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Model reduction strategy of doubly-fed induction generator-based wind farms for power system small-signal rotor angle stability analysis

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HIGHLIGHTS

- The eigenvalue-oriented participation level is more accurate in assessing the damping.
- The modeling adequacy assessment to explain damping mechanism of DFIGs is proposed.
- The model reduction strategy can indicate how to efficiently reduce DFIG models.
- The work provides system operator with a practical and useful tool for dynamic study.
- The work is valuable for fast online stability analysis with high wind penetration.

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ABSTRACT

Following the decarbonisation and decentralisation of energy industry, wind energy is becoming a promising generation source to reduce greenhouse emission, and meet future energy demand. Unlike traditional generation using synchronous generators, many wind turbines use induction generators, e.g., doubly-fed induction generators, due to the cost effective design of adjustable-speed operation and flexibility in reactive power control. However, a growing number of doubly-fed induction generator-based wind farms has significantly increased the complexity of system dynamic model, and hence increased the computational burden of power system dynamic study. This becomes a serious concern in the electricity system operation, where a fast power system stability assessment is required to assure the real-time system security during high levels of wind power penetration. In this paper, a novel model reduction strategy of doubly-fed induction generators is derived to improve the efficiency of power system dynamic study, while the study accuracy is still maintained to an acceptable level. To achieve this, a method to assess the modeling adequacy of doubly-fed induction generators for small-signal rotor angle stability analysis is firstly introduced. By evaluating the damping torque contribution to stability margin from different dynamic model components of doubly-fed induction generators, the proposed method provides a quantitative index (i.e., participation level) to show the involvement of each dynamic model component of doubly-fed induction generators in affecting power system damping, and thus can instruct how to reduce the model of doubly-fed induction generators in an efficient and accurate manner. On this basis, five model reduction plans and a model reduction strategy have been proposed according to the previously defined participation levels. The effectiveness of the proposed strategy is demonstrated in the New England test system and a real large power grid in Eastern China respectively. It has been proved that the proposed the model reduction strategy of doubly-fed induction generators for power system dynamic study is undoubtedly useful to the electricity system operator, with a key benefit in reducing model complexity and improving computational efficiency of a large-scale power system with an increasing number of wind power generation.

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Nomenclature

DFIG	doubly-fed induction generator
SG	synchronous generator
RSC	rotor-side converter
GSC	grid-side converter
MRM	model reduction margin
ΔX_w	vector of state variables of DFIGs
ΔX_g	vector of state variables associated with non-DFIG elements including SGs
ΔV_w	vector of terminal voltage associated with DFIG buses
ΔV_g	vector of terminal voltage associated with non-DFIG buses
Y	admittance matrix of the system
$\Delta\delta$	vector of variation of power angle of SGs
$\Delta\omega$	vector of variation of angular speed of SGs
Δz	vector of other state variables of SGs
Δs	vector of variation of slip of DFIGs
ΔE_d	vector of variation of d-axis electromotive force of DFIGs
ΔE_q	vector of variation of q-axis electromotive force of DFIGs
ΔX_c	vector of state variables of converter integral controllers as well as the DC link of DFIGs

1. Introduction

Modern technologies, energy policies and business models are driving the transition of energy industry to a low-carbon [1,2] and decentralised future [3,4]. Wind energy plays a key role in facilitating such a transition by providing sustainable electricity to power grid with negligible carbon emission [5]. Following the decommissioning of fossil-fuel power generation, wind energy is also becoming a promising energy resource to meet future electricity demand [6,7]. As a result, most countries encourage the development of wind power generation capacity by significantly increasing the number and size of wind power generation connected to electricity grids [8,9].

The dominant type of wind power generation in the world market is doubly-fed induction generators (DFIGs), due to their cost effective design, the ability to operate at variable speed, and flexibility in reactive power dispatch [10]. Compared with conventional generation, DFIG-based wind power generation is equipped with power electronics converters, which enables its characteristic of a faster response and better control [11]. However, on the other hand, the converter controllers have also raised the modeling complexity and dimensionality of wind power generators [12]. As a result, the size of the dynamic model of a power system integrated with large numbers of DFIG-based wind farms could be considerably increased. Since the model size can significantly affect the efficiency of system dynamic study, especially for time-domain simulation, it is crucial to assess the modeling adequacy and reduce model complexity of DFIGs for power system small-signal rotor angle stability analysis.

