showed that increasing the magnitude of power ratio in a DC transportation system can greatly improve the system stability.

In 2005 a paper[5] is published, in which authors conclude that due to the instantaneous dynamic nature of algebraic constraints, it is difficult to analyze and simulate

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the nonlinear DAE by direct integration. So they explore the requirements and explored the complexities to introduce the fast dynamics. Based on singular perturbation and Taylor's Expansion, they proposed a new approach to model power system dynamics by a singularly perturbed ODE. Also, a simple criterion has been proposed in his paper to measure the accuracy of remodeled system'

In a paper[6], author investigates the dynamic stability using the small signal analysis method. The stability type is distinguished by the modal participation factors of the state variables. Firstly, the equilibrium manifold is traced by a locally parameterized continuation method. Then, the dynamic stability of each equilibrium point is analyzed using th e small disturbance analysis method considering the components dynamics

In a paper[7] published in IEEE in 2010, it is concluded that under parametric variations, the phase portraits of a dynamical system such as a power system undergoes qualitative changes at bifurcation points. Several global co dimension-two bifurcation points such as Zero-Hopf, generalized Hopf, Bogdanov–Takens, among others, can move the system much close to its instability limit, and lead to confusion

In a paper[8], researcher apply pseudo-transient continuation which is a theoretical-based numerical method in power system long-term stability analysis. Pseudo-transient continuation method can be implemented directly in the long-term stability model to accelerate simulation speed compared with conventional implicit integration method. On the other hand, the method can also be applied in the QSS model to overcome possible numerical difficulties due to good stability property.

II. DYNAMIC STABILITY ASSESTMENT

Small-signal stability, is the ability of the power system to maintain synchronism when subjected to small disturbances. A disturbance is measured to be small if the equations that depict the resulting response of the system may be linearized for the purpose of analysis. The small-signal stability problem is typically one of inadequate damping of system oscillations. Dynamic stability can be defined as the ability of the power system to maintain synchronism when subjected to a small-disturbance. Instability may result due to rotor oscillations with increasing amplitude in cases of lack of adequate damping torque . Various methods have been used to study problematic system oscillation to analysis and reduce the effect of oscillation on power system operation. The main techniques that can be used to assess the power system stability are:

- Time-domain-simulation can be used to observe the simple cases of oscillations but it is time consuming and often difficult to understand the results.
- Identification techniques are normally used to analyze the oscillatory modes in power system based on the recorded electrical signals, which can be obtained from system measurements or transient stability simulation In these methods the parameters of the exponentially modulated sinusoidal signals of the measurements can be obtained and used to identify oscillatory stability
- Modal analysis is a technique has been used to analysis of the oscillatory modes based on the mode parameters. These parameters can be obtained after the system differential equations have been linearized around the current operating point.

In modern practical power systems, dynamic stability is mainly a problem of inadequate damping of oscillations. The time frame of interest in dynamic stability studies is on the order of 10 to 30 s following a disturbance. Because of the high dimensionality and complication of stability problems, it is essential to make simplifying assumptions and to analyze specific types of problems using the right degree of detail of system representation.

A. Eigen Value and Eigen Vector Method

The most direct way to assess dynamic stability is through eigen value analysis of a model of the power system. Once the non-linear model of the system has been linearised, many techniques are available for the calculation of the system eigen values. For stability, all of the eigen values must lie in the left half complex plane. Any eigen value in the right half plane denotes an unstable dynamic mode and system instability. The way in which system operating conditions, system parameters and controllers influence dynamic stability can be demonstrated by observing their influence on the loci of critical eigen values, i.e. the +eigen values furthest to the right in the complex plane. The eigen values of the state matrix specify the natural modes of system response, which provide valuable information regarding the stability characteristics of the power system. The n eigen values of the state matrix can be computed by solving the characteristic equation of system The real part σ represents the damping of the corresponding mode. The system is asymptotically stable with damped oscillation when the real part of the eigen value is negative (a damped oscillation) and a positive real eigen value represents a periodic instability where the oscillation has an increased amplitude. If the state matrix is real, complex eigen values always occur in conjugate pairs. Each pair corresponds to an oscillatory mode.

