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Stability analysis of power systems described with detailed models by automatic method

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ABSTRACT

The power system stability analysis is approached taking into explicit account the dynamic performance of generators internal voltages and control devices. The proposed method is not a direct method in the usual sense since conclusion for stability or instability is not exclusively based on energy function considerations but it is automatic since the conclusion is achieved without an analyst intervention. The stability test accounts for the nonconservative nature of the system with control devices such as the automatic voltage regulator (AVR) and automatic generation control (AGC) in contrast with the well-known direct methods. An energy function is derived for the system with machines forth-order model, AVR and AGC and it is used to start the analysis procedure and to point out criticalities. The conclusive analysis itself is made by means of a method based on the definition of a region surrounding the equilibrium point where the system net torque is equilibrium restorative. This region is named positive synchronization region (PSR). Since the definition of the PSR boundaries have no dependence on modelling approximation, the PSR test conduces to reliable results.

1. Introduction

There is no need for an explanation about the importance of the power system stability studies since the quality and continuity of the power delivery is strongly dependent on it. So, stability is a main concern of power system planning and operation strategies and a lot of digital methods for analysis were developed. The oldest one is the so-called step-by-step method and even in the present days this is the more reliable method. Indeed, its results are taken as bench mark for evaluating results of other methods. In step-by-step method the model sophistication is practically unlimited and also the accuracy of numerical integration is not a drawback. However, this method requires the analysis of swing curves in order to conclude for stability or instability. This necessity makes the method precluded for use in planning or operation automatic procedure and then the interest for direct methods development came in order to overcome this difficulty. The first of them was based on the strict-sense application of the second method of Lyapunov leading to stability domain definition (see [4]). Then the analysis of swing curves is not necessary anymore, and the stability test is based on relative values of the Lyapunov function at an initial condition and at a stability domain border. Along decades the direct methods have being subject of a great number of improving approaches leading to very interesting and useful results (see [1,4]), and the interest still goes on by proposing modelling improvements (like the ones in [2,7]) and accuracy enhancements (with [2] as an example). However, there still remain some open matters. For instance, let observe that the main strictly formal results are based on conservative properties of the system and they apply to the machines classical model. So it is in [2] where the goal is to circumvent the difficulties with the transfer conductances. Also, while an improvement for the controlling unstable equilibrium point (CUEP) is proposed in [7] with network structure-preserving the machines are still described by the classical model.

The use of direct methods makes possible to obtain a large number of alternative results in planning studies or a fast (even on-line) solution in automatic operation procedure. However, if accurate and reliable results are needed it is necessary to consider detailed machine model and take into account control and compensation devices. But if such model sophistication is accounted for the dynamic system is not conservative. Then the direct methods as they were strictly proposed do not apply and this is the motivation for looking for a method which can handle system model as detailed as needed. Furthermore, not only the machine and controllers models detailing are interesting to be accounted for, but there are also other devices exerting influence on system dynamic performance and they have to be considered. There is no doubt that the FACTS devices are among them. A Lyapunov approach to the transient stability analysis of multimachine power system with FACTS is presented in [8] where the network structure is preserved in order to account for a TCSC installed at a generic transmission line.

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In this paper an analysis method is proposed with the synchronous machines represented by the forth-order model with automatic voltage control (AVR) and automatic generation control (AGC). The stability analysis method is not a direct method in strict-sense but it is automatic since the concluding result for stability/instability is achieved without explicit swing curve analysis.

The stability test is based on the following principle. If the operation point is stable, its neighbourhood is a region where the generalized system forces (including net shaft torques) qualify as equilibrium restorative actions. In strict-sense: they are synchronizing. This region is named positive synchronization region (PSR) and it is defined with respect to net shaft electrical and mechanical torques and voltages. Since there is a precise definition for the PSR, the stability test is concerned to its boundaries by observing if system trajectory does or does not cross a PSR boundary. In [3] there is the first approach of the PSR method. The subject then was the single-machine infinite bus (SMIB) power system including the effects of the AVR and with synchronous machine given by the so-called one-axis model.

Finally, the conclusion of the stability test is not based on the transient energy but it is merely used as a key for the analysis procedure starting and also to indicate critical cut sets in the system.

2. Power system representation

This section presents the models used to represent the multi-machine power system transient performance.

2.1. Synchronous machines

The i-th synchronous machine is described by the two-axis model [5]. With variables and parameters defined as usual in the bibliography the equations are (see [5]):

$$\dot{\delta}_i = \omega_i \tag{1}$$

$$\dot{\omega}_i = \frac{1}{M_i}(-D_i\omega_i + Pm_i - Pe_i) \tag{2}$$

$$T_{do_i}\dot{E}'_{q_i} = -E'_{q'_i} - (x_{d_i} - x'_{d_i})i_{d_i} + E_{fd_i} \tag{3}$$

$$T_{qo_i}\dot{E}'_{d_i} = -E'_{d'_i} + (x_{q_i} - x'_{q_i})i_{q_i} \quad i = 1,2,3,\ldots,n \tag{4}$$

