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).

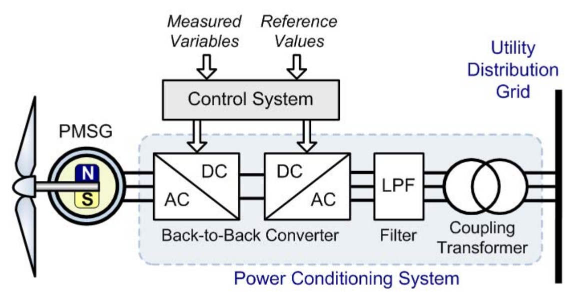


Fig. 1. General scheme of the proposed direct-driven PMSG wind turbine system connected to the utility distribution grid

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

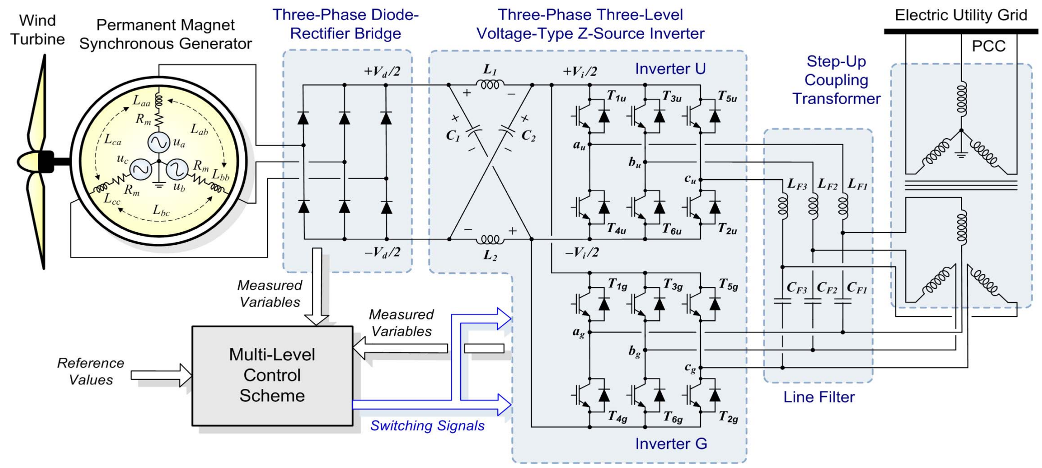


Fig. 2. Detailed model of the proposed direct-driven PMSG wind turbine system connected to the utility distribution grid

output mechanical power available from a variable speed wind turbine can be expressed through the following algebraic relation.

$$P_m = \frac{1}{2} \rho \, A \, v^3 \, C_p(\lambda, \beta) \ , \tag{1}$$

where:

ρ: air density (typically 1.225 kg/m^3 at sea level with standard conditions, i.e. temperature of 15 °C and atmospheric pressure of 101,325 kPa).

A: area swept by the rotor blades

v: wind speed

C_p: so-called power coefficient (aka coefficient of performance) of the wind turbine.

The power coefficient C_p is a nonlinear function of the blade pitch angle β and the tip-speed ratio λ as given by (2).

$$\lambda = \left(\frac{R \, \omega_m}{v} \right), \tag{2}$$

with:

R: radius of the turbine blades.

ω_m: angular speed of the turbine rotor.

As can be derived from (1), the power coefficient C_p is given in terms of the blade pitch angle β and the tip-speed ratio λ. Since the proposed wind turbine can operate over a wide range of rotor speeds, the assumption of linear torque versus speed characteristic (at a given wind speed and blade pitch angle) cannot be used and thus the aerodynamic system results very complex to be analytically determined. Consequently, numerical approximations have been developed in order to calculate the mechanical power characteristic of the implemented wind turbine and a bi-dimensional characteristic function of C_p has been used and validated in the laboratory [6].

$$C_p(\lambda, \beta) = \frac{1}{2} \left(\frac{98}{\lambda_i} - 0.4\beta - 5 \right) \exp\left(\frac{-16.5}{\lambda_i} \right), \tag{3}$$

with:

$$\lambda_i = \left[\frac{1}{(\lambda + 0.089)} - \frac{0.035}{(\beta^3 + 1)} \right]^{-1}, \tag{4}$$

The maximum value of C_p, that is C_{pmax}=0.47, is achieved for β=0º and λ=6.75. This specific value λ_{opt} results in the point of optimal efficiency where the maximum power is captured from wind by the wind turbine.

