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Integrated model of brushless wound-rotor synchronous starter-generator based on improved Parametric Average-Value Model of rotating rectifier

Ningfei Jiao[a,*], Weiguo Liu[a], Ji Pang[a], Zan Zhang[a], Yu Jiang[b]

[a] Department of Electrical Engineering, Northwestern Polytechnical University, Xi'an 710072, China
[b] AVIC Shaanxi Aero Electric Co., Ltd, Xi'an 710065, China

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ABSTRACT

Brushless wound-rotor synchronous starter-generator (WRSSG) is drawing more and more attentions in aircraft power system applications because of advantages such as high safety and low cost in maintenance. Detailed analysis and optimal start control research for the WRSSG system need an accurate and time-efficient integrated model of WRSSG. Because of the presence of the rotating rectifier, there is a complex nonlinear relationship between electrical variables of the brushless exciter and main generator in WRSSG, which makes the building of the integrated model a very tough work. In this paper, an improved Parametric Average Value Model (PAVM) of the rotating rectifier with coefficients varying with load impedance and load current was proposed, and coefficients of the improved PAVM were obtained from simulations of the detailed joint Voltage-Behind-Reactance (VBR) model of WRSSG. Based on the improved PAVM of the rotating rectifier, an integrated model of the WRSSG with a two-phase brushless exciter was proposed in classic state-variable formulation. Computer studies verified that the proposed integrated model of the WRSSG is sufficiently accurate in simulations of both steady and transient states, and it is very computationally efficient compared with detailed switching models.

1. Introduction

With the rapid development of the More-Electric Aircraft (MEA), integrated starter-generator (ISG) with less volume and weight is drawing more and more attentions in aircraft power system applications [1,2]. Because the wound-rotor synchronous machine (WRSM) with a brushless exciter has advantages of high safety (possibility of canceling of the field current in case of short-circuit and overhigh voltage in the generation mode) and low cost in maintenance (without brush and slip ring), it becomes an attractive candidate for ISG in aircrafts [2,3].

Detailed analysis and optimal start control research for the brushless wound-rotor synchronous starter-generator (WRSSG) need an accurate and time-efficient model of the WRSM. A typical WRSSG with a two-phase brushless exciter [3,4], as illustrated in Fig. 1, contains a brushless Exciter with two-phase field winding, a rotating diode rectifier and a Main Generator (MG). Rotors of the Exciter and the MG are in the same shaft, and the Exciter supplies field current for the MG through the rotating rectifier. So there is a complicated mechanical and electromagnetic coupling between the Exciter and the MG. Separate modelling and analysis for the Exciter and the MG failed to take the coupling into consideration, and made the analysis of the whole ISG system imprecise.

Integrated model of the brushless WRSSG considers the system as a whole, and it helps to explore the start control method and finally obtain collaborative optimal control for the WRSSG in a system perspective. However, due to the presence of the rotating rectifier, there is a complex nonlinear relationship between electrical variables of the Exciter and the MG, which makes the building of the integrated model of the brushless WRSSG a very tough work. So how to deal with the rotating rectifier is the first and important step to be considered in order to obtain the integrated model.

Traditional *dq* models of electric machines, taking voltages as inputs and currents as outputs for both the rotor and stator, cannot be interfaced with power electronics circuits (the rotating rectifier in this research) directly. Several solutions have been proposed to deal with this interface problem. In [5], the current output signals were converted into current sources, which can be connected with power electronics circuits directly. However, a fictitious load was added to the current sources to make the circuit a closed loop, and it may affect the model accuracy. In [6], coupled-circuit phase domain machine models were suggested in order to simplify the machine model–circuit interface, but a time-varying inductance matrix was used in the machine model, which made the model complicated. In [7–11], the Voltage-Behind-

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[*] Corresponding author.
E-mail address: jiaoningfei@gmail.com (N. Jiao).

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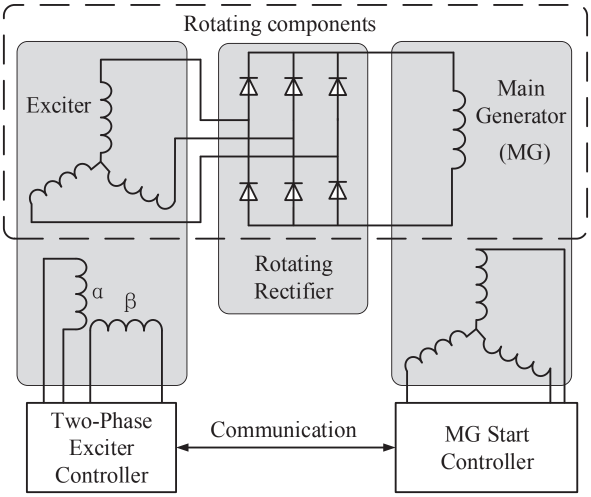

Fig. 1. Structure diagram of the wound-rotor synchronous starter-generator with a two-phase Exciter.

Reactance (VBR) models of synchronous machines and induction machines, which can be directly interfaced with power electronics circuits, were proposed, and the VBR-Converter model was proven to have high simulation accuracy. In all of the above models, the diode rectifiers were represented by actual power electronic circuits, so these models were all time-consuming in simulations as the power electronics needed to be turned on and turned off all the time.

