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Wind power system state estimation with automatic differentiation technique

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ABSTRACT

A wind power system state estimation method based on automatic differentiation technique is presented in this paper. A simplified RX model of wind turbine is introduced and used to be equivalent to wind power generator. As one of the state variables, the slip of wind power generator is introduced into state estimation process and the corresponding mathematical model is established. The proposed method takes into account the own characters of asynchronous generator and can easily combine with the original state estimation program. Furthermore, unlike the traditional method which needs to deduce all the formulas of derivatives and code them by hand, the Jacobian matrix is built automatically using automatic differentiation with sparse technique in the proposed method, the truncation error is avoided effectively, and the computational efficiency, speed and precision can be significantly improved. This paper demonstrates that the burdens of software developers are relieved greatly by automatic differentiation technique instead of hand-coded derivatives and the simplified RX model instead of the traditional RX model. Finally, it follows from the simulation results that the proposed method possesses good performance and can be well applied to state estimation for power system containing wind power generators.

1. Introduction

As the complementarity of centralized generation, wind power has gained increasing interest in recent years, because it can reduce power losses and on-peak operating costs, improve voltage profiles, defer or eliminate system upgrades, and mitigate environment pollution. Due to some special properties of wind power, the traditional analyzing methods cannot be applied directly. Therefore, analysis power grids connected wind generators is one of the hot topics in the power engineering research field [1–3]. Thus, it is urgent to analyze the impact of wind power on power system state estimation. If the required degree of accuracy is not high, wind turbine generator can be equivalent to the traditional PQ bus in general. However, due to the randomness of wind power, PQ model cannot reflect the essence of wind power. In [4–7], the RX model of wind turbine was introduced, the model took into account its own characteristics of asynchronous generator, and showed the characteristics of the active and reactive power in detail. The simulation results show that the RX model can meet the requirements of calculating accuracy in [4–7], but the mathematical formulas of the RX model are complex and messy, and the calculating burdens are heavy.

With the growth of power grid, the structure and operation mode are becoming more and more complicated, and the automation of power system control center is also needed to develop gradually from junior to senior. Thus energy management system (EMS) has been applied widely. State estimation is the core software in EMS, providing a reliable and integrated real-time database for other senior software in power system based on system structure, parameters and real-time measurements. State estimation is the basis of power system operation and security assessment. Thus, it is important and has actual significance to study the state estimation algorithms. In [8], Schweppe proposed the classical weighted least squares algorithm, later it becomes the basic algorithm and the most widely used algorithm in power system state estimation. In [9–17], based on the method in [8], many new or improved algorithms were introduced, but all of them did not consider the impact of wind power on power system state estimation. In [6,7], the impact of wind power was considered in the proposed algorithms of power system state estimation, and in [7], multi-types distributed generators were considered in the proposed algorithm for state estimation in distribution networks. However, due to the hand-coded derivatives are used to compute the Jacobian matrix and the RX model of wind turbine is used to simulate wind generator in Refs. [6,7], the calculating burdens are heavy, messy and inefficient.

To compute the Jacobian matrix, the traditional approach, in which the programmers have to deduce all the formulas of deriva-

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tives and code them by hand, is very messy and easy to make mistakes. However, automatic differentiation (AD) technique has overcome the disadvantages of hand-coded derivatives and is introduced into power systems. It is a completely new technique in the field of the numerical calculation and analysis. Differentiation is defined as algebraic operation by AD technique. As compared with other differentiation methods (such as numerical differentiation and symbols differentiation), it can automatically calculate the arbitrary-order derivatives without truncation errors using smaller CPU time and less memory space. In [18–20], AD algorithms were used in the power system load flow analysis. In [21], an application of AD was presented to compute the Jacobian matrix and sensitivities in the continuation power flow. In [22], AD was used to compute the Jacobian matrix in MINOS-based OPF solver. In [23], an efficient implementation of AD was proposed in interior point optimal power flow. Up to now, AD technique has been successfully applied to power flow calculation, sensitivity analysis, optimal power flow calculation and so on, to our best knowledge, there is no results on wind power system state estimation based on AD technique.

Therefore, based on the above discussions, this paper presents an efficient implementation of AD technique in wind power system state estimation. The motivation of this paper is to improve the execution speed of wind power system state estimation, relieve the burdens and troubles of computing the Jacobian matrix and the mathematical model of wind turbine generator, and avoid the truncation errors. In the proposed method, combining with the classical weighted least squares (WLS), a simplified RX model of wind turbine generator, and AD technique, ADOL-C (Automatic Differentiation by Overloading in C++) tool based on operator overloading is applied to the WLS state estimation algorithm for power system containing wind power generators. The simulations of test systems indicate that the proposed method using AD technique instead of the traditional hand-coded derivatives to compute the Jacobian matrix and the simplified RX model of wind turbine instead of the RX model to simulate wind generator is straightforward and more efficient, the calculating burdens are lighter and the accuracy is well satisfied.

The rest of this paper is organized as follows. In Section 2, the mathematical model of state estimation based on WLS is presented and the iterative function of WLS state estimation is then formulated. In Section 3, a simplified RX model of wind turbine generator is proposed, whose output of active and reactive power are formulated and can be used to realize wind power system state estimation. In Section 4, basic principles of AD technique and AD tools are introduced, which can be easily introduced into the state estimation algorithm. In Section 5, the AD technique is applied to wind power system state estimation, the wind power system state estimation with AD technique is derived in detail. In Section 6, illustrative examples are provided to show the effectiveness of the obtained results. In Section 7, some comparison results and discussions are provided. The conclusion is drawn in the last section.