Fig. 3 illustrates the mechanical power versus the rotating speed of the proposed wind power system with no blade pitch angle control (β=0º) at various wind speeds. As can be derived, there exists a good agreement between the results obtained with both scaled laboratory prototype and the corresponding model. It can be also observed that, for each wind speed, there exists a specific point in the wind generator power characteristic, aka maximum power point (MPP), where the output power is maximized. Thus, the control of the wind turbine power results in a variable speed operation aiming at tracking the MPP for the particular operating conditions such that the maximum power can be continuously extracted from the wind (MPP tracking control or MPPT).

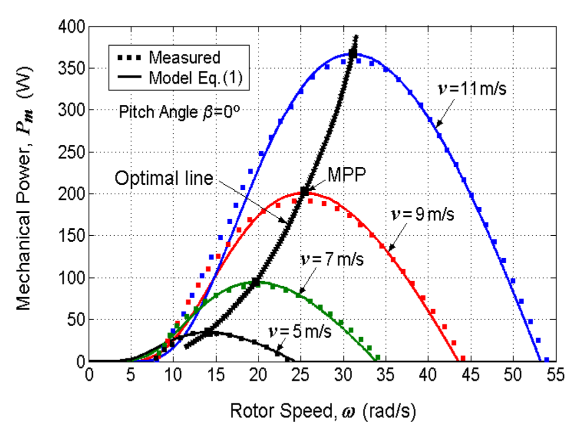


Fig. 3. Mechanical power vs. rotor speed curves measurements and simulations at various wind speeds for the studied wind turbine generator

The wind turbine rotor dynamics can be mechanically modeled using a single-mass lumped-parameter model that neglects the shaft dynamics, as expressed in (5). It should be noted that this is only allowed for variable speed wind turbines, because in this case the shaft properties are hardly reflected at the grid connection due to the decoupling effect of the power electronic converter.

$$T_e = T_l + B_f \omega_m + J_c \frac{d\omega_m}{dt}, \tag{5}$$

where:

T_l: load torque.

B_f: viscous friction coefficient.

J_c: inertia moment of the wind turbine rotor.

B. Power Conditioning System

The proposed PCS is composed of a back-to-back ac/dc/ac power converter that fulfills all the requirements of high quality electric power, flexibility, efficiency and reliability imposed to modern RES-based DG applications. Since the adjustable speed wind turbine is directly coupled to the synchronous generator, this later produces output voltages with variable amplitude and frequency. This condition demands the use of an extra conditioner to meet the amplitude and frequency requirements of the utility grid. A three-phase uncontrolled full-wave rectifier bridge is proposed here for performing the ac/dc conversion. This device has the benefit of being simple, robust, cheap, and needs no control system. On the other hand, a three-phase dc/ac voltage source inverter (VSI) using IGBTs is employed for connecting to the grid. The output voltage control of this VSI can be achieved through pulse width modulation (PWM) techniques. The connection to the utility grid is made through a step-up transformer and a low pass filter in order to reduce the perturbation on the distribution system from high-frequency switching harmonics generated by the PWM control. As the VSI needs a fixed dc link in order to allow a decoupled control of both active and reactive powers exchange with the electric grid, an interface in the dc side of the VSI is required. For this purpose, an intermediate dc/dc converter (or chopper) in a boost topology can be used [3], [7], thus allowing linking the output of the full-wave rectifier bridge to the dc bus of the inverter using only one switching device. This arrangement of rectifier-chopper allows replacing the conventional six-pulse voltage source inverter employed in the rectifier mode, while resulting in a lower cost and simpler control. This two-stage configuration represents a good solution in terms of greatly reducing the inverter current rating and hence the cost of the whole system. However, still retains some disadvantages when compared to single-stage topologies:

- Reduced power conversion efficiency: because of the two-stage configuration (dc/dc boost converter and dc/ac inverter), which inevitably reduces the power conversion efficiency.
- Reduced reliability: because more components are used in this configuration with the addition of the chopper.
- Higher volume and weight: the boost stage increases system size and weight because of the extra components used.

