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Rotor angle small signal stability assessment in transmission network expansion planning

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ABSTRACT

Transmission network expansion planning involves various types of static and dynamic analyses. The complexity and increasingly difficult operating conditions of power systems raise the importance of dynamic analyses on the expansion planning stage. Primary studies in the field of dynamic analyses include rotor angle stability, voltage ride-through and frequency stability analyses. This paper presents four methods of rotor angle small signal stability assessment, which can be used in transmission network expansion planning. For each of these methods, the requirements for the calculation model and computational accuracy are discussed, among other aspects. Practical considerations related to the use of particular methods in planning analyses are presented. Theoretical considerations are illustrated with the results of stability assessment of a multi-machine test system.

1. Introduction

Transmission network expansion planning is one of the core activities of energy companies. This task involves finding ways to expand the existing transmission network in order to satisfy the needs of the energy market, taking into account specific economic, environmental and technical constrains [1,2]. Such technical constrains, called the "planning criteria", are imposed by transmission system operators or government agencies responsible for power system security [3].

Power system analyses are performed for specific scenarios of transmission network expansion. These analyses aim to verify the reliability of the power system and its ability to withstand various disturbances. In general, power system analyses that verify whether or not technical criteria of planning are met can be divided into static and dynamic analyses [2]. Transmission network operators largely agree about the scope of static analyses to be performed for expansion planning. Such analyses have to be conducted for the states before and after a contingency. These include: (i) thermal overload analysis of network elements and network constraints, (ii) analysis of voltage value (violations on voltage limits) and preliminary definition of reactive power compensation, (iii) voltage stability analysis, (iv) short-circuit quantitative analysis (sizing of circuit breakers or network reconfiguration).

There is no such agreement with regard to dynamic analyses. A typical approach is to assume that the scope of dynamic analyses of stability should depend on the planning time horizon. One of the obligations of transmission system operators is to plan expansion in various time horizons: long-term ($\geq$15 years), mid-term (10 years) and short-term ($\leq$5 years). Primary studies in the field of dynamic analyses include [4]:

- Rotor angle stability analysis, which includes
  - (a) Rotor angle transient stability analysis,
  - (b) Rotor angle small signal stability analysis,
- Voltage ride-through analysis,
- Frequency stability analysis.

This paper discusses rotor angle small signal stability analysis in transmission network expansion planning using the experiences from stability analyses conducted for an extensive, real-life power system, i.e. the Polish Power System [5]. Various methods to assess small signal stability are known, but gaps in knowledge on the practical determinants and limitations of particular methods often results in such analyses being conducted only to a limited extent at the stage of transmission network expansion planning. This paper describes methods to assess small signal stability and the relationships between the selected stability indicators. The waveform-based method and its relationship with the eigenvalue-based method of analysis are discussed in particular

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detail. Theoretical considerations are complemented with results illustrating the characteristics of different approaches to small signal stability assessment.

2. Stability of power systems

Stability is an essential precondition of power system operation and from the technical point of view means the ability to regain equilibrium following physical disturbance [4]. From among various types of stability classified in the report [6], this paper discusses rotor angle small signal stability, which describes the ability of a power system to maintain synchronism following small disturbances. Small signal stability is associated with electromechanical phenomena [4].

Oscillations in a power system can be classified by their local or global nature in the following way:

- Local-plant mode oscillations, with approximate frequency range of 0.8–2.0 Hz,
- Inter-area mode oscillations, with approximate frequency range of 0.2–0.8 Hz.

The diversity of oscillations linked to small signal stability means that the time frame of interest in small signal stability studies is between 10 and 20 s following a disturbance.

3. Methods for assessing rotor angle small signal stability

3.1. Method 1. The assessment of small signal stability based on the eigenvalue analysis

Small signal stability analysis narrows the assessment of stability of a power system to the case in which the system is subject to a small disturbance. The disturbance is assumed to be so small that it justifies the use of linear approximations of the power system [7,8] for the purpose of analysis.

Dynamic response of the power system to a small disturbance may be examined by various methods. One of the most common approaches to small signal stability assessment uses Lyapunov's first method that can be applied to the linearized model of a power system [4].

