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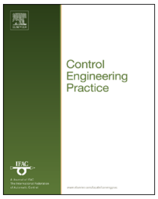

Hedge-algebra-based voltage controller for a self-excited induction generator

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ABSTRACT

This paper presents an indirect rotor-flux-oriented (IRFO) control system of the self-excited induction generator (SEIG) in which excitation is achieved by means of a current-controlled voltage source inverter (CC-VSI) and a single electrolytic capacitor. In the proposed control scheme, both the iron losses and the magnetic saturation are taken into account and calculated online. The main objective is to keep the DC voltage across the capacitor constant and equal to the reference value, regardless of changes in the rotor speed and load. The study is mainly focused on the DC voltage control and, more specifically, on selection of the appropriate DC voltage controller. Besides considering widely accepted types of controllers, i.e., the classical PI controller and the fuzzy logic (FL) controller, this paper proposes an alternative solution – a new type of DC voltage controller based on hedge algebra. To our best knowledge, this is the first time that such a controller is considered for application in electrical engineering. The performance of the developed hedge algebra (HA) controller is evaluated through comparison with the optimal-tuned classical PI controller and the Sugeno-type FL controller. The simulation and experimental analysis are carried out in reasonably wide ranges of the DC voltage, load and rotor speed, including the case of a variable rotor speed. It is shown that the proposed HA controller provides superior performance in terms of tracking the reference DC voltage value as well as robustness to speed and load disturbances in the system.

1. Introduction

Squirrel-cage induction generators are known to have many advantages over other types of electric generators, such as brushless construction, reduced size and cost per kW, ability to excite without an external power source, self-protection against short circuits and overloads, etc. This has led to their increased application in stand-alone power generating systems, especially in those employing wind or hydro energy. The ability of squirrel-cage induction generators to self-excite was discovered in the 1930s (Basset & Potter, 1935; Wagner, 1939), however the widespread application of self-excited induction generators (SEIGs) was for a long time hampered by the problems related with variable frequency and amplitude of the generated voltage. Namely, they both vary with the speed of the prime mover, the excitation capacitance, the machine's parameters and the connected load. Only recent developments made in the field of control engineering, spurred by the advent of insulated-gate bipolar transistors (IGBTs) and microcontrollers in the 1980s, allowed overcoming these problems.

Today, vector control algorithms are dominantly applied in SEIG power generating systems, largely because of their superior dynamic control features compared to the scalar counterparts. Most of the SEIG vector control systems reported in literature employ classical PI controllers for voltage and/or flux control (Idjdarene, Rekioua, Rekioua, & Tounzi, 2008; Leidhold, Garcia, & Valla, 2002; Liao & Levi, 1998; Margato, Faria, Resende, & Palma, 2011), which is mainly because of the inherent simple design and application, and mostly satisfactory performance in the operating range of interest. More advanced controllers, such as those based on the fuzzy logic or artificial neural networks, have also been considered, but mainly for the efficiency optimization purposes (Hilloowala & Sharaf, 1996; Vukadinović & Bašić, 2011).

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Unfortunately, advantages that such controllers have over the classical PI controller are always to some extent diminished and sometimes even outmatched by their drawbacks. For instance, it is often pointed out that fuzzy-logic (FL) controllers do not require knowledge of a detailed mathematical model of the control system and allow a more intuitive approach to design compared to the PI controller because the fuzzy sets used in fuzzy control aim to capture the semantics of natural linguistic terms present in the fuzzy controller knowledge. In addition, they have the capability of handling uncertain and noisy signals, and usually lead to better results compared to the classical PI controller in terms of response time, settling time and robustness (Zurada, Marks, & Robinson, 1994). On the down side, all this is achieved at the expense of a substantial increase in the computational requirements compared to the classical PI controller, whereas the design process itself usually relies on the expert knowledge of the control system. The latter observation stems from the fact that the there is no formalized linkage of the fuzzy sets with the natural linguistic term semantics, so, in practice, this linkage is established by the fuzzy controller designers in their intuitive manner. This drawback limits not only the ability of fuzzy sets in modeling natural language, e.g., they do not preserve the inherent order relationships between terms, but also the performance of the designed controllers. An emphasis should be made on the fact that when formulating the fuzzy rule based knowledge of fuzzy controllers, human experts must utilize the order relationships between the terms of interest.