A state machine model of the excitation system, including the brushless Exciter and the rotating rectifier, was proposed in [12], and it gave a detailed description of the currents in the Exciter rotor windings and the rotating rectifier. However, modelling of the excitation system based on state machine is quite a laborious task, and finding a stable method to commutate between states is challenging. Average Value Models (AVMs) of the diode rectifier, wherein the effects of fast switching are “neglected” or “averaged” within a prototypical switching interval, are computationally efficient in simulations [13–19]. Development methods for the AVM of a rectifier can be classified into two categories: analytical derivation [13–15] and parametric approach [16–19]. In analytical derivation methods, the voltage and current equations of the system are derived mathematically in every single switching pattern or operational mode, so the derivation process is pretty challenging. And many analytical AVMs end up with implicit nonlinear equations in the final model, which need to be solved numerically [13,15]. In parametric-AVM (PAVM) methods, the input variables and output variables of the rectifier are related through explicit algebraic parametric functions with coefficients obtained from simulations of the system detailed switching model numerically [16–19]. The PAVM of a rectifier can be obtained easily and it has been proven to be accurate sufficiently both in steady and transient states. Besides, in the PAVM, the relationship between the input and output variables of the rectifier is given in a straightforward manner. So the PAVM can be easily used to connect the variables in the exciter side with the variables in the MG side in the integrated-modelling of the WRSSG.

In [16], the coefficients in the PAVM were constant and not dependent on operating conditions, which may result in significant errors in simulation results as shown in [17]. The PAVM presented in [16] was improved in [17] with variable coefficients which were dependent on operational conditions. However, in [17], these variable coefficients were only dependent on load impedance, and load currents of the rectifier were not considered. Neglecting the dependence on the load currents may also result in simulation errors, as will be shown in this paper. So improved PAVM of the rectifier with variable coefficients dependent on both load impedance and load current was proposed in this paper.

Inspired by the PAVM of the diode rectifier, in this paper, an integrated model of brushless WRSSG with two-phase Exciter was proposed based on the improved PAVM of the rotating rectifier. Detailed joint VBR model of the WRSSG was first built, and then the improved PAVM of the rotating rectifier was obtained using coefficients acquired from simulation of the detailed joint VBR model. Using the improved PAVM of the rotating rectifier as the bridge, voltage equations and flux linkage equations of the Exciter and MG on the rotor sides were connected. Finally, a five-order integrated model of the WRSSG in classic state-variable formulation was obtained with stator currents of the Exciter, stator currents and rotor current of the MG as the state variables. Computer studies showed that the proposed integrated model of the WRSSG is sufficiently accurate in simulations of both steady and transient states, and it is very computationally efficient compared with detailed switching models.

2. Detailed joint VBR model of brushless WRSSG

Before the development of the PAVM for the rotating rectifier, detailed switching model of the WRSSG needs to be built and simulated to acquire necessary data. In this paper, the VBR models of the Exciter and the MG were first built in order to be interfaced with the rotating rectifier directly. As the rotating rectifier is in the rotor part, both the VBR models of the Exciter and the MG were derived in the rotor side, and the stator equations were in the traditional dq reference frame. Then, the detailed joint VBR model of the WRSSG can be obtained by connecting the VBR models of the Exciter and MG through the rotating rectifier represented by actual power electronics circuit.

2.1. VBR model of the two-phase Exciter

The voltage equations and flux linkage equations of the two-phase Exciter in the rotor reference frame are shown in (1) and (2), respectively. For convenience, all stator variables and parameters of the Exciter are referred to the rotor side by appropriate turns ratio.

$$\begin{aligned} u_{eds} &= r_{es} i_{eds} + p\lambda_{eds} - \omega_e \lambda_{eqs} \\ u_{eqs} &= r_{es} i_{eqs} + p\lambda_{eqs} + \omega_e \lambda_{eds} \\ u_{edr} &= r_{er} i_{edr} + p\lambda_{edr} - (\omega_e - \omega_{er})\lambda_{eqr} \\ u_{eqr} &= r_{er} i_{eqr} + p\lambda_{eqr} + (\omega_e - \omega_{er})\lambda_{edr} \end{aligned} \tag{1}$$

$$\begin{aligned} \lambda_{eds} &= L_{els} i_{eds} + \lambda_{emd} \\ \lambda_{eqs} &= L_{els} i_{eqs} + \lambda_{emq} \\ \lambda_{edr} &= L_{elr} i_{edr} + \lambda_{emd} \\ \lambda_{eqr} &= L_{elr} i_{eqr} + \lambda_{emq} \end{aligned} \tag{2}$$

$$\begin{aligned} \lambda_{emd} &= L_{eM}(i_{edr} + i_{eds}) \\ \lambda_{emq} &= L_{eM}(i_{eqr} + i_{eqs}) \end{aligned} \tag{3}$$

where u_{eds}, u_{eqs}, u_{edr}, and u_{eqr} are d-/q-axis stator and rotor voltages of the Exciter, respectively. i_{eds}, i_{eqs}, i_{edr}, and i_{eqr} are d-/q-axis stator and rotor currents of the Exciter, respectively. λ_{eds}, λ_{eqs}, λ_{edr}, and λ_{eqr} are d-/q-axis stator and rotor flux linkages of the Exciter, respectively. r_{es} and r_{er} are stator and rotor resistances of the Exciter. λ_{emd} and λ_{emq} are d-/q-axis magnetizing flux linkages of the Exciter. L_{els}, L_{elr}, and L_{eM} are stator leakage inductance, rotor leakage inductance, and magnetizing inductance of the Exciter, respectively. ω_{er} and ω_e are the rotor electrical angular velocity and the angular frequency of stator voltage of the Exciter, respectively. p is the derivative operator. In order to be distinguished from variables and parameters of MG, all variables and parameters of the Exciter are indicated with subscript ‘*e*’.

Referring to the derivation method for the VBR model of an induction machine in [10], the VBR model of the two-phase Exciter was derived as shown below. Unlike the VBR model of the induction machine in [10], in the VBR model of the two-phase Exciter, the rotor is