To overcome these problems, this paper proposed the use of a novel inverter topology capable of coping with the output voltage variation of the primary energy source and still preserving a fixed higher voltage dc link, all in one single-stage. This structure utilized to realize both inversion and boost function in a single stage is an impedance-source (or impedance-fed) power inverter (aka Z-source inverter) [8], and is shown in Fig. 2 (middle side). A unique impedance source (Z-source), consisting of a two-port network with a couple of inductors (or a split-inductor) and capacitors connected in X shape, is used for coupling the dc power source converter (the rectifier bridge output terminals in this case) to the standard three-phase inverter. In this way, with the proper design of the PWM scheme to the inverter, the voltage boosting (or bucking) function can be realized simultaneously and independently of the inverter operation, without affecting the voltage waveforms seen from the electric grid within a wide range of obtainable voltages.

The Z-source concept uses a modified PWM control technique based on introducing an additional switching state (or vector) to the eight states (six active and two null states) of the traditional three-phase voltage source inverter [9]. The traditional three-phase VSI has six active vectors when the dc voltage is applied to the load (coupling transformer to the electric grid in this case) and two zero vectors when the load terminals are shorted through either the lower or upper three IGBT devices, respectively. However, the three-phase Z-source inverter has one extra zero state when the load terminals are shorted through both the upper and lower devices of any one phase leg (i.e., both devices are switched on), any two phase legs, or all three phase legs. This shoot-through zero state provides the unique buck-boost feature to the inverter.

Without changing the total zero-state time interval, shoot-through zero states are evenly allocated into each phase, so that the active states (or non-shoot-through states) are unchanged. However, the equivalent dc link voltage to the inverter is boosted because of the shoot-through states. Mathematically, the boosted dc link average voltage V_i is related to the Z-source input dc average voltage in steady-state as follows:

$$V_i = \frac{1}{1 - 2\frac{T_0}{T}} V_d = \frac{1}{1 - 2D_0} V_d = B\,V_d, \tag{6}$$

where,

T_0: total shoot-through time interval.

T: switching period.

D_0: shoot-through duty ratio, $D_0 \in [0, 1-m_i]$.

B: boost factor, $B \in [1, \geq 1]$

The peak value V_{inv} of the phase-to-neutral output ac voltage for the Z-source VSI can be expressed through (7).

$$V_{inv} = m_i\, a\, B \frac{V_d}{2}, \tag{7}$$

where:

m_i: modulation index of the VSI, $m_i \in [0, 1]$.

$a = \frac{n_2}{n_1}$: turns ratio of the coupling transformer.

Clearly from (6) and (7), the inverter ac output voltage depends on both B and m_i, and can be boosted by increasing B above unity or stepped down by holding B at unity and decreasing m_i.

The Z-source inverter can be considered as an ideal sinusoidal voltage source shunt-connected to the electric system at the point of common coupling (PCC) through an equivalent inductance L_s, accounting for the leakage of the step-up coupling transformer and an equivalent series resistance R_s, representing the transformer winding resistance and VSI semiconductors conduction losses. The magnetizing inductance of the step-up transformer can also be taken into consideration through a mutual equivalent inductance M. Under the assumption that the three-phase system has no zero sequence components, all currents and voltages can be uniquely transformed into the synchronous-rotating dq reference frame. Thus, the new coordinate system is defined with the d-axis always coincident with the instantaneous voltage vector (v_d=|v|, v_q=0). As a result, the d-axis current component contributes to the instantaneous active power and the q-axis current component represents the instantaneous reactive power. Rotating reference frame is used because offers higher accuracy than stationary techniques.

