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Flying start and sensorless control of permanent magnet wind power generator using induced voltage measurement and phase-locked loop

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ABSTRACT

This paper proposes a new method for the estimation of the rotor angle of interior permanent magnet generators used in wind power applications. The proposed method provides the flying restart and the continuous operation of permanent magnet generators. The paper addresses the problem of switching on the converter (start of the pulse-width modulation) when the generator rotates and the occurrence of inrush current if the converter is not synchronized with the generator. The proposed method is based on the induced voltage measured at generator terminals before switching on the generator converter and on a phase-locked loop with a proportional-integral position controller, which ensures the decoupled sensorless control of the permanent magnet generator. The simulation results show a comparison between the performances of the proposed method and the method based on the back-EMF. The proposed method is implemented in a digital control system and verified on a laboratory model. The experimental tests carried out on a 375 kW interior permanent magnet generator show the effectiveness of the proposed method.

1. Introduction

Permanent magnet generators (PMGs) provide a very acceptable solution for wind industry due to their high efficiency at all speeds and power density. Available solutions for the PMG in wind turbine systems are the low-speed direct driven solution and the high speed geared solution [1–4]. One of the structures of a variable-speed wind energy conversion system (WECS) with a PMG and a full-scale converter is shown in Fig. 1. For the control of PMGs, standard vector control techniques are used. To increase the reliability and availability, advanced sensorless control structures of PMGs have been researched recently.

A relevant overview of the methods researched to estimate rotor position is given in [5,6]. The rotor position estimation methods can be classified into model based methods, saliency based methods and artificial intelligence based methods. The model based methods can be further divided into nonadaptive and adaptive model based methods. The nonadaptive model based methods obtain the rotor position based on a permanent magnet machine model and the estimated flux or the back-EMF [7–9]. The main drawback of the back EMF method is inaccuracy at low speeds. However, a WECS will be only started when it reaches the cut-in speed, so the low-speed problem can be ignored, and the back-EMF method can be applied in the WECS. The adaptive model based methods are based on a comparison of the error between the measured output of a real machine and the calculated estimated output of a machine model and they adapt the parameters of the model with the aim to minimize the error between the real machine and the model. This group includes estimators based on a model reference adaptive system (MRAS) [10,11], sliding mode techniques [12–14], the Luenberger observer [15,16] and the extended Kalman filter [17–19]. Moreover, the saliency based methods are based on the tracking of machine saliency, and one of the approaches is to apply high frequency stator voltage or current component and evaluate effects of the machine anisotropy on the amplitude of the corresponding stator component [20–23]. Finally, the artificial intelligence based methods include neural network and fuzzy logic based systems, and can be robustly resistant to parameter variations [24,25].

However, algorithms described in scientific papers are commonly used to estimate the rotor angle of a synchronous motor when the machine is running from zero speed [26]. The specificity of the control of a PMG in a WECS is that before switching on the generator converter the rotor of the PMG rotates and induces a voltage at the terminals of the PMG that is proportional to the rotor speed. So, if the same algorithms are applied to the PMG in the case when the rotor rotates before switching on the generator converter,

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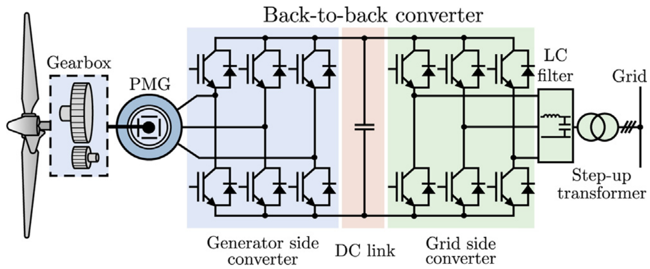

Fig. 1. Structure of a variable-speed WECS with a PMG.

the inrush current is inevitable. Therefore, before switching on the generator converter the control algorithm implemented in a digital system should determine the rotor angle, the rotor speed and the induced voltage at the terminals of the machine to minimize the inrush current. This process is referred to as synchronization of the converter and the generator. If any of these conditions is not met, the inrush current and impact of the mechanical torque occur. By using a position sensor before switching on the generator converter it is possible to determine the rotor angle and speed, and based on the measured speed it is possible to calculate the induced voltage. Without the position sensor these requirements represent a research challenge. An error in identifying the rotor position can cause large inrush currents at the beginning of the flying start process.

Furthermore, the inrush current and impact of the mechanical torque are higher if the stator resistance of the PMG is lower. Small power generators (several kW) have a higher stator resistance, hence the inrush current is reduced to an acceptable level. Nevertheless, due to the flying start request the aforementioned algorithms cannot be applied to large power generators because of the low stator resistance and accordingly, the large inrush current and the adverse mechanical torque impact.