B. Ringdown and Prony Analysis

The time response signals which can be obtained by measuring or simulation may be analyzed by means of signal processing techniques to obtain useful information that can be used to capture the dynamic response of a power system. A proper identification technique and probing signal are required to analyze the dynamic response accurately. In the ring down analysis, the system may be excited by a large perturbations, such as sever short circuit or tripping of large component, resulting a transient response that can be observed and distinguished from ambient noises. These signals can be analyzed by any efficient identification technique such as Prony analysis or Matrix Pencil methods to extract the oscillation modes contents. Prony analysis has been widely applied to estimate small-signal dynamic properties, develop equivalent linear models, and tune power system controllers such as power system stabilizers from measured or simulated data. Prony analysis is used to extract the valuable information from a uniformly sampled signal and to build a series of damped complex exponentials or sinusoids. A proposed time varying function should be

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fitted the sampled waveform that represents the dynamic system behavior in order to extract the model contents. The problem is to minimize the error between the actual time varying data and the proposed function

C. Singular Perturbation

The dynamic stability analysis of power system can be formulated as a parameter dependent Differential Algebraic Equation (DAE) with two types of state variables: the instantaneous state variable *y* and the dynamic state variables *x*. Variable *x* describe the state of generation dynamics in the power systems, such as those in the exciter control systems. The instantaneous variables *y* satisfies algebraic constraints, such as power flow equations. *Y* can be interpreted as instantaneously converging transients that converges to the algebraic constrained manifold. Due to the instantaneous dynamic nature of algebraic constraints, it is difficult to analyze and simulate the nonlinear DAE by direct integration. Singular perturbation is a suitable technique to model interacting dynamics with large speed differences. Accordingly, we apply singular perturbation to remodel a DAE system by a singularly perturbed ordinary differential equation (ODE) form. Based on the singular perturbation, one way to handle the algebraic constraints is to slow down the instantaneous modes by introducing fast dynamics to replace the algebraic equations. Thus the DAE of power system dynamics is converted to a singularly perturbed ODE. Numerical integration techniques can be directly applied to obtain ODE solutions to approximate the DAE solutions.

D. Zero-Hopf Bifurcation Theory

Bifuration theory is often used in power systems analysis due to their non-linear nature. This theory assumes a slow parameter variation and helps to predict how and when the system becomes instable [4]. On the other hand, it is extremely important to know the operation safe limits of a power system, aimed to establish prevention measurements by the determination of the stability margins. This is not always enough, considering the complex behavior of such systems, because in case of the same external perturbation the system could maintain the stability conditions or also could degenerate in an instability situation. Considering the previously exposed, the stability study in power systems could not be oriented only to the interpretation of a single dimensional bifurcation analysis, because it is necessary to characterize the boundaries of the stable points by using a co-dimension of two bifurcation analysis. This helps to determine the possible dynamics which could make the system unstable, as a consequence of parameters interaction.

E. Pseudo Transient

Time-domain simulation is an important approach for power system dynamic analysis. However, the com- plete system model, or interchangeably the long-term stability model, typically includes different components where each component requires several differential and algebraic equations (DAE) to represent, at the same time, these dynamics involve different time scales from millisecond to minute. As a result, the total number of DAE of a real power system can be formidably large and complex such that time domain simulation over long time intervals is expensive. These constraints are even more stringent in the context of on-line stability assessment. Intense efforts have been made to accelerate the simulation of long-term stability model. One approach is to use a larger time step size to filter out the fast dynamics or use automatic adjustment of step size according to system behavior in time- domain simulation from the aspect of numerical method. Another approach is to implement the Quasi Steady- State (QSS) model in long-term stability analysis from the aspect of model approximation. Nevertheless, the QSS model suffers from numerical difficulties when the model gets close to singularities. Moreover, the QSS model can not provide correct approximations of the long-term stability model.

III. LINEARIZATION OF POWER SYSTEM

The analysis of dynamic stability can be performed by deriving a linearized state space model of the system in the following form

$$p\,X = A\,X + B\,u \qquad (1)$$

Where the matrices A and B depend on the system parameters and the operating conditions.

- The Eigen values of the system matrix A determine the stability of the operating point.
- The Eigen value analysis can be used not only for the determination of the stability regions, but also for the design of the controllers in the system.

In this method it is not necessary to reduce the power system network to eliminate non-generator buses. The same network used for load flow studies can also be used for the dynamic stability calculations. The development of system model proceeds systematically by the development of the individual models of various components and subsystems and their interconnection through the network model.

