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An interval Taylor-based method for transient stability assessment of power systems with uncertainties

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ABSTRACT

Transient stability assessment needs to be further studied when confronted with uncertainties brought in by the integration of renewable energy and measurement errors. This paper outlines a novel method based on interval Taylor expansion incorporated optimal solution technique to solve the uncertainty model for transient stability assessment. Uncertainty assessment framework for power systems transient stability is described as ordinary differential equations with interval variables, which can be equivalently transformed into three sets of ordinary differential equations with only deterministic parameters using the interval Taylor method with second-order expansion. In order to further reduce the overestimation, a quadratic programming model is constructed to estimate upper and lower boundaries of state variables. Application of the proposed method is implemented in SIMB system and IEEE-30 system and the results are demonstrated in details. Comparisons with affine arithmetic (AA)-based method and Monte Carlo method verify the effectiveness and better performance of the proposed method.

1. Introduction

With the integration of large-scale renewable energy (e.g., photovoltaic and wind energy), these introduce inherent uncertainties into power systems on the generation side due to the variable nature of solar insolation and wind speed [1,2], and flexible loads (e.g., plug-in hybrid electric vehicles) are randomly distributed into power systems, which introduce driven uncertainties on the load side [3]. Ref. [4] reviewed wind power variability and its different impacts on power systems, and the issue of quantifying effects of model uncertainty on transmission security was addressed in Ref. [5]. Therefore, all these uncertainties bring new problems arising from power systems security and stability [6], which require some methods to assess transient stability under uncertainties [7].

Transient stability analysis is required for planning, operation and control, which are used to assess the capability of power systems to remain in synchronism when subjected to large and sudden system disturbances [8]. To take consideration of the uncertainties of the factors associated with the practical operation of power systems [9], such as fault type, fault location, fault clearing process, system parameters and reclosing process, some probabilistic methods, for example, Monte Carlo method [10,11], probabilistic collocation method [12] and probabilistic weighting method [13], were proposed to assess transient stability. Among the three probabilistic assessment methods, Monte Carlo method was widely used to address the transient stability problem under uncertainties. Although Monte Carlo method is straightforward, accurate and easy to implement, it is very time consuming as a large number of random time domain simulations are needed to determine the probabilistic transient stability index [14]. Apart from Monte Carlo method, the analytical method handles uncertainties based on linearization and obtains the probability of random output variables, can be more computationally efficient [15]. Most of these probability-based approaches require enough historical data to achieve the probability density function of the uncertain variables, or assume that it obeys a certain probability distribution.

Special attention has also been paid in the literature to the stochastic calculus-based methods [16]. In Ref. [17], the stochastic Lyapunov stability method and the numerical solution of stochastic differential equations were combined to present a new approach that develops a quantitative assessment of probabilistic stability. In Ref. [18], a stochastic power system model based on stochastic differential equations (SDEs) was proposed to consider the uncertain factors such as load levels and system faults, and two numerical methods, namely the stochastic Euler and Milstein schemes, were employed to solve SDEs

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numerically. The singular perturbation method for SDEs was the first attempt to conduct stability analysis for power systems with uncertainties arising from load variations and other renewable energy in Ref. [19]. All these assessment methods adopted the stochastic differential equations to model power systems under uncertainties, and some new stochastic numerical solution techniques were developed to solve them. However, the stochastic calculus-based approaches exhibit some assumptions in properly modeling the uncertainties, and suffer low computational efficiency and unclear impact mechanism, because of their complexity.

As an alternative to probability-and stochastic calculus-based methods, non-probabilistic interval analysis method was applied in Ref. [20] for transient stability simulation under system parameters uncertainty which were modeled as intervals numbers. While the resultant interval differential equations were solved by means of the method that combines interval arithmetic and Taylor series expansion, leading to overestimation with the simulation time progressing. Therefore, affine arithmetic (AA) [21–23], which was introduced in Ref. [24] as an improvement of interval arithmetic, has been proposed to take into account the correlation between uncertain operands and sub-formulas involved in the interval calculation. One of the advantages of AA-based method is transforming the interval variable to affine form, overcoming the drawback of conservatism. However, the affine form formulation only used first-order Taylor expansion, may also causing the interval solution enlarged, which may be an issue in some applications. Besides the affine arithmetic, there also exist some other efficient methods, such as interval vertex method [25], parameter perturbation method [26], and collocation method [27,28] and so on. Although these interval methods were used in mechanical systems, these methods can also be applied to the power system stability assessment with necessary extensions.

To overcome the deficiency of using AA-based method, a novel method for uncertain transient stability assessment is proposed in this paper, which applies interval Taylor method [29,30] with second-order expansion for establishing the nonlinear optimization model instead of linear optimization model. First of all, the paper utilizes the multi-machine classical model [31] to formulate transient stability assessment framework with interval variables, then by means of the interval Taylor method with second-order expansion, the original ordinary differential equations with interval variables for transient stability assessment are equivalently transformed into three sets of ordinary differential equations with only deterministic parameters. In the end, a quadratic programming model [32] to estimate upper and lower boundaries of state variables are constructed to further reduce the overestimation.

