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Using trajectory sensitivity analysis to find suitable locations of series compensators for improving rotor angle stability

Amin Nasri *, Robert Eriksson, Mehrdad Ghandhari

Department of Electric Power System, KTH Royal Institute of Technology, 10044 Stockholm, Sweden

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ABSTRACT

This paper proposes an approach based on trajectory sensitivity analysis (TSA) to find most suitable placement of series compensators in the power system. The main objective is to maximize the benefit of these devices in order to enhance the rotor angle stability. This approach is formulated as a two-stage problem, whose first-stage describes prior to fault occurrence and whose second-stage represents the power system behavior involving a set of severe faults. The first-stage focuses on small signal stability, while the second-stage deals with transient stability of power system. In this vein, the trajectory sensitivities of the rotor angles of generators with respect to the reactances of transmission lines are calculated. Two equivalent rotor angles are introduced to find stability indices corresponding to the first- and the second-stage of the proposed approach. Numerical results from IEEE 10-machine 39-bus test system demonstrate the usefulness of the proposed method.

1. Introduction

1.1. Motivation and aim

Deregulation in electricity markets, increasing electricity demands and high penetration of renewable energy sources have increased the power transactions within and between regions in today's power systems. The installation of new transmission lines cannot be carried out easily because of its heavy costs and environmental concerns. As a result, this competitive environment pushes the existing transmission systems to be operated close to their critical conditions which may result in higher risk of transient instability. Moreover, small signal oscillations occur more frequently in a heavy-loaded interconnected power system. In this situation, rotor angle stability would be one of the main concerns of the power system operators.

Series flexible AC transmission systems (FACTS) devices, e.g., Thyristor Controlled Series Capacitor (TCSC), can have a significant impact on operational flexibility and controllability of the power system. They can manipulate the reactance of transmission lines and control the power flow through lines in a way to increase the transient stability margins. These devices, equipped with the proper controller, can also be used to improve the small signal stability. Since the impact of these compensators on the system stability is strongly dependent on their locations, it is required to provide useful information to the system planners regarding the best possible locations to install them. In this paper, an effective approach is proposed to identify the most suitable placement of series compensators for improving both the transient and small signal stability of the power system.

1.2. Literature review

Assessment of rotor angle stability is essential to study the dynamic behavior of the power system. Time domain simulation is the traditional way for transient stability assessment which has two main disadvantageous, namely time-consuming computation requirement and incapability to provide any information regarding the stability margin [1]. The other method which has been widely used for this purpose is transient energy function (TEF) method [2–4]. The significant advantage of this method is its capability to provide a stability index [1]. Several methodologies have been proposed based on the sensitivity of TEF to determine the effectiveness of FACTS devices in improving the transient stability. For instance, [5] proposes a methodology based on sensitivities of the critical energy of post-fault system with respect to some system parameters, e.g., reactance of the lines for series compensations and injected reactive power into nodes for shunt compensations. A structure preserving energy margin sensitivity based analysis is carried out in [6] for placement of series and shunt FACTS devices.

* Corresponding author. Tel.: +46 707 305063; fax: +46 8 790 6510.
E-mail addresses: amin.nasri@ee.kth.se, amin.nasri@gmail.com (A. Nasri), robert.eriksson@ee.kth.se (R. Eriksson), mehrdad.ghandhari@ee.kth.se (M. Ghandhari).

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Despite all the advantages of the TEF based methods, the main shortcoming of them is their high complexity in the following situations: (i) considering differential-algebraic equation (DAE) models of power systems, (ii) dealing with the detailed models of the system's components, and (iii) when a number of system's parameters have to be taken into account for the sensitivity analysis [7–9].

Applications of trajectory sensitivity analysis (TSA) have been introduced as an alternative to overcome the mentioned shortcoming of the TEF based method [7]. Ref. [10] uses TSA to calculate the critical values of some power system parameters, e.g., fault clearing time and mechanical input power of generators. The proposed method in [10] is based on the computation of the norm of trajectory sensitivities of rotor angles and speeds of generators with respect to the parameters of interest. Ref. [8] discusses the application of TSA to power systems containing series and shunt compensators. A transient stability index is introduced based on a numerical estimation of TSA, and is calculated for the power system with different locations of series and shunt compensators. Ref. [11] identifies the optimal location and proper design of the TCSC-controller with the help of TSA for a power system involving several fault conditions. Using numerical formulation of TSA, considering the compensators' models in the study and simulating the power system for all the possible locations of compensators causes high computational burden for the proposed method in [8,11]. Ref. [9] develops a multi-parameter trajectory sensitivity approach to find the best locations of series compensators in order to improve the transient stability. An index of proximity to instability is determined based on the norm of trajectory sensitivities of the rotor angles and the speeds of generators with respect to the transmission line susceptances. Using the analytical formulation of TSA in [9] and also in the current paper, the cumbersome computational process becomes much simpler compared to the numerical method which is used in [8,11]. As it is explained completely in [9], the analytical formulation of TSA reduces the required number of time domain simulations from $(n_l+1)\times n_z$ to n_z for a power system with n_l transmission lines and n_z fault scenarios. Compared to [9], the method proposed in this paper is also capable to determine the transmission lines on which the installed compensators could have an opposite effect on the system stability. The latter will be addressed in details in this paper.