The study of DFIG modeling for dynamic analysis could date back over ten years and quite a few efforts have been devoted to the work, which can be generally divided into two categories: the detailed dynamic modeling and model reduction for DFIGs. The detailed DFIG models [13,14] are widely used to study the dynamics of DFIG controllers and wind power generators' own stability issues [15,16]. In addition, the impact of DFIG integration on comparatively small-scale power system dynamics can be also analysed by the detailed DFIG models [17,18]. Different from the conventional vector control scheme, a phase angle controlled DFIG model is introduced in the study to support the stability of a 3-machine power system [17]. An enhanced DFIG dynamic model is proposed in [18] to investigate the impact of the ancillary service of a DFIG-based wind farm on the small-signal rotor angle stability of a 4-machine 2-area power system. On the other side, the reduced models retain certain aspects of DFIG dynamic behaviors and are more suitable for the analysis of a large-scale power system with a high penetration level of wind power generation. Initially, most of reduced DFIG models are obtained by numerous trials of different models [19] and then validated by comparing the stability curves from time-consuming simulations [20,21]. Later some theoretical model order reduction techniques are developed to derive the reduced DFIG models, e.g., selective modal analysis in [22] and balanced truncation in [23]. Then these techniques are further used to establish the aggregate model for DFIG-based wind farms, such as selective modal analysis in [24] and singular perturbation analysis in [25]. However, most of model reductions mentioned above only focus on reduction impact on the dynamics of DFIG itself (e.g., wind power output), which might not meet the requirement of the electricity system operator, whose responsibility is to analyse the dynamic performance of the overall system. Hence, besides time-consuming trials by the modal analysis and time domain simulation, there is no study seen to deal with the DFIG model reduction from the perspective of the whole system impact (e.g., the impact on the system small-signal rotor angle stability and inter-area electromechanical oscillation modes). Moreover, the existing publications have not yet addressed all the reduction possibilities according to different system operational conditions.

In this paper, a novel model reduction strategy for DFIGs based on the proposed modeling adequacy assessment is presented, which is applicable to both the individual DFIG model and wind farm aggregate model. The main contributions of this paper are clarified as follows: 1. Compared with the existing participation factor from the modal analysis [26], the proposed eigenvalue-oriented quantitative index (i.e., participation level) from damping torque analysis is more accurate in assessing the damping performance of each DFIG dynamic model component as the damping is essentially the decaying rate of the oscillation, which is related to the real part of the eigenvalue. If the participation factor can assess the damping in a qualitative manner, the proposed participation level can assess the damping in a quantitative manner; 2. Compared with the existing damping torque calculation method proposed in [27], the proposed modeling adequacy assessment can facilitate the understanding of each internal component of DFIG dynamic model and their damping contribution mechanism to small-signal rotor angle stability analysis; 3. The model reduction strategy can indicate how to efficiently reduce the DFIG model complexity by recommending which model component(s) of DFIG can be certainly ignored, while still maintain the modeling accuracy and adequacy to an acceptable level; 4. The model reduction strategy not only aims to simplify each individual DFIG model, but most importantly also aims to further reduce the aggregate models of wind farms on top of the equivalent aggregate model strategy (e.g., [24,25]) as a second-stage reduction strategy; 5. The work provides electricity system operator with a practical tool that could significantly reduce the study time and calculation burden for power system dynamic study, which is particularly useful when dealing with fast on-line stability calculation with high penetration levels of wind energy.

The paper is organized as follows. In Section 2, a method to assess the modeling adequacy of DFIGs for the study of system critical oscillation mode is firstly introduced. The participation level of each order of DFIG dynamic model in damping contributions to the electromechanical loop of synchronous generators (SGs) is assessed respectively. In Section 3, a model reduction strategy of DFIGs for small-signal rotor angle stability analysis is proposed, and five reduced dynamic models with their linearised forms are derived according to five participation level conditions from the previous modeling adequacy assessment. Two case studies are presented in Section 4, where the proposed model reduction strategy and modeling adequacy assessment of DFIGs are validated by modal analysis and time-domain simulation. Finally,