In the following context, transient stability assessment framework under interval uncertainty is presented in Section 2, and then the complete formula for solving interval boundaries is derived through interval Taylor method and the detail calculation procedure is given in Section 3. It is followed by case studies presented in Section 4 in which two cases, a single-machine infinite-bus (SMIB) system and IEEE-30 system for demonstrating the effectiveness of the proposed method. Finally, Section 5 summarizes the main conclusions and contributions of the paper.

2. Transient stability assessment formulation under interval uncertainty

2.1. Classical model for transient stability assessment

To assess power systems transient stability, dynamic simulations based on numerical integration methods are performed to obtain time-domain trajectories following a large and sudden disturbance, and then such time-domain trajectories are analyzed with different security criteria, such as rotor angle [33] and post-transient voltage recovery [31]. Mathematical models are developed to describe the dynamic behaviors of various system components, which consist of first-order ordinary differential equations representing dynamics of generators and their controllers; and algebraic equations representing the network coupling between generators, loads, and transmission system.

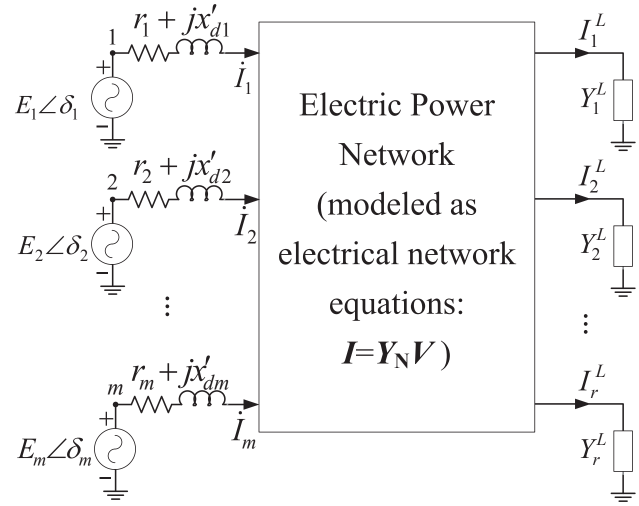

Fig. 1. Description of multi-machine classical model.

In this study, the multi-machine classical model [31] for transient stability analysis is used, which is shown in Fig. 1. In Fig. 1 $\boldsymbol{I}$ denotes the current injected into the network, $\boldsymbol{Y}_{\mathrm{N}}$ is the system admittance matrix, and $\boldsymbol{V}$ denotes the bus voltage. In this model, all the loads are assumed to be constant impedances and network nodes are eliminated by network simplification. Node 1, 2, …, m are internal generator nodes. The initial values $E_i\angle\delta_i, i \in (1,m)$ are determined by the steady-state power flow, and remain constant in the transient period.

As seen in the portion of the network shown in Fig. 1, the network equation can be defined as

$$\begin{bmatrix} \boldsymbol{Y}_G & \boldsymbol{Y}_{GN} \\ \boldsymbol{Y}_{NG} & \boldsymbol{Y}'_N \end{bmatrix} \begin{bmatrix} \boldsymbol{E} \\ \boldsymbol{V} \end{bmatrix} = \begin{bmatrix} \boldsymbol{I} \\ \boldsymbol{0} \end{bmatrix} \tag{1}$$

where $\boldsymbol{E} = [E_i\angle\delta_i]^T$, $\boldsymbol{I} = [\dot{I}_i]^T$, $i \in (1,m)$. $\boldsymbol{Y}'_N$ is the augmented nodal admittance matrix, which includes the constant impedances of the r loads. $\boldsymbol{Y}_G$ is the self-admittance matrix of the generator nodes. Both $\boldsymbol{Y}_{GN}$ and $\boldsymbol{Y}_{NG}$ are the mutual admittance matrix between the generator nodes and the network nodes.

Eliminating all nodes of the network, thus (1) can be simplified to

$$\boldsymbol{YE} = \boldsymbol{I} \tag{2}$$

$$\boldsymbol{Y} = \boldsymbol{Y}_G - \boldsymbol{Y}_{GN}(\boldsymbol{Y}'_N)^{-1}\boldsymbol{Y}_{NG} \tag{3}$$

Define

$$\boldsymbol{Y} = [Y_{ij}] \in R^{m\times m}, Y_{ij} = G_{ij} + jB_{ij} \tag{4}$$

So (2) can be rewritten as

$$I_i = \sum_{j=1}^{m} Y_{ij}E_j, i \in (1,m) \tag{5}$$

And real electrical out power of the internal node i is given by $P_{ei} = \mathrm{Re}(E_i I_i^*)$, i.e.,

$$P_{ei} = E_i^2 G_{ii} + \sum_{j=1,j\neq i}^{m} E_i E_j Y_{ij}\cos(\theta_{ij}-\delta_{ij}) = E_i^2 G_{ii} + \sum_{j=1,j\neq i}^{m} (C_{ij}\sin\delta_{ij} + D_{ij}\cos\delta_{ij}) \tag{6}$$

where $C_{ij} = E_i E_j B_{ij}$, $D_{ij} = E_i E_j G_{ij}$. Therefore, the multi-machine classical model becomes