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Experimental investigation on the performance of an autonomous wind energy conversion system

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ABSTRACT

Distributed generation seems to be a very interesting solution to provide electricity especially for the remote areas far from the electrical grid. In this paper, an autonomous wind energy conversion system and the control strategies applied to feed an isolated site were presented. A test bench was achieved in order to emulate the behaviour of a variable speed wind turbine connected to isolated loads. This study shows that the use of resonant controllers ensures the stability of the three-phase source supplying the loads which may be unbalanced and subjected to abrupt variations. A comparison between simulation and experimental results proves the effectiveness of the test bench and the control strategies implemented in real time.

1. Introduction

The environmental policies of many countries all over the world immensely contributed and contribute to the increase of the renewable energies use especially for producing electricity [1]. Among these renewable energies, the most promising one is the wind energy with a high level of interest because of its potential in electricity generation [2]. The technological progress in wind energy conversion system (WECS) equipments such as electrical machines, converters and power electronics allows the exploitation of the variable speed wind turbines (VSWTs) instead of those at fixed speed [3,4]. The use of power converters in a WECS gives the advantage of extracting the maximum power and controlling the energy transfer towards the network or an isolated site. This control offers the possibility to improve the generated power quality of a wind turbine [5–7].

Since huge wind farms are running to generate electricity for National Grids, another field of wind energy is also emerging. Stand-alone wind turbines offer a new tendency in producing electricity for remote locations or isolated sites where the connection to the grid should be very expensive and even impossible. However, in order to ensure a permanent electricity supply to the isolated site, it is necessary to associate an energy storage system (ESS) with the wind turbine. The essential role of the ESS is to remedy the wind fluctuation and then to ensure a balance between the unpredictable wind turbine power generation and the isolated site demand [8,9].

An autonomous WECS which will be able to accommodate all the requirements of an isolated site should have good performances and high stability [10]. These characteristics mainly depend on the applied control strategies. Many techniques were investigated in recent researches but most of them are intended for grid connected wind turbines. Ref. [11] presents a control strategy for extracting maximum power from a VSWT based on a permanent magnet synchronous generator (PMSG) with a diode bridge rectifier and a DC-to-DC boost converter. Refs. [12,13] illustrate the performance of the PMSG-based wind turbine with back-to-back converters in the grid interconnection. Ref. [5] considers that adding a flywheel energy storage system to the WECS can improve its performance for grid integration. Ref. [14] compares three power converter topologies used in WECS (matrix, two-level and multilevel) and shows that the use of the multilevel converter offers the best WECS performance.

Stand-alone wind turbines need more development with an aim to circumvent the constraints on which the power generation system is subjected. The most important constraint for a distributed source is the terminal voltage control which ensures the system stability and the permanent supply. Within this framework, the main purpose of this study is to experiment a control technique based on resonant controllers for the connection of a three-phase load to a VSWT. In order to reproduce the behaviour of a real VSWT, a test bench was assembled with two dSPACE 1104 cards ensuring the supervision of the experimental platform.

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Nomenclature

v_w	wind speed
λ	tip speed ratio
λ_{opt}	optimum value of the tip speed ratio
C_p	power coefficient
$C_{p_{max}}$	maximum value of the power coefficient
ρ	air density
R	blade radius
I_{aw}	DC motor armature current
E	electromotive force
k_ϕ	electromotive force coefficient of the DC motor
Ω	rotational speed
θ	angular position
R_s	stator winding resistance
L_s	stator winding inductance
p	number of pole pairs
V_{sd}, V_{sq}	d and q components of the stator voltages
I_{sd}, I_{sq}	d and q components of the stator currents
ϕ_m	permanent magnetic rotor flux
I_g	wind turbine generator current
I_{inv}	inverter input current
U_{dc}	DC bus voltage
R_t	filter resistance
L_t	filter inductance
C_t	filter capacitance
U_{m1}, U_{m2}	inverter voltages
U_{c1}, U_{c2}	line-to-line voltages
I_{t1}, I_{t2}, I_{t3}	inverter output currents
I_{L1}, I_{L2}, I_{L3}	load currents
R_{L1}, R_{L2}, R_{L3}	load resistances
L_{L1}, L_{L2}, L_{L3}	load inductances

The remainder of this paper is structured as follows. Section 2 presents a brief description of the test bench structure. Section 3 is devoted to the control strategies applied to each component of the experimental platform. Section 4 gives a comparative discussion between experimental and simulated results. Finally, some conclusions are summarized in Section 5.