Hedge algebras were developed by Nguyen and Wechler (1990) to model the order-based semantics of the terms in term-domains of linguistic variables. Then, the fuzzy rules can be viewed as to define points in a Cartesian product of suitable hedge algebras, and approximate reasoning method on the controller knowledge can be transformed into an interpolation method on a real surface defined by these points by using fuzziness parameters values (Nguyen, Vu, & Le, 2008). Since this transformation is defined by Semantically Quantifying Mappings (SQMs) of hedge algebras, which may preserve the relations between the variables based on the order-based semantic of terms in the controller knowledge, the resulting surface can be considered as an appropriate mathematical model of the controller knowledge. So, hedge algebras may provide a sound formalized basis to develop effective new reasoning methods for a kind of controllers, called hedge algebra (HA) controllers.

In this paper, a new HA controller is developed and applied for control of the SEIG's generated voltage in the indirect rotor-flux-oriented (IRFO) control system. To our best knowledge, this is the first time that such a controller is considered for application in electrical engineering. The performance of the proposed HA controller is analyzed and evaluated both on the simulation and experimental level, by encompassing wide ranges of the DC voltage, load and rotor speed. Moreover, the case of a variable rotor speed is considered as it can be encountered in the SEIG control systems utilizing a variable-speed prime mover (e.g., variable-speed hydro or wind turbine). The performance of the proposed HA controller is compared with that of the classical PI and FL controllers. In the considered IRFO control system, both the iron losses and the magnetic saturation are taken into account and calculated online as proposed by Bašić and Vukadinović (2013), thus improving the control system's accuracy and reliability.

2. Vector control system of self-excited induction generator

Basic configuration of the proposed IRFO control system is shown in Fig. 1, with the main components as follows: the squirrel-cage induction generator (IG), the prime mover (fixed or variable speed), the IGBT power converter, the IRFO controller and the DC link. The battery in the DC link provides the initial voltage across the excitation capacitor C, which is required for initial excitation of the SEIG. As soon as the voltage across the excitation capacitor rises to a value higher than the battery voltage, the battery is automatically switched off by means of the diode connected in series. The resistive DC load R_{dc} is connected at the excitation capacitor terminals. The DC voltage control is achieved by adjusting the active and reactive power flow in the system, which is, in turn, achieved through control of the power converter switching pulses generated at the output of the hysteresis current controllers. The proposed control scheme requires measurement of the following variables: the rotor speed, the DC voltage and the stator phase currents – all three or, in the case of an isolated stator neutral, only two.

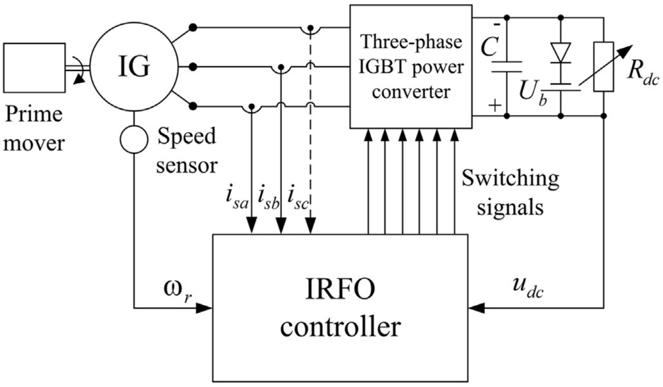

Fig. 1. Basic configuration of the SEIG vector control system.

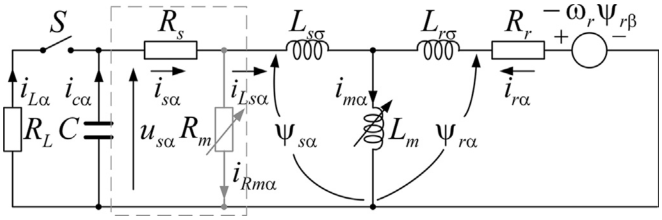

Fig. 2. SEIG equivalent circuit in the stationary reference frame (α-axis) including variable iron loss resistance.

The main objective of the control is to keep the DC voltage constant and equal to the reference value regardless of changes in the rotor speed and load. Such approach allows a DC load to be connected directly at the excitation capacitor terminals, as in this paper, or, alternatively, an AC load can be connected via an additional inverter. The equations of the control algorithm are derived from the equations of the advanced SEIG model proposed by Bašić, Vukadinović, & Petrović (2012). This particular model was selected because of its reported higher accuracy compared to the conventional SEIG model, in which the iron losses are omitted. In addition, the numerical stability and computational requirements of the selected model are shown to be satisfactory by Bašić et al. (2012).

2.1. Self-excited induction generator model

The equivalent circuit of the SEIG model is shown in Fig. 2. As it can be seen, it is suitable as such for applications where there is no system that regulates the terminal voltage, with the excitation capacitance and the resistive load being connected directly at the stator terminals. However, it can also be used as the starting point for design of the IRFO control system.

In Fig. 2, only the equivalent circuit for the α-axis of the stationary reference frame is given having in mind the fact that all the physical phenomena along the β-axis are analogous to those