At any bus k of an N-bus network the following equations apply

$$\Delta P_k = \sum_{j=I_k}\left(\frac{\partial P_k}{\partial \theta_j}\Delta\theta_j + \frac{\partial P_k}{\partial V_j}\Delta V_j\right) \qquad (2)$$

$$\Delta Q_k = \sum_{j=I_k}\left(\frac{\partial Q_k}{\partial \theta_j}\Delta\theta_j + \frac{\partial Q_k}{\partial V_j}\Delta V_j\right) \qquad (3)$$

Where I_k is the set of buses that are connected to bus k.Also it would be shown that for each bus,(ΔP,ΔQ)or(ΔV $\Delta\theta$) can be eliminated depending on the type of bus. The A matrix formulation is based on identifying the interconnections among the various subsystems of the power system. Development of the system model is based on the formulation of the individual component models and identifying the various interconnections between the subsystems. The linearized network algebraic equations are solved in terms of the system state variables resulting in the final system model.

A. Generator Unit Equations

The rotor circuit differential equations, including its motion, are given by

$$p\,X_m = [A_m]\,X_m + b_{me}\,\Delta v_{fd} + b_{mg}\,\Delta P_m + [B_p]\,\Delta S_g \quad (4)$$

$$Y_m = [C_m]\,X_m \quad (5)$$

where,

$Xm = [\Delta I_d\ \Delta I_q\ \Delta\varphi_f\ \Delta\varphi_k\ \Delta\omega\ \Delta\delta]^t$

$Y_m = [\Delta I_d\ \Delta I_q\ \Delta\omega\ \Delta\delta]^t$

$\Delta S_g = [\Delta P_g\ \Delta Q_g]^t$

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Also, the generator terminal bus voltage magnitude and phase angle are expressed in the form

$$\Delta Z_g = [D_m]\, Y_m + [D_p]\, \Delta S_g \qquad (6)$$

Where,

$\Delta Z_g = [\Delta\theta_g \; \Delta V_g]^t$

And ΔI_d and ΔI_q are state variables derived from the rotor flux linkages.

B. Excitation System Equations

The excitation and governor control systems used in modern generators fall into standard categories compiled in IEEE Committee reports. While it was initially thought that high gain voltage regulator loop with a fast acting static exciter would improve transient stability, the practical experience was that it led to dynamic instability. Power system stabilizer (PSS) which introduces supplementary stabilizing signal to suppress rotor oscillations has become a desirable part of any excitation system. The change in the magnitude of the terminal voltage, ΔVg, is one of the inputs for the excitation system and this has to be expressed in termsof the state variables and is given in the equation.

The state space model of excitation system is represented in the form

$$p\,X_e = [A_e]\, X_e + [B_{em}]\, Y_m + [B_{ep}]\, \Delta Sg + b_e\, u_e \qquad (7)$$

$$y_e = [C_e]\, X_e \qquad (8)$$

$$y_e = \Delta V_{fd} \qquad (9)$$

$$u_e = \Delta V_{ref} \qquad (10)$$

where X_e, u_e and y_e are respectively the state, input and output quantities; and the structures of the associated matrices are obtain for the Type 1 excitation system

C. Turbine-Governer Equations

The state space model of governor control system can be represented in the form

$$p\,X_g = [A_g]\, X_g + [B_m]\, Y_m + b_g\, u_g \qquad (11)$$

$$y_g = [C_g]\, X_g \qquad (12)$$

$$y_g = \Delta P_m\,;\; u_g = \Delta P_{mo} \qquad (13)$$

where X_g,u_g & y_g are respectively the state, input and output quantities; and the structures of the associated matrices are obtained for an IEEE system model.

IV. State Space Model of Power System

The following state space model is obtained,where all the component element are matrices

$$\begin{bmatrix} pX_m \\ pX_e \\ pX_g \end{bmatrix} = \begin{bmatrix} A_m & B_{me} & B_{mg} \\ B'_{em} & A_e & 0 \\ B'_{gm} & 0 & A_g \end{bmatrix} \begin{bmatrix} X_m \\ X_e \\ X_g \end{bmatrix} + \begin{bmatrix} B_p \\ B_{ep} \\ 0 \end{bmatrix} \Delta S_g + \begin{bmatrix} 0 & 0 \\ b_e & 0 \\ 0 & b_g \end{bmatrix} \begin{bmatrix} u_e \\ u_g \end{bmatrix} \qquad (14)$$

$$\begin{bmatrix} Y_m \\ y_e \\ y_g \end{bmatrix} = \begin{bmatrix} C_m & 0 & 0 \\ 0 & C_e & 0 \\ 0 & 0 & C_g \end{bmatrix} \begin{bmatrix} X_m \\ X_e \\ X_g \end{bmatrix} \qquad (15)$$

$$[B_{me}] = b_{me}\, T^t_{el} \qquad (16)$$

$$[B_{mg}] = b_{mg}\, T^t_{gl} \qquad (17)$$

$$[B'_{em}] = [B_{em}]\, [C_m] \qquad (18)$$

$$[B'_{gm}] = [B_{gm}]\, [C_m] \qquad (19)$$

and T_{el} and T_{gl} are vectors containing only one non zero element each equal to one and defined by the following equations