In general, a multi-machine power system is described by non-linear differential and algebraic equations. These equations can be reduced to the following general form:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{u}), \tag{1a}$$

$$0 = \mathbf{g}(\mathbf{x}, \mathbf{y}, \mathbf{u}) \tag{1b}$$

where $\mathbf{x}$ is the vector of state variables, $\mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{u})$ is the vector of differential equations, $\mathbf{g}(\mathbf{x}, \mathbf{y}, \mathbf{u})$ is the vector of algebraic equations, $\mathbf{y}$ is the vector of auxiliary algebraic variables associated with modules and arguments of nodal voltages, $\mathbf{u}$ is the vector of control variables.

In order to assess small signal stability, Eqs. (1a) and (1b) are linearized around the point of operation of the system, which leads to linearized equations and state matrix $\mathbf{A}$. The theory underlying the linear model is described extensively in books [7,9] and numerous brochures and papers, including in [8,10]. The linear system is locally stable when all eigenvalues $\lambda_i = \sigma_i \pm j\omega_i$ meet the following condition $\sigma_i < 0$. Furthermore, from the point of view of small signal stability of a power system, it is required that local and inter-area oscillations are adequately damped. For a given eigenvalue λ_i, the damping ratio and the frequency of oscillation can be determined as follows:

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}, \quad f = \frac{\omega}{2\pi} \tag{2}$$

where ζ means the damping ratio.

To ensure an adequate level of security of operation of the power system, a minimum damping ratio not less than the assumed value is required (e.g. 0.05) [11], which corresponds to 5% of the stability margin.

3.2. Method 2. The assessment of small signal stability based on the waveform analysis

In this approach, the solution of Eqs. (1a) and (1b) in the time domain is defined. For this purpose, various computer simulation tools dedicated to the analysis of dynamic states of the power system are used. It is worth noting that there are much more computer programs for determining waveforms in large power systems than for eigenvalue analysis. This is of practical importance at the stage of transmission network expansion planning.

For stability assessment, it is assumed that the subject of observation are signals associated with synchronous generators, such as generator rotor angles $\delta(t)$, angular velocity of generator rotors $\omega(t)$, generated real powers $P(t)$. Time domain analysis should be performed for different contingency planning [3]. For the study of local and inter-area oscillations, a contingency such as three-phase temporary short circuit close to power station busbar may be analysed.

The theory of dynamic systems uses various indices to determine the quality of control on the basis of waveform analysis [12,13]. Some of them are used to evaluate the damping of oscillations in the power system, and thus to assess small signal stability. The following indices may be used to assess small signal stability: (i) decrement of damping χ; (ii) settling time t_s; (iii) halving time $t_{50\%}$. Decrement of damping χ is the ratio of successive peak displacements in the same direction: $A(t)/A(t+T)$. Settling time t_s is the time after which the amplitude of oscillation no longer exceeds a predetermined value. To determine the settling time, you need to specify the error band Δ_{err}. Halving time $t_{50\%}$ is the settling time for which the error band is 50%.

Determination of decrement of damping or settling time using waveforms is simple for linear systems. For power systems, which are non-linear, the halving time $t_{50\%}$ is the time after which the waveform $\Delta\delta(t) = \delta(t) - \delta(t=0)$ no longer exceeds 50% of the first peak. This is illustrated in Fig. 1.

In general, the selection of index (decrement of damping, settling time, halving time) for the purpose of assessing oscillation

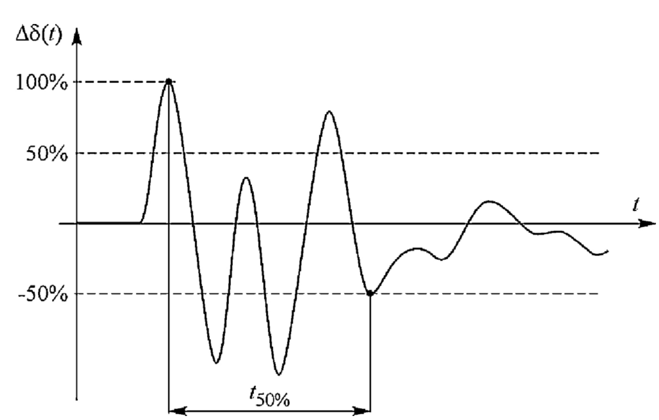

Fig. 1. Illustration of the definition of halving time.