2. Experimental platform description

The achieved test bench is based on a 3 kW DC motor driving a PMSG in order to emulate the behaviour of a VSWT. The PMSG is directly connected to a back-to-back converter. It consists of a force-commutated rectifier which ensures the maximum power point tracking (MPPT), a common DC bus and a force-commutated inverter. An LC filter is inserted after the inverter in order to attenuate switching harmonics as well as creating the sinusoidal voltage source for supplying the three-phase load [15]. Since the load power demand is variable and the generated power is unpredictable, a dump load is connected to the DC bus through a chopper. In the case of an overproduction, the excess of energy is diverted in the dump load and this is the case that will be considered in the trials.

The real time control of the test bench is ensured by two dSPACE 1104 cards with some interfaces for the data acquisition and the signal level adjustments [16,17].

The test bench parameters are given in the Appendix.

3. Experimental platform control

Fig. 1 shows an overview of the test bench architecture. This structure is divided into four levels. The first one gives the test bench configuration. The second one is dedicated for the data acquisition such as voltages, currents and rotational speed. The third level is devoted to the signal level adjustments in order to adapt the dSPACE input and output signals with the converters and sensor signals. The last level describes the control strategies applied on the test bench.

3.1. DC motor control strategy

The DC motor control is based on the armature current regulation. The reference of this current "I_{aw_ref}" is obtained from the electromagnetic torque "T_t" of the wind turbine model calculated in simulation as the following equations describe:

$$\begin{aligned} T_{em\_DCM} &= T_t \\ I_{aw\_ref} &= \tfrac{T_t}{K_\phi} \end{aligned} \quad (1)$$

with:

$$T_t = \frac{\rho \pi R^3 v_w^2 C_p}{2\lambda} \quad (2)$$

As depicted in the «DC motor control strategy» part of Fig. 1, the Proportional–Integral (PI) controller output and the electromotive force "E" give the supplying voltage of the DC motor armature "U". The ratio of this voltage to the nominal armature voltage "U_n" allows the determination of the duty cycle applied to the pulse width modulation (PWM) control signal driving the chopper. In order to adapt the PWM signal generated from the dSPACE card ($0 - 5V$) with the chopper driving signal ($\pm 15v$), a driver card is inserted.

3.2. PMSG control strategy

The PMSG control strategy is structured around two regulation loops of the d–q component stator currents "I_{sd}" and "I_{sq}". In practice, these currents are obtained from the Park transformation of the measured currents "I_a", "I_b" and "I_c". Two PI controllers are used to regulate the stator currents with respect to the reference currents "I_{sq_ref}" and "I_{sd_ref}". The vector control strategy applied to the PMSG imposes the following reference currents [4,18,19]:

$$\begin{cases} I_{sd\_ref} = 0 \\ I_{sq\_ref} = \frac{T_{em\_PMSG\_ref}}{p\phi_m} \end{cases} \quad (3)$$

with $T_{em\_PMSG\_ref}$ is the electromagnetic reference torque of the PMSG. In order to ensure the MPPT from the PMSG, this torque should have the following expression [18]:

$$T_{em\_PMSG\_ref} = \frac{\rho \pi R^5 C_{p_{max}}}{2\lambda_{opt}^3} \Omega^2 \quad (4)$$

After the regulation of the stator currents, the stator voltages "V_{sd}" and "V_{sq}", in the Park reference frame, are calculated according to the following equations [10,17]:

$$\begin{aligned} V_{sd} &= R_s I_{sd} + L_s \tfrac{dI_{sd}}{dt} - p\Omega L_s I_{sq} \\ V_{sq} &= R_s I_{sq} + L_s \tfrac{dI_{sq}}{dt} + p\Omega L_s I_{sd} + p\Omega \phi_m \end{aligned} \quad (5)$$

The inverse Park transformation of these voltages gives the three-phase voltages "V_a", "V_b" and "V_c". Three duty cycles are then determined to generate three PWM signals for the rectifier control.