The dynamics equations governing the instantaneous values of the three-phase output voltages in the ac side of the Z-source VSI and the current exchanged with the utility grid can be derived in the dq reference frame as follows:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_s - M} & \omega \\ -\omega & \frac{-R_s}{L_s - M} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \begin{bmatrix} \frac{|v|}{L_s - M} \\ 0 \end{bmatrix} \tag{8}$$

where,

$s = \frac{d}{dt}$: Laplace variable, defined for t > 0.

ω: synchronous angular speed of the grid voltage at the fundamental frequency.

Multi-level inverters have found extensive applications in the industry and to date are increasingly preferred for medium- and high-power applications due to their many inherent advantages, like 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 two-level topologies. Particularly, neutral point clamped (NPC) inverters are commonly the preferred topology for medium voltage ac drives, and have recently been explored for other low-voltage applications including grid-interfacing and high-speed drive. Despite their generally favorable output performance, NPC inverters suffer from the constraints of having additional clamping diodes and limited redundant switching states for equalizing switching losses among the semiconductor switches, besides the imbalance problems among the dc bus capacitors (neutral point balance complications) which gives rise to an unwanted waveform distortion. Therefore, to provide an effective multi-level topological alternative for the present Z-source inverter application, this work proposes the use of a modified three-level Z-source cascaded inverter implemented using two three-phase two-level inverter bridges and supplied by one uniquely design Z-source impedance network. These three-phase bridges are series connected (cascaded) at their ac outputs using three single-phase step-up coupling transformers to form a dual Z-source inverter, whose secondary terminals are wye connected [10]. This dual Z-source inverter with transformer isolation can be controlled using different modulation approaches due to the presence of various additional redundant switching states within a phase leg comparing to NPC or other topologies. Particularly, using a modified phase-shifted-carrier (PSC) PWM scheme with shoot-through states inserted, it is shown that the dual inverter can efficiently be implemented using only a single Z-source network, with a significant saving in cost, while still achieving the correct switching loss equalization among the semiconductor devices. In addition, smaller dc ripple currents are expected to flow into the three-phase bridges, as compared to those flowing into the single-phase H-bridges of a traditional cascaded inverter.

Within the dual inverter, each Z-source bridge is controlled to switch between shoot-through and nonshoot-through states with the former corresponding to the short-circuiting of a phase leg and the later corresponding to the eight switching states of a traditional inverter. Operating the bridges with an appropriate phase shift then gives rise to three distinct voltage levels, together with the upper and lower Z-source shoot-through conditions. A feature noted is that the output voltage of zero can effectively be generated by two redundant switch combinations, which in turn, can be used for equalizing switching losses among the semiconductor devices, and to achieve other advantages since they produce high-quality ac output waveforms that can either be stepped up or down. Furthermore, the proposed inverter topology with the appropriate control design allows simply reconfiguring their relevant gating signals so as to ride-through virtually all type of semiconductor failures with minimized waveform distortion, negligible drop in voltage amplitude, and elimination of common-mode voltage. This feature of semiconductors fault tolerance is very significant for modern applications of wind power systems.

IV. Proposed Control Strategy of the Wind Power System

The proposed multi-level control scheme for the grid-connected wind power system is depicted in Fig. 4. This control system consists of three distinct blocks with different hierarchies and their own control objectives, namely the external, middle and internal level. Various advance control approaches can typically be used in each control level whereas no alteration is needed for the other ones.

A. External Level Control

The external level control (left side of Fig. 4) is responsible for determining the active and reactive power exchange between the wind power system and the utility grid. The proposed external level control scheme is designed for performing simultaneously two major control objectives, that is the active power control mode (APCM) and the voltage control mode (VCM).

The VCM is designed for controlling (supporting and regulating) the voltage at the PCC of the VSI through the modulation of the reactive component of the output current (fundamental quadrature component, i_{q1}) [11]. To this aim, the magnitude of the voltage vector at the PCC (v_m) is compared to a voltage reference (v_r). An error signal is produced and then fed to a proportional-integral (PI) controller with a regulation droop R_d, which acts as a first-order lag-compensator (LC_1).