2.2. Network relations

Since the machines are considered as non-salient poles, the voltages E'_{di} and E'_{qi} are the direct- and quadrature-axis components of the machine internal voltage E'_i which lies behind the transient direct-axis reactance (X'_{d_i}). The loads are supposed constant admittances allowing the reduction of the network to the machines internal busses. The bus current at i-th bus is

$$I_i = \sum_{j=1}^{n} Y_{ij}E'_j \tag{5}$$

or, at each bus:

$$i_{di} = G_{ii}E'_{di} - B_{ii}E'_{qi} + \sum_{\substack{j=1\\ j\neq i}}^{n}\left[B_{ij}(E'_{dj}\sin\delta_{ij} - E'_{qj}\cos\delta_{ij})\right] + \sum_{\substack{j=1\\ j\neq i}}^{n}[G_{ij}(E'_{dj}\cos\delta_{ij} + E'_{qj}\sin\delta_{ij})] \tag{6}$$

$$i_{qi} = G_{ii}E'_{qi} + B_{ii}E'_{di} + \sum_{\substack{j=1\\ j\neq i}}^{n}\left[B_{ij}(E'_{dj}\cos\delta_{ij} + E'_{qj}\sin\delta_{ij})\right] + \sum_{\substack{j=1\\ j\neq i}}^{n}[G_{ij}(-E'_{dj}\sin\delta_{ij} + E'_{qj}\cos\delta_{ij})] \tag{7}$$

where δ_i is the i-th machine rotor angle, B_{ij} and G_{ij} are the transfer susceptance and conductance between busses i and j, and the subscripts ($_d$) and ($_q$) designate direct- and quadrature-axis reference frame. The real power delivered by the i-th machine is given by $P_{e_i} = E'_{q_i}i_{q_i} + E'_{d_i}i_{d_i}$. Thus

$$\begin{aligned}P_{ei} = {} & G_{ii}(E'^2_{di} + E'^2_{qi}) + \sum_{\substack{j=1\\ j\neq i}}^{n}\{B_{ij}[(E'_{di}E'_{dj} + E'_{qi}E'_{qj})\sin\delta_{ij} \\ & + (-E'_{di}E'_{qj} + E'_{dj}E'_{qi})\cos\delta_{ij}]\} + \sum_{\substack{j=1\\ j\neq i}}^{n}\{G_{ij}[(E'_{di}E'_{dj} + E'_{qi}E'_{qj})\cos\delta_{ij} \\ & + (E'_{di}E'_{qj} - E'_{dj}E'_{qi})\sin\delta_{ij}]\}\end{aligned} \tag{8}$$

Since $\delta \in R^n$ there exist m (=$(n(n-1)/2)$ pairs of machines, with angular displacements $\delta_{ij} = \delta_i - \delta_j$. Taking the equilibrium point at origin, define $\sigma_k = \delta_{ij} - \delta^0_{ij}$, for a generic pair $k = (i,j)$. Let now define deviations with respect to the equilibrium point. $\boldsymbol{\sigma}$ is the angular displacement deviation vector defined as

$$\boldsymbol{\sigma} = \mathbf{K}(\boldsymbol{\delta} - \boldsymbol{\delta}^{\mathbf{0}}) \tag{9}$$

where $\mathbf{K} \in R^{m\times n}$ is the element-node incidence matrix defined in [4] built for the reduced network. The *i-th* machine internal voltages deviations are

$$e_{di} = E'_{di} - E'^0_{di};\ e_{qi} = E'_{qi} - E'^0_{qi} \tag{10}$$

Then the power deviations at i-th machine terminal is

$$\Delta P_{ei} \cong \mathbf{K}_i^T\mathbf{f}(\boldsymbol{\sigma}, \mathbf{e_d}, \mathbf{e_q}) \tag{11}$$

where $\mathbf{K}_i$ is the i-th column of the matrix $\boldsymbol{K}$ and the vector $\mathbf{f}(\boldsymbol{\sigma},\mathbf{e_d},\mathbf{e_q}) \in R^m$ has entries

$$\begin{aligned}f_k(\sigma_k, e_{di}, e_{dj}, e_{dj}, e_{dj}) = {} & B_{ij}[(E'_{di}E'_{dj} + E'_{qi}E'_{qj})\sin(\sigma_k + \delta^0_{ij}) \\ & - (E'^0_{di}E'^0_{dj} + E'^0_{qi}E'^0_{qj})\sin\delta^0_{ij} + (-E'_{di}E'_{qj} + E'_{dj}E'_{qi})\cos(\sigma_k + \delta^0_{ij}) \\ & - (-E'^0_{di}E'^0_{qj} + E'^0_{dj}E'^0_{qi})\cos\delta^0_{ij}] \quad k = 1,2,\ldots,m\end{aligned} \tag{12}$$

The voltage variations dependent terms resulting from the self-conductance term in (8) are not present in (12) due to structural reason and this approximation applies only to the construction of the Lyapunov function (LF). Their effects appear as a little fluctuation in the function time-decaying when simulating the system without this simplifying assumption. Furthermore, since the conductance's terms lead to path-dependent integrals, they were neglected in the LF derivation. Their effects can be taken into account in digital simulation by means of numerical integration, as usual in the related bibliography.

Similarly the currents deviations are computed as follows:

$$\Delta i_{di} = G_{ii}e_{di} - B_{ii}e_{qi} + g_i(\sigma, e_d, e_q) \tag{13}$$

$$\Delta i_{qi} = G_{ii}e_{qi} + B_{ii}e_{di} + h_i(\sigma, e_d, e_q) \tag{14}$$

with:

$$g_i(\sigma, e_d, e_q) = \sum_{\substack{j=1\\ j\neq i}}^{n}\{B_{ij}[E'_{dj}(\sin(\sigma_k + \delta^0_{ij}) - \sin\delta^0_{ij}) - E'_{qj}(\cos(\sigma_k + \delta^0_{ij}) - \cos\delta^0_{ij})]\} \tag{15}$$

$$h_i(\sigma, e_d, e_q) = \sum_{\substack{j=1\\ j\neq i}}^{n}\{B_{ij}[E'_{dj}(\cos(\sigma_k + \delta^0_{ij}) - \cos\delta^0_{ij}) + E'_{qj}(\sin(\sigma_k + \delta^0_{ij}) - \sin\delta^0_{ij})]\} \tag{16}$$