Advanced Power Conditioning System for Grid Integration of Direct-driven PMSG Wind Turbines

Marcelo G. Molina
Member, IEEE
CONICET, Instituto de Energía Eléctrica – IEE,
Universidad Nacional de San Juan – UNSJ,
San Juan, Argentina
mgmolina@ieee.org

Euzeli C. dos Santos Jr.
Member, IEEE
Laboratório de Eletrônica Industrial,
Universidade Federal de Campina Grande – UFCG,
Campina Grande, Paraíba, Brazil
euzeli@cefetpb.edu.br

Mario Pacas
Senior Member, IEEE
Institute of Power Electronics and Electrical Drives – LEA,
Universität Siegen,
Siegen, Germany,
jmpacas@ieee.org

Abstract -- **The increasing use of distributed generation (DG), particularly based on wind power systems, requires new strategies for the operation and management of the power distribution system, especially with high installed capacity. Under this scenario, the power electronic technology plays an important role in the integration of DG into the electrical grid since the DG system is subject to requirements related not only to the renewable energy source itself but also to its effects on the power system operation. This paper proposes an improved structure of power conditioning system (PCS) for the effective grid integration of wind turbine generators (WTGs). The topology employed consists of a three-level Z-source cascaded inverter and allows the flexible, efficient and reliable generation of high quality electric power from the WTG system. A full detailed model is described and its control scheme is designed. Validation of models and control schemes is performed using the MATLAB/Simulink environment.**

Index Terms-- **Control techniques, detailed modeling, distributed generation, maximum power point tracking (MPPT), permanent magnet synchronous generator (PMSG), power conditioning system (PCS), three-level Z-source cascaded inverter, wind turbine generator (WTG).**

I. Introduction

In the past decade, many problems related to energy factors (oil crisis), ecological aspects (climatic change), electric demand (significant growth) and financial/regulatory restrictions of wholesale markets have arisen worldwide. Under these circumstances, distributed or dispersed generation (DG) arises as the technological alternative with the ability of giving an effective solution to such difficulties. Here it is promoted the growth of clean non-conventional generation technologies based on renewable energy sources (RES) that do not cause environmental pollution.

Medium to large grid-connected wind turbine generators (WTGs) are particularly becoming today the most important and fastest growing form of electricity generation among the renewable technologies. This trend is expected to be increased in the near future, sustained by the cost competitiveness of wind power technology and the development of new power electronics technologies, new circuit topologies and control strategies [1], [2].

The growing number of distributed generators, particularly based on wind power systems, brings new challenges to the operation and management of the power distribution system, especially when the intermittent energy source constitutes a significant part of the total system capacity. Under this scenario, the power electronic technology plays an important role in the integration of DG into the electrical grid since the DG system is subject to requirements related not only to the RES itself but also to its effects on the power system operation [3]. The use of power electronic converters enables wind turbines to operate at variable (or adjustable) speed, and thus permits to provide more effective power capture than the fixed-speed counterparts. In variable speed operation, a control system designed to extract maximum power from the wind turbine and to provide constant grid voltage and frequency is required. With the advance of power electronics technology, direct-driven permanent magnet synchronous generators (PMSG) have increasingly drawn more interests to wind turbine manufactures due to its advantages over other variable-speed wind turbines [4].

In recent years, numerous topologies of power conditioning systems (PCSs), varying in cost and complexity, have been developed for integrating PMSG wind turbine systems into the electric grid. In modern PMSG wind turbines designs, the PCS is typically built using a full-scale power converter made up of a two-stage power conversion hardware topology that meets all the constraints of high quality electric power, flexibility and reliability imposed for applications of modern distributed energy resources. This PCS design is composed of a back-to-back ac/dc/ac power converter that enables to control simultaneously and independently the active and reactive power flows exchange with the electric grid. In this respect, multi-level converters are increasingly preferred for medium- and high-power applications due to their ability to meet the increasing demand of power ratings and power quality associated with reduced harmonic distortion, lower electromagnetic interference, and higher efficiencies when compared with the conventional topologies [5].