The main purpose of a grid-connected wind power system is to transfer the maximum wind generator power into the electric system. In this way, the APCM aims at matching the active power to be injected into the electric grid with the maximum instant power capable of being generated by the WTG. Maximum power point tracking means that the wind turbine is always supposed to be operated at maximum output voltage/current rating. From (3) and (4), the optimal rotational speed ω_{opt} of the wind turbine rotor for a given wind speed can be used to obtain the maximum turbine efficiency $\eta_{h\max}$ and then the maximum mechanical output power of the turbine. Unfortunately, measuring the wind flowing in the wind turbine rotor is difficult and increases complexity and costs to the DG application; so that to avoid using this measurement for determining the optimal rotor speed, an indirect approach needs to be implemented [7].

The proposed MPPT strategy is based on directly adjusting the shoot-through duty ratio of the casaded Z-source inverter and consequently the generator rotor speed, according to the result of the comparison of successive output power measurements. The control algorithm uses a "Perturbation and Observation" (P&O) iterative method widely used in photovoltaic systems with good results, and proves to be efficient in tracking the MPP of the wind turbine for a wide range of wind speeds. The algorithm has a simple structure and requires few measured variables. The WTG MPPT algorithm operates by constantly perturbing, i.e. increasing or decreasing, the rectified output voltage V_d at the present perturbation step k of the WTG (and thus controlling the rotational speed of the turbine rotor) via the Z-source inverter and comparing the actual output power $P_d(k)$ with the previous perturbation sample $P_d(k-1)$. If the power is increasing, the perturbation will continue in the same direction in the following cycle so that the rotor speed will be increased, otherwise the perturbation direction will be inverted. This means that the wind turbine output voltage is perturbed every iteration cycle k at sample intervals T_{trck}. Therefore, when the optimal rotational speed ω_{opt} for a specific wind speed is reached, the P&O algorithm will have tracked the MPP and then will settle at this point but with small oscillations.

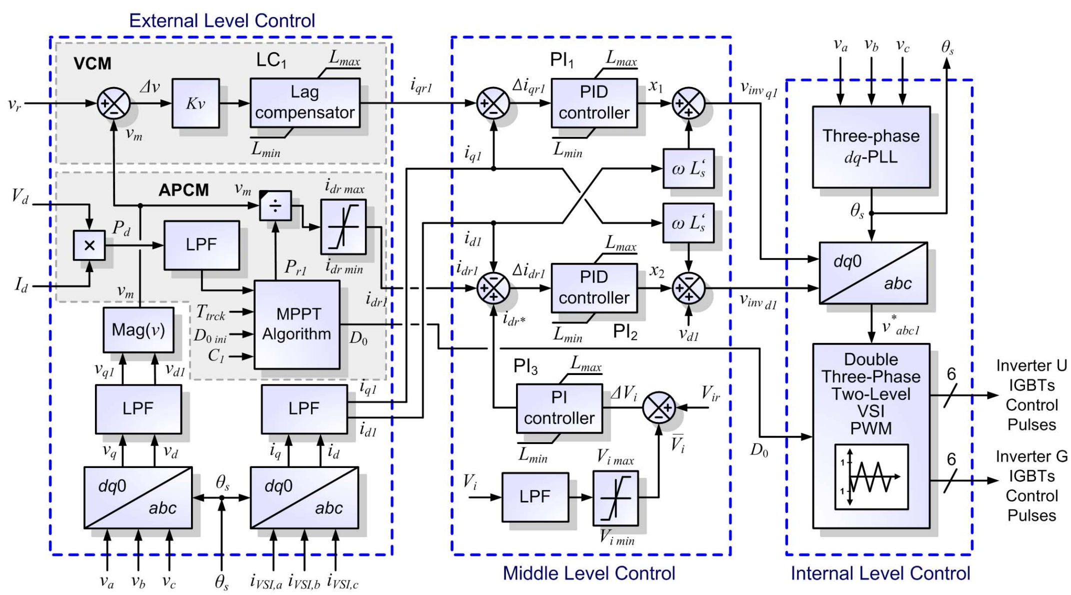


Fig. 4. Proposed multi-level control scheme for the three-phase grid-connected wind power system