Although different solutions for the sensorless control of PMGs have been proposed in research studies, little has been published on the sensorless flying start of PMGs [27–31]. An excellent review of the problem is given in [27] proposing a method for the flying start of high-inertia scalar controlled permanent magnet motors. The methods proposed in [27–31] are based on the application of zero-voltage pulses in order to estimate the rotor position and assume constant rotor speed between pulses. However, due to a short time interval between two zero-voltage pulses a position estimation error can occur. The methods proposed in [32–35] require injection of a high frequency current component to identify the rotor position. The injection based methods require a complex demodulation procedure, and an observer or a state filter to extract information on the rotor position. In addition to the complexity of the injection based algorithm, as presented in [36], the accuracy of the rotor position detection depends strongly on the saliency and the geometry of the rotor of the permanent magnet machine. The saturation and the *dq* cross-coupling effect significantly affect the accuracy of the injection based methods. Also, commercially available speed sensorless drives contain a flying start function of permanent magnet motors, but these methods usually include a position sensor.

This paper investigates the flying start of an interior PMG used in wind power applications and proposes a new method for the flying start and speed sensorless control of PMGs, which is easy for implementation in a digital control system, the computing is inexpensive and the method is suitable for industrial use in large power PMGs. The proposed method is based on the measuring of the induced generator voltage and on the phase-locked loop (PLL) technique. Several research papers have recently focused on the application of the PLL technique in sensorless control. In these studies, the PLL technique is used for magnetization of the speed sensorless squirrel-cage induction generator for wind power applications [37], the induction machine stator frequency estimation [38], the speed estimation of a doubly fed induction generator (DFIG) [39], in the control of grid-connected power converters [40–43], for FACTS devices [44], as a flux observer of surface-mounted permanent magnet motor drives [45], for the sensorless speed control of a PMG for wind power applications [46], and as a rotor position controller for the sensorless control of permanent magnet motors [47].

In [48], the operating principle and an analysis of the synchronous reference frame PLL (SRF-PLL) for grid-synchronisation is given. Under the unbalanced and distorted grid voltage condition, the SRF-PLL bandwidth should be reduced at a cost of lower dynamic performance [42], [43]. To overcome this problem, many different PLLs have been developed [48,49]. As proposed in [46,47], the PLL used for speed estimation of a PMG should be synchronised with the PMG voltage, i.e. the back-EMF. Since the back-EMF is the balanced sinusoidal voltage, a simplified SRF-PLL can be employed.

The flying start method of a PMG based on the induced generator voltage and a PLL has been proposed in [50]. However, continuous operation is not provided since the rotor angle is correctly estimated only under the no-load condition. In order to extend the proposed method to the continuous operation, the rotor angle estimation schemes proposed in [7,47], based on the estimated back-EMF, can be employed. In this paper, the flying start method based on the induced generator voltage is combined with the rotor angle estimation scheme based on the estimated magnetic flux. Compared to the methods reported in [7,47], the proposed estimation method is less dependent on machine parameters, it does not include derivatives which could amplify the noise in the measured signals and does not require estimated speed as an input signal.

Also, in this paper, an experimental evaluation of a new PLL-based method for the flying start and continuous operation of a speed sensorless PMG is presented. The proposed method uses a PLL-based proportional-integral (PI) position controller which ensures accurate rotor angle estimation of the PMG. The paper is organized as follows. The proposed method is described in Section 2, and the simulation results of the comparison between the proposed method and the back-EMF based method are given in Section 3. The implementation in a digital control system and the verification through experiments on a 375 kW PMG is described in Section 4 and conclusions are presented in Section 5.

2. Method proposed for rotor angle estimation

The measurement of the output voltage is usually not carried out in standard frequency converters, but the voltage of the machine is estimated based on the measured voltage of the DC link and the switching states of IGBTs in the converter. For the application of the proposed method which enables synchronization of the converter to the generator it is necessary to perform the measurement of the generator induced voltage before switching on the generator converter, i.e. prior to the start of the PWM. Prior to the start of the PWM in the pre-synchronization phase, the proposed method estimates the rotor angle based on the measured induced voltage and on the PLL based rotor position controller. When the rotor angle is detected, the synchronization phase can be performed, meaning that the PWM can be started. Subsequent to the synchronization phase the PLL position controller further estimates the rotor angle and thus allows continuous sensorless operation of the PMG.

2.1. Pre-synchronization phase

The structure for the determination of the rotor angle in the pre-synchronization phase is shown in Fig. 2. By using the Clarke transformation the measured line voltages of the PMG are trans-