This paper proposes an enhanced structure of PCS for an effective grid integration of direct-driven PMSG wind turbine systems, which is based on a simple arrangement that differs from the conventional proposals in the use of a novel single-stage power conversion topology. The converter employed corresponds to a three-phase three-level Z-source inverter and offers significant advantages respect conventional structures. A full detailed model is described and its control scheme is designed, comprising a full decoupled current control strategy in the *d-q* reference frame. The dynamic performance of the proposed models and control schemes is validated through digital simulations in MATLAB/Simulink.

II. Overview of the Wind Power System

Wind turbines can either be designed to operate at fixed speed (actually within a speed range about 1 %) or variable speed. Many low-power wind turbines built to-date were constructed according to the "Danish concept", in which wind energy is transformed into electrical energy using a simple squirrel-cage induction machine directly connected to a three-phase power grid. The rotor of the wind turbine is coupled to the generator shaft with a fixed-ratio gearbox. At any given operating point, this turbine has to be operated basically at constant speed. On the other hand, modern high-power wind turbines in the 3-5 MW range are mainly based on variable speed operation with blade pitch angle control by means of power electronic equipment. These wind turbines can be developed using either a direct-in-line system built with a direct-driven (without gearbox) PMSG grid-connected via a full-scale power converter, or a doubly-fed induction generator (DFIG) system that consists of a DFIG with a full-scale converter connected to the rotor windings.

Major advantages of variable speed generators (VSGs) compared to fixed speed counterparts include more effective power capture, cost-effectiveness, simple pitch control, lesser mechanical stress, improved power quality and system efficiency, reduced acoustic noise, and island-operation capability. Among VSGs, multi-pole PMSGs have increasingly drawn more interests to wind turbine manufactures due to the advantages in PMSG wind turbine integration with the electric grid. As the full scale power converter decouples entirely the generator system from the utility grid, grid codes such as fault ride through and grid support are easier to be accomplished. In addition, since a direct-in-line system can operate at low speeds, the gearbox can be omitted. Consequently, a gearless construction represents an efficient and robust solution that is beneficial, especially for offshore applications, where low maintenance requirements are essential. Moreover, due to the permanent magnet excitation of the generator, the dc excitation system is eliminated, again reducing weight, losses, costs, and maintenance requirements. Even more, due to the intensified grid codes around the world, PMSG wind turbines could be favored in future compared to FDGI wind turbine concepts.

The modeling approach of the proposed direct-in-line wind power system is based on the structure of Fig. 1. The wind power system consists of a variable speed wind turbine directly coupled to a PMSG and connected to the electric distribution grid through an original high-efficiency single-stage power conversion topology. This PCS design is composed of a back-to-back ac/dc/ac full power converter based on a novel single-stage power conversion topology that offers significant advantages with respect to standard arrangements previously described in the literature. The proposed PCS is composed of a three-phase rectifier bridge (ac/dc conversion), and a power inverter (dc/ac conversion) built using a three-phase three-level impedance-source (or impedance-fed) inverter design (aka Z-source inverter).

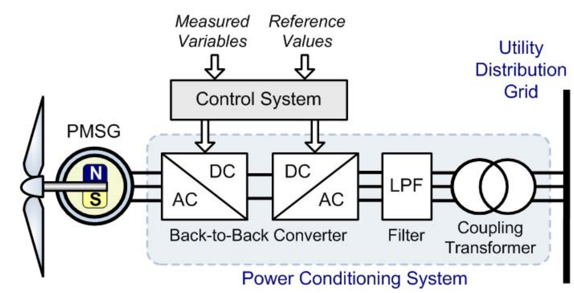

Fig. 1. General scheme of the proposed direct-driven PMSG wind turbine system connected to the utility distribution grid

III. Modeling of the Wind Power System

Fig. 2 summarizes the detailed model of the proposed wind power system employed as a DG for dynamic performance studies in distribution power systems.

A. *Wind Turbine*

The wind turbine employed in this work is a classic three-bladed horizontal-axis (main shaft) wind turbine design. This turbine was implemented and characterized using a laboratory-scale 0.5 kW rated power (at 12.5 m/s) prototype. Since the turbine corresponds to a small-scale one, no active blade pitch control is implemented and instead a self-regulation (passive stall control) through blades twisting is employed.

The proposed model is based on the steady-state aerodynamic power characteristics of the wind turbine. The