2. Mathematical model based on WLS state estimation

State estimation is an important part of EMS, which plays an important role in the operation control of power system. There are two alternatives for the implementation of state estimation algorithms [8–17]: Gaussian-type least squares general algorithm (such as WLS method, fast decoupled method, and measurement transformation method) and Kalman-type successive estimation algorithm. Among the above methods, WLS algorithm is the most basic algorithm of state estimation. It has good convergence feature and high efficiency of estimation, and thus is applied more widely than the other state estimation algorithms. Therefore, in this paper, we focus on the algorithm based on WLS.

Given network conjunctions, line parameters and system measurements, nonlinear measurement equations of power system state estimation can be presented as

$$\boldsymbol{z} = \boldsymbol{h}(\boldsymbol{x}) + \boldsymbol{e} \tag{1}$$

where $\boldsymbol{z} \in R^m$ is the measurement vector, which generally includes the voltage amplitude measurements for buses, power injection measurements for buses and power flow measurements for lines, $\boldsymbol{h}(\boldsymbol{x})$ is a nonlinear function vector relating measurements to states, and it must conform to basic rules of circuit system including KVL, KCL and power function, $\boldsymbol{x} \in R^n$ is the state variable vector, $\boldsymbol{e}$ is the measurement error vector, and it is supposed to have the normal distribution (its mean value vector is zero and its standard deviation vector is $\boldsymbol{\sigma}$). Without loss of generality, there are m measurements and n state variables, $n < m$.

State estimation is to estimate state variable vector $\hat{\boldsymbol{x}}$ by minimizing the objection function $J(\boldsymbol{x})$ as an optimization problem with equality and inequality constraints, and its mathematical model can be formulated as follows

$$\mathrm{Min}_{\boldsymbol{x}} \quad J(\boldsymbol{x}) = [\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})]^T \boldsymbol{R}^{-1} [\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})] \tag{2}$$

subject to

$$\boldsymbol{c}(\boldsymbol{x}) = 0 \tag{3}$$

$$\boldsymbol{g}(\boldsymbol{x}) \leqslant 0 \tag{4}$$

where $\boldsymbol{R}$ is a diagonal matrix with diagonal elements σ_i^2, σ_i^2 is the variance of the ith measurement error, $\boldsymbol{x}$ is the state variable vector, $\boldsymbol{c}(\boldsymbol{x})$ are the equality constraints representing perfectly accurate measurements (zero injections), and $\boldsymbol{g}(\boldsymbol{x})$ are inequality constraints normally used to represent physical operating limits.

Since $\boldsymbol{h}(\boldsymbol{x})$ is a nonlinear function vector with respect to $\boldsymbol{x}$, normally, Eq. (2) cannot be solved directly. Mostly used method is linearization of the nonlinear function vector, then using Newton–Raphson method to solve the problem. Suppose k as iterative number, and $\hat{\boldsymbol{x}}^{(k)}$ and $\Delta\hat{\boldsymbol{x}}^{(k)}$ as estimated state vector and correction of the state vector at kth iteration, respectively, then the iterative formulation of WLS state estimation algorithm can be derived as follows

$$\begin{cases} \Delta\hat{\boldsymbol{x}}^{(k)} = [\boldsymbol{H}^T(\hat{\boldsymbol{x}}^{(k)})\boldsymbol{R}^{-1}\boldsymbol{H}(\hat{\boldsymbol{x}}^{(k)})]^{-1}\boldsymbol{H}^T(\hat{\boldsymbol{x}}^{(k)})\boldsymbol{R}^{-1} \times [\boldsymbol{z} - \boldsymbol{h}(\hat{\boldsymbol{x}}^{(\boldsymbol{k})})] \\ \hat{\boldsymbol{x}}^{(\boldsymbol{k+1})} = \hat{\boldsymbol{x}}^{(\boldsymbol{k})} + \Delta\hat{\boldsymbol{x}}^{(\boldsymbol{k})} \end{cases} \tag{5}$$

where k is iterative number, $\boldsymbol{H}$ is the Jacobian matrix of the nonlinear function vector $\boldsymbol{h}(\boldsymbol{x})$.

3. Model of wind power generator

Distributed generation (DG) is small-scaled and installed close to the consumer generation. In order to satisfy the consumer's request and improve load operation reliability and power quality, DG is being utilized widely all around the world. According to whether the first energy resources are renewable, DG can be divided into two categories: the first category is DG which uses renewable energy resources (i.e., solar energy, wind energy, geothermal energy, and ocean energy), the second category is DG which uses fossil fuels (i.e., internal-combustion engine, heat and power cogeneration, micro-turbines, and Fuel Cell) [24,25]. This paper studies DG using wind energy. The simulation investigation realizes wind power system state estimation based on AD technique.

At present, wind turbine generators (WTGs) are generally asynchronous machines without exciting units, in which the magnetic field is formed by the reactive power, and it has to absorb the reactive power from power system [26]. Therefore, the wind farms