$$\Delta V_{fd} = T^t_{el}\, X_e \qquad (20)$$

$$\Delta Pm = Ttgl\, Xg \qquad (21)$$

A. Load Representation

The usual constant power, constant current and constant impedance type loads and any other voltage dependent nonlinear loads can be represented in the general form

$$P_L = k_p V_L^{np} \qquad (22)$$

$$Q_L = k_q V_L^{nq} \qquad (23)$$

where consent coefficients k_p, k_q and the exponents np and nq depend upon the type of load under consideration. Linearizing

where,

$$\Delta S_t = [A_l]\, \Delta Z_l$$

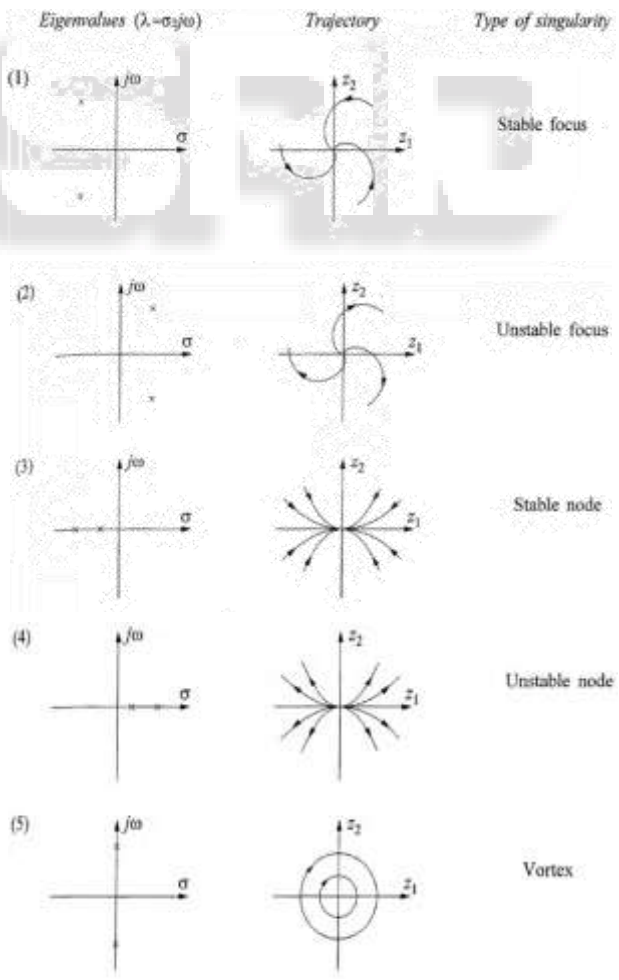
$$\Delta S_t = [\Delta P_L \; \Delta Q_L]^t$$

$$\Delta Z_t = [\Delta_L \; \Delta V_L]^t$$

$$[A_l] = \begin{bmatrix} 0 & n_p k_p V_L^{np-1} \\ 0 & n_q k_q V_L^{nq-1} \end{bmatrix}$$

The nonlinear loads dependent on the bus frequency, if present in the system, can also be handled without any difficulty, if desired. The various subsystems described earlier can be assembled together for the analysis of large-scale power systems including large number of machines and loads.

B. Different Stability Modes According To Eigen Value



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V. CONCLUSION

Since dynamic stability generally deals with continuous small disturbances occurring in the system like variation in loading ,change in turbine speed in this small disturbance generally generator does not loose synchronism. If system non linearity is not so large the eigen value and eigen vector analysis give better result and it is quite simple method. Eigen value analysis is the most direct way to assess dynamic stability of a model of the power system. Once the non-linear model of the system has been linearized, many techniques are available for the calculation of the system eigen values. For stability, all of the eigen values must lie in the left half complex plane. Any eigenvalue in the right half plane denotes an unstable dynamic mode and system instability. Small-signal analysis based on linear techniques is ideally suited for investigating problems associated with oscillations. Here, the characteristics of a power system model can be determined for a system model linearized about a specific operating point. The stability of each mode is clearly identified by the system's eigenvalues. Such methods are ideally suited for detailed analysis for system oscillation problems confined to a small portion of the power system. In summary, a complete understanding of power systems oscillations generally requires a combination of analytical tools. Small-signal stability analysis complemented by nonlinear time-domain simulations is the most effective procedure of studying power system oscillations.

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