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Magnetization of speed sensorless squirrel-cage induction generator for wind power application using a phase-locked loop

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ABSTRACT

The paper proposes a new method for magnetizing speed sensorless squirrel-cage induction generators used in wind power applications. These generators are magnetized at non-zero speeds, and for this reason, their successful magnetization is difficult to achieve. If the generator speed is not known, the required converter output frequency is also unknown and it is impossible to control the magnetization process by using the existing voltage-based flux estimation methods. This paper proposes a magnetization method which is based on a phase-locked loop (PLL) and ensures successful magnetization of the generator when voltage-based flux estimation methods are used. The proposed method is implemented in a digital control system and verified on a laboratory model using two different voltage-based flux estimation methods. The experimental tests carried out on a 560 kW squirrel-cage induction generator show the effectiveness of the proposed method.

1. Introduction

Wind power has nowadays become the most promising renewable energy source. Despite its exponential growth over the last decade, wind power still has great potential for future development based on ever increasing reliability and ever reducing costs in wind power generation. With the development of power electronics and control technology, the cost per kW of a power converter has lowered and a squirrel-cage induction generator (SCIG) with a full-scale power converter has become an attractive solution in variable-speed wind energy conversion systems (WECSs) [1,2]. Robustness, affordable price and low maintenance requirements as well as costs make the SCIG a prospective choice for wind generation. Moreover, recent research studies [3,4] show that the penetration of variable-speed WECS configurations with SCIGs and full-scale converters will increase significantly in the future. Although the use of an SCIG in wind power applications requires a gearbox which is considered to be a troublesome component in WECSs [5], the advantages of the robust, low price, low-voltage induction machine, which has been an industrial workhorse for the past few decades, have been recognized. The structure of a variable-speed WECS with an SCIG and a full-scale converter is shown in Fig. 1.

For the control of SCIGs, standard vector control techniques are used. However, according to the statistical data given in [5] sensor failures cause more than 14% of failures in wind power plants. So, with the aim of increasing the reliability of the plant as well as of reducing its overall cost, advanced sensorless control structures of SCIGs have been researched recently. An outstanding overview of the researched methods for induction machines is given in [6–10]. Although different solutions for the sensorless control of induction machines have been proposed in research studies [6–19], the magnetization at non-zero speeds of SCIGs has still remained a research challenge.

Magnetization is one of the key features of speed sensorless control of SCIGs used in wind power applications. Since in wind power applications SCIGs are magnetized at non-zero speed, achieving a completely controlled magnetization process with a successful outcome is a demanding task. The main problem is the unknown speed of the generator. If the generator speed is not known, the required converter output frequency is also unknown and it is impossible to control the magnetization process when the existing flux estimation methods are used. The experimental studies presented in this paper show that, if the q component of the stator current is kept at the zero value, the machine flux is built up only when the converter output frequency matches the rotor speed. Hence,

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Nomenclature

α, β	stationary reference frame components
d, q	synchronous reference frame components
*	reference value
γ	angle of stator current vector
ω_c	LPF cutoff frequency
ω_r	shaft angular frequency
ω_{sl}	slip angular frequency
ω_s	synchronous angular frequency
ψ_r	rotor flux magnitude
$\theta_{\psi r}$	angle of rotor flux linkage vector
$\theta_{\psi s}$	angle of stator flux linkage vector
θ_{PLL}	PLL generated rotor flux angle
$\boldsymbol{\psi_r}$	rotor flux linkage vector
$\boldsymbol{\psi_s}$	stator flux linkage vector
$\boldsymbol{emf}$	back emf vector
$\boldsymbol{i_r}$	rotor current vector
$\boldsymbol{i_s}$	stator current vector
$\boldsymbol{u_s}$	stator voltage vector
f_r	rotor speed frequency
f_s	synchronous frequency
k_p	proportional gain of PLL
k_{sg}	sawtooth generator gain
L_m	magnetizing inductance
L_s, L_r	stator and rotor total inductances
p	number of pole pairs
R_r	rotor resistance
R_s	stator resistance
T	integral time constant of PLL
T_e	electromagnetic torque
T_{PMSM}	measured torque supplied by PMSM
T_r	rotor time constant
T_{SCIG}	electromagnetic torque of SCIG
$\delta = \theta_{\psi r} - \theta_{PLL}$	error angle
$\sigma = 1 - L_m^2/(L_s L_r)$	leakage factor

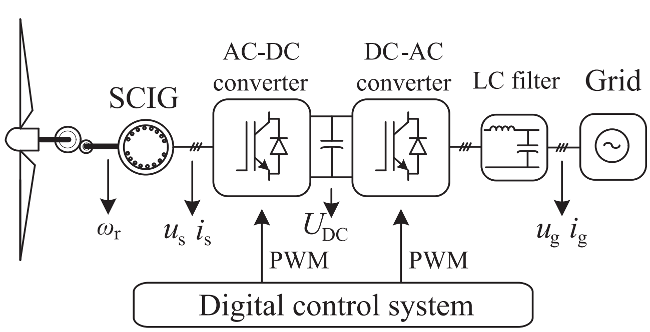

Fig. 1. Structure of the variable-speed WECS with SCIG.

in order to achieve a successful magnetization using voltage-based flux estimation methods, these methods have to be modified.