B. Middle Level Control

The middle level control makes the expected output to dynamically track the reference values set by the external level (middle side of Fig. 4). In order to derive the control laws for this block, the state-space averaged mathematical model of the Z-source VSI in *d-q* coordinates described by (8) is employed. Inspection of (8) shows a cross-coupling of both components of the inverter output current (through ω). Therefore, in order to achieve a decoupled active and reactive power control, it is simply required to decouple the control of i_d and i_q. By using two conventional PI controllers (PI_1 and PI_2) with proper feedback of the inverter output current components i_{dI} and i_{qI} yields a resultant overall model with no crosscoupling of ω, as described in-detail in [12]. In addition, as also treated in [12], there exits an additional coupling from the dc link voltage V_i, as much in the dc side as in the ac side of the inverter. This problem demands to maintain the dc bus voltage as constant as possible, in order to decrease the influence of the dynamics of V_i. The solution to this problem is obtained by using a PI controller (PI_3) which eliminates the steady-state voltage variations at the dc link of the dual Z-source inverter, by forcing the instantaneous balance of power between the dc and the ac sides of the inverter through the contribution of a corrective signal i_{dr*}, and thus by the modulation index m_i.

C. Internal Level Control

The internal level (right side of Fig. 4) is responsible for generating the switching signals for the twelve IGBTs of the three-phase three-level dual Z-source inverter, using a carefully designed phase-shifted-carrier (PSC) PWM scheme based on [10]. Using this PSC approach, the carrier-reference comparison is first used to produce an appropriate state sequence for controlling the upper VSI bridge (labeled as inverter U in Fig. 4) in the dual inverter, while the negation of the references and the same carrier are compared to produce another sequence for driving the lower VSI bridge (labeled as inverter G). The generated sequences and resulting dual inverter output states are obtained by subtracting the bridge sequences, where it is observed that both VSI bridges request for the off state at the same time instant and for the same duration. This is important because the resulting dc link short-circuit caused by the inverter U will then not affect the voltage average of the inverter G connected to the same dc network. The combined dual inverter output then gives the correct voltage average with three-level switching and the appropriate off intervals inserted for buck/boost control.

This level is also mainly composed of a line synchronization module, which simply synchronizes the VSI PWM switching pulses with the positive sequence components of the ac voltage vector at the PCC using the phase θ_s of a phase locked loop (PLL). The design of the PLL is carried out using *dq* reference frame-based techniques.

V. Digital Simulation Results

In order to investigate the effectiveness of the proposed models and control algorithms, digital simulations were performed using SimPowerSystems of MATLAB/Simulink [13]. For validation of both control strategies, i.e. APCM and VCM of the wind power system, two sets of simulations were employed.

Simulations depicted in Fig. 5 show the case with only active power exchange with the utility grid, i.e. with just the APCM activated at all times, for the studied 0.5 kW WTG connected to a 380V/50Hz weak feeder. The incident wind flowing at the WTG rotor blades is forced to vary quickly in steps every 1s in the manner described in Fig. 5(a). This wind speed variation produces proportional changes in the maximum power that can be drawn from the WTG (MPP actual power shown in red dashed lines). As can also be observed in blue solid lines, the P&O maximum power tracking method proves to be accurate in following the MPP of the WTG with a settling time of almost 0.35 s. The trade-off between fast MPP tracking and power error in selecting the appropriate size of the perturbation step can notably be optimized in efficiency. As can be noted in Fig. 5(b), all the active power generated by the WTG is injected into the electric grid trough the PCS, except losses, with small delays in the dynamic response (blue dashed lines). It can also be seen the case with fixed voltage control of the rectified voltage V_d, i.e. with no MPPT control (T_0=0 at all times) and

