Enhancing Grid Integration and Design of Low Speed PMSGs by Exploiting SRF-PLL-Based Sensorless Control and Holistic Modeling

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***Abstract*—This article proposes a holistic co-design framework with a low-cost approach for a permanent magnet synchronous generator (PMSG) that enables to optimizes both the electromagnetic and mechanical design, in conjunction with the injection of the maximum available power towards the power grid through a controlled electronic back-to-back converter. The proposed sensorless controller includes a hybrid PLL with a dynamically adjustable tabulated gains system and a feedforward frequency estimator. These add-ons allow to precisely track the speed and angle of the rotor shaft for near-zero speeds. This methodology includes the development of analytical models for the structural, magnetic and electrical components. The efficiency and performance of the machine and controller is verified by simulation under different load conditions and high angular speed variability of a 1.5 kW scale prototype in JMAG and Matlab & Simulink™ environments, reaching an efficiency of 80%.**

***Index Terms*—Back to back, mechanical design, phase locked loop, PMSG, wind turbine.**

I. Introduction

WIND power plants are rapidly growing around the world due to its economic, environmental and technological advantages [1]. In this context, permanent magnet synchronous generators (PMSGs) embedded in type-4 wind turbines (WTs) play an important role caused by its competitive strengths, including: gearless construction, elimination of DC excitation system, high power density, low noise, simple structure, low maintenance and full system control capability for maximum wind energy extraction with interface to the grid [2], [3].

On the other hand, low-power PMSGs generate electrical power from wind speed cut-in as low as 2.5 m/s, being enabled for operation in low wind speed regimes. Furthermore, the efficiency, reliability and lifetime of the electronic power converter are significantly boosted when the PMSG works at low wind speeds. Under these conditions, switching and conduction losses in the power converter decrease, improving overall efficiency by partially compensating the generator losses [4], [5].

According to the literature, the massive adoption of PMSGs-based WTs face with three major concerns: i) accurate and reliable estimation of the angular speed of the shaft, ii) the electromagnetic and electromechanical designs, and iii) the electronic power converter design for on-grid interconnection purposes [6], [7]. Most of the previous works are limited to analyze separately the mechanical design and the electronic converter, neglecting the advantages of the coupled design [3], [8], [9]. Optimal design approaches should integrate the requirements and constraints, including magnet, rotor and stator geometry; in conjunction with magnetic circuit analysis, novel materials, reduced volume and cost, and high efficiency. Meanwhile, the power converter stage has to deal with high variability of generation conditions, which cause fluctuations in amplitude and frequency [7], [10].

Power converter performance and the extraction of the maximum power generated by WTs depend significantly on the accurate estimation of the rotor at low speed [7], [11]. These measurements can be obtained by encoders or speed transducers. However, these mechanical sensors have a high failure rate, reducing the reliability of the system [12]. In recent years, several sensorless control approaches relying on observers and speed/position estimators have been proposed to avoid this problem [2], [3], [13]. Among these, PLL-based estimators stand out for their simplicity, ease of application and low computational burden. Despite their advantages, most PLLs adopt integral proportional controllers with fixed gains, constraining the bandwidth and dynamic behavior of the estimator. Furthermore, these systems are designed to operate at a fixed nominal frequency, representing a major challenge for its application in variable speed systems [2], [3].

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