It is interesting to note that, although this subject matter is very attractive, little has been published about it [20–22]. The methods proposed in [20–22] require transient excitation of the machine or injection of the DC stator current component to identify the necessary speed without using a speed sensor. However, commercially available speed sensorless drives contain a flying start function and are thus able to determine the rotor speed of a non-magnetized induction machine during the start-up.

This paper deals with the magnetization of speed sensorless SCIGs used in wind power applications and proposes a new method for magnetization based on the PLL technique. Several research studies have recently focused on the application of the phase-locked loop (PLL) technique in sensorless control. In these studies, the PLL technique is used for the induction machine stator frequency estimation [23], the speed estimation of a doubly fed induction generator (DFIG) in a wind power system [24], in the control of grid-connected power converters [25,26], as a rotor position controller for the sensorless vector control of a permanent magnet synchronous machine (PMSM) [27], as flux observer for the direct torque control of surface-mounted PMSM drives [28], and for the sensorless speed control of a PMSG for wind power applications [29]. All studies concluded that the proposed PLL-based techniques are able to produce accurate results and are thus suitable for practical application.

In this paper, an experimental evaluation of a new PLL-based method for magnetization of the speed sensorless SCIG at non-zero speeds is presented. The proposed method uses a PLL-based rotor flux position controller which ensures successful magnetization of the SCIG when different flux estimation methods are used. The controller changes the output frequency of the converter to keep the q component of the rotor flux equal to zero. As a result, it not only ensures successful magnetization of the induction generator, but also improves the accuracy of the estimated rotor flux angle. The proposed method is implemented in a digital control system and verified through magnetization processes of a 560 kW SCIG.

2. Voltage-based flux estimation methods

The traditional solution for the rotor flux estimation in the sensorless vector control of induction machines are voltage-based flux estimators usually referred to as voltage model (VM) flux observers. They can be obtained from an induction machine model in the stationary reference frame expressed as follows:

$$\boldsymbol{u_s} = R_s \boldsymbol{i_s} + \frac{d\boldsymbol{\psi_s}}{dt} \tag{1}$$

$$0 = R_r \boldsymbol{i_r} + \frac{d\boldsymbol{\psi_r}}{dt} - j\omega_r \boldsymbol{\psi_r} \tag{2}$$

$$\boldsymbol{\psi_s} = L_s \boldsymbol{i_s} + L_m \boldsymbol{i_r} \tag{3}$$

$$\boldsymbol{\psi_r} = L_m \boldsymbol{i_s} + L_r \boldsymbol{i_r} \tag{4}$$

The electromagnetic torque of the induction machine can be computed from the vector product of the rotor flux linkage and the stator current as follows:

$$\boldsymbol{T_e} = \frac{3}{2}\frac{L_m}{L_r} p(\boldsymbol{\psi_r} \times \boldsymbol{i_s}) \tag{5}$$

The rotor flux is obtained from voltage-based flux estimator by using Eqs. (1), (3) and (4) as follows:

$$\boldsymbol{\psi_r} = \frac{L_r}{L_m}\left[\boldsymbol{emf}(t_0) + \int_{t_0}^{t} \boldsymbol{emf}(\tau) \cdot d\tau - \sigma \cdot L_s \boldsymbol{i_s}\right] \tag{6}$$

However, the implementation of a pure integrator in the digital system experiences certain difficulties. Pure integrators have DC drift and initial value problems [16,30] which are usually solved by replacing the pure integrator with a first-order low pass filter (LPF). Obviously, the LPF will produce errors in the magnitude and phase angle of the estimated flux and these errors will increase as the machine frequency approaches the LPF cutoff frequency. In order to solve the problems associated with pure integrators, numerous flux estimation methods have been proposed in the literature. Since our study focuses on magnetization, we do not present analyses and comparisons of different rotor flux estimation methods.

From various voltage-based estimation methods proposed in the literature [16,31–34], an LPF and an LPF with adaptive compensation have been chosen for the experimental verification of