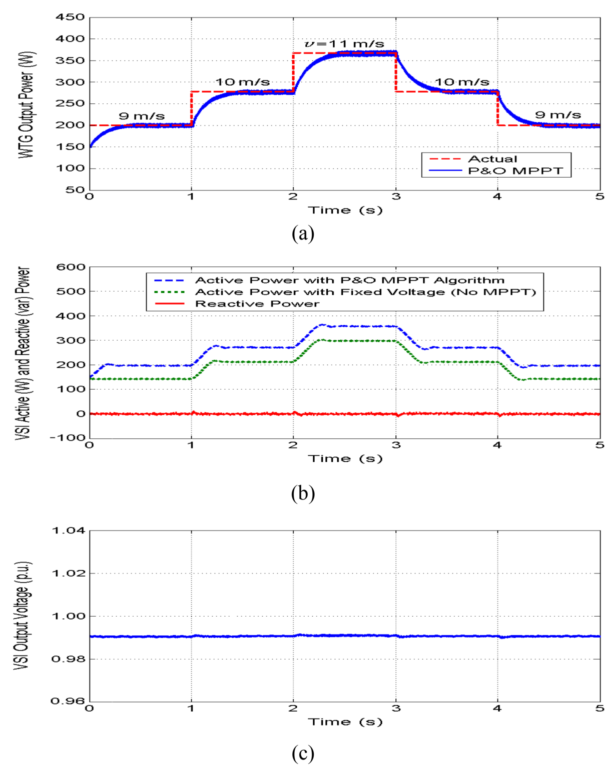
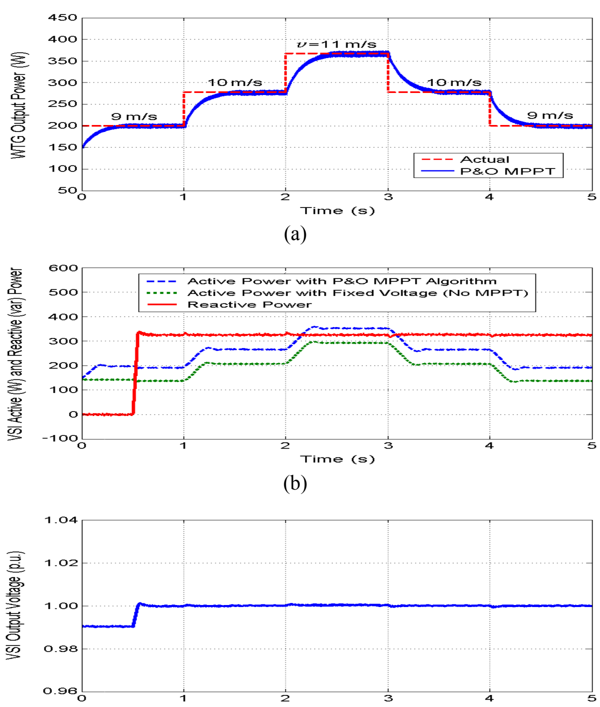


Fig. 5. Simulation results for active power exchange with the utility distribution grid (APCM)

consequently with near constant rotor speed operation (green dotted lines). In this case, the power injected into the electric grid is much lesser than with MPPT, about up to 30 % in some cases. Eventually, no reactive power is exchanged with the electric grid since the VCM is not activated (shown in red solid lines). In this way, as can be observed in Fig. 5(c), the instantaneous voltage at the point of coupling to the ac grid is maintained almost invariant at about 0.99 p.u. (per unit of 380 V base line-line voltage). It is also verified a very low transient coupling between the active and reactive (null in this case) powers exchanged by the grid-connected WTG due to the proposed full decoupled current control strategy in *d-q* coordinates.

Simulations of Fig. 6 show the case with both, active and reactive power exchange with the utility grid, i.e. the APCM is activated all the time while the VCM is activated at t=0.5 s. The WTG is now subjected to the same previous profile of wind speed variations, as described in Fig. 6(a). As can be seen, the maximum power for each wind speed condition is rapidly and accurately drawn by the P&O MPPT method in the same way as in the previous case study, as depicted in blue solid lines in Fig. 6(b). This power is injected into the electric grid (blue dashed lines), except losses. These losses are increased with the injection of reactive power, causing a slightly lower exchange of active power than the previous case studied with both controls of the Z-source inverter (with and without MPPT). As shown in Fig. 6(c), the rapid injection of almost 320 var of reactive capacitive power into



(a) (b) (c)

Fig. 6. Simulation results for simultaneous active and reactive power exchange with the utility distribution grid (APCM and VCM)

the electric utility system (red solid lines) when the VCM is activated aims at controlling the magnitude of the instantaneous voltage at the PCC around the reference voltage of 1 p.u. (or 380 V). Here it is also verified a very low transient coupling between the active and reactive powers injected into the ac grid due to the full decoupled current control strategy in the *d-q* reference frame.