In the technical literature, there are also some works focusing on suitable placement of FACTS devices for improving small signal stability, e.g., [12,13] which propose controllability indices in order to find such a placement. Ref. [14] uses an eigenvalue sensitivity approach to determine the transmission line whose reactance modulation would be more effective to damp out the oscillatory modes of interest. It is important to note that, in previous literature, there is no thorough placement approach considering both the transient and small signal stability improvements, and such approach is addressed in this paper.

1.3. Contributions

Considering the works analyzed in the literature review, the contributions of this paper are threefold:

1. To propose a novel approach based on analytical formulation of TSA for suitable placement of series compensators in order to improve both the transient and small signal stability of the power system.
2. To formulate the proposed approach as a two-stage problem analyzing the pre-fault and post-fault behavior of power system.
3. To demonstrate the conditions where installing series compensators in the transmission lines deteriorates the power system stability.

1.4. Paper organization

The rest of this paper is organized as follows: Section 2 presents how to formulate the TSA technique. Section 3 explains the application of TSA for transient and small signal stability assessments. Section 4 proposes an approach for suitable placement of series compensators in order to improve rotor angles stability. Section 5 provides results from a case study, and finally Section 6 provides a number of relevant conclusions.

2. Trajectory sensitivity

2.1. Power system modeling and analytical formulation of trajectory sensitivity

Power systems can be modeled by the following differential algebraic equations [15]

$$\dot{x} = f(x, y; \lambda) \tag{1}$$

$$0 = g(x, y; \lambda) \tag{2}$$

$$x(t_0) = x_0, \quad y(t_0) = y_0 \tag{3}$$

where x is a vector containing the dynamic states, y is a vector of algebraic states and λ is a vector of system parameters. Rotor angles of the generators (δ), magnitude and angle of bus voltages and reactances of the transmission lines are the examples of the dynamic states, algebraic states and parameters of the power system, respectively. Vectors x_0 and y_0 are the initial conditions of dynamic and algebraic states. Function f is the set of differential equations which model the dynamics of equipments such as generators. The algebraic equations g consist of the network equations based on Kirchhoff's current law, i.e. the sum of all current (or powers) flowing into each bus must be equal to zero. To write the equations in a more organized way, vectors of $\underline{x}$ and $\underline{f}$ are defined as follows:

$$\underline{x} = \begin{bmatrix} x \\ \lambda \end{bmatrix}, \quad \underline{f} = \begin{bmatrix} f \\ 0 \end{bmatrix} \tag{4}$$

and therefore

$$\dot{\underline{x}} = \underline{f}(\underline{x}, y) \tag{5}$$

$$0 = g(\underline{x}, y) \tag{6}$$

To calculate the trajectory sensitivities analytically, the derivatives of (5), (6) are calculated with respect to $\underline{x}_0$

$$\dot{\underline{x}}_{\underline{x}_0} = \underline{f}_{\underline{x}}(t)\underline{x}_{\underline{x}_0} + \underline{f}_y(t)y_{\underline{x}_0} \tag{7}$$

$$0 = g_{\underline{x}}(t)\underline{x}_{\underline{x}_0} + g_y(t)y_{\underline{x}_0} \tag{8}$$

The initial conditions for $\underline{x}_{\underline{x}_0}$ and $y_{\underline{x}_0}$ are obtained by differentiating (3) with respect to $\underline{x}_0$. It is obvious that the initial value for the trajectory sensitivities of dynamic states is an identity matrix. Using this identity matrix, the initial values for the trajectory sensitivities of algebraic states can be also computed from (8).

$$\underline{x}_{\underline{x}_0}(t_0) = I, \quad y_{\underline{x}_0}(t_0) = -(g_y(t_0))^{-1} g_{\underline{x}_0}(t_0) \tag{9}$$

where $\underline{f}_{\underline{x}}$, $\underline{f}_y$, $g_{\underline{x}}$ and g_y are time varying functions which are calculated along the system trajectories. To find the trajectory sensitivities, the DAEs (5)–(8) should be solved simultaneously considering the initial conditions described above. The solution method is explained in detail in the next section.