VI. Conclusion

In this paper, an improved power conditioning system and the control strategy of a three-phase grid-connected direct-driven PMSG wind turbine system, incorporating a MPPT for dynamic active power generation jointly with reactive power compensation of distribution systems, has been presented. Simulation studies and experimental results demonstrate the effectiveness of the proposed detailed models and control approaches in *dq* reference frame. The fast response of power electronic devices and the enhanced performance of the control allow taking full advantage of the wind power system as a distributed generating system.

References

[1] S. Heier, *Grid Integration of Wind Energy Conversion Systems*, 2nd ed., United Kingdom: John Wiley & Sons, 2006.

[2] T. Ackermann, *Wind Power in Power Systems*, 1st ed., United Kingdom: John Wiley & Songs, 2005.

[3] J. M. Carrasco, L. Garcia-Franquelo, J. T. Bialasiewicz, E. Galván, R. C. Portillo, M. A. Martín, J. I. León, and N. Moreno, "Power electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. on Industrial Electronics*, vol. 53, no. 4, pp. 1002-16, 2006.

[4] S. Li, T. A. Haskew, E. Muljadi, and C. Serrentino, "Characteristic study of vector-controlled direct-driven permanent magnet synchronous generator in wind power generation," Electric Power Components and Systems, vol. 37, no. 10, pp. 1162-79, Oct. 2009.

[5] J. Rodriguez, J. S. Lai, F. Z. Peng, "Multilevel inverters: a survey of topologies, controls, and applications. *IEEE Trans. on Industrial Electronics*, vol. 49, no. 4, pp. 724-738, 2002.

[6] K. Raiambal, and C. Chellamuthu, "Modeling and Simulation of Grid Connected Wind Electric Generating System", in Proc. IEEE TENCON, India, pp.1847–1852, 2002.

[7] M. G. Molina, and P. E. Mercado, "A New Control Strategy of Variable Speed Wind Turbine Generator for Three-Phase Grid-Connected Applications", *in Proc. IEEE/PES Trans. & Distrib. LA*, Bogotá, Colombia, 2008.

[8] F. Z. Peng, "Z-Source Inverter," *IEEE Transactions on Industry Applications*, vol. 39, no. 2, pp. 504-510, March/April 2003.

[9] P. C. Loh, D. M. Vilathgamuwa, Y.S. Lai, G.T. Chua, and Y. Li, "Pulsewidth modulation of Z-source inverters," *IEEE Trans. Power Electronic,* vol. 20, pp. 1346-55, 2005.

[10] F. Gao, P. C. Loh, F. Blaabjerg, and D. M. Vilathgamuwa, "Performance Evaluation of Three-Level Z-Source Inverters Under Semiconductor-Failure Conditions," *IEEE Trans. on Industry Applications.*, vol. 45, no. 3, pp. 971-981 May/June 2009.

[11] M. G. Molina, and P. E. Mercado, "Control Design and Simulation of DSTATCOM with Energy Storage for Power Quality Improvements", *in Proc. IEEE/PES Trans. & Distrib. LA*, Caracas, Venezuela, 2006.

[12] M. G. Molina. *Dynamic Modelling and Control Design of Advanced Energy Storage for Power System Applications*, *Dynamic Modelling*, A. V. Brito (Ed.), 1st ed., Austria: Intech, 2010. [Online]. Available: http://sciyo.com/articles/show/title/dynamic-modelling-and-control-design-of-advanced-energy-storage-for-power-system-applications.

[13] The MathWorks Inc., "SimPowerSystems for use with Simulink: User´s Guide", 2010. [Online]. Available: http://www.mathworks.com.