Modeling and Control of Wind Power Conversion System with a Flywheel Energy Storage System and Compensation of Reactive Power

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Abstract- In this paper, a control of a variable speed wind generator (VSWG) system based on a doubly fed induction machine connected to the network associated to a flywheel energy storage system (FESS) is considered. The maximum power point tracking (MPPT) method, the independent control power of generator, the grid connection, and the control of flywheel energy storage system are studied. The flywheel energy storage system consists of a power electronic converter supplying a squirrel-cage induction machine coupled to a flywheel. This study investigates also, the possibility to compensate the reactive power. In order to validate the control method and to show the performances of the proposed system, its model is simulated for different operating points.

Keywords- MPPT, Doubly fed induction generator, Variable speed wind turbine, Independent power control, Flywheel energy storage system.

1. Introduction

Grid-connected wind power generation is the most effective way to develop the utilization of wind energy in large scale. While the renewable wind power generation brings important advantages for utilities and customers, some challenging issues associated with the interaction between wind turbine and power grid are continuously increasing. For example, the wind power quality brings adverse effect the economy operation of power grid, and the grid disturbance deteriorates the continuous running of grid-connected wind turbines. Some potentiality of regulation in wind turbines can be achieved due to the development of wind power generation technology. Over the last few years, doubly-fed inductive generator based wind turbines (DFIG WT) has been one of the mainstream type of wind turbines [6], it provides the cheapest solution to realize variable speed constant frequency (VSCF) operation with less converters size, flexible power control which the active and reactive power can be controlled independently, and higher efficiency of wind energy utilization in wide wind speed range. Due to the wind speed in most time are at low level, then the active power output of

DFIG WT is far less than its rated power, it is possible that the DFIG systems have large free margin of power capacity which can be used for reactive power adjustment. Normally the designing power factor of DFIG is range from capacitive 0.95 to inductive 0.95, currently many operators prefer unity power factor operation for the active power production is rewarded. Therefore the ability of reactive regulation in DFIG WT was not used sufficiently [1].

Among the drawback of wind energy is that is very fluctuant because of the random and intermittent wind nature. Despite that, the development of this type of production is remarkable.

Several studies [3, 4, 5] have been concentrated around the regulation of power produced to ensure the balance between production and consumption by exploiting the idea of storing energy .The operating principle is to store excess power under kinetic energy form in the flywheel. This latter energy is reconverted into the electrical form for use as a top up in case of deficit. FESS may thus be used as power regulators over short periods of time for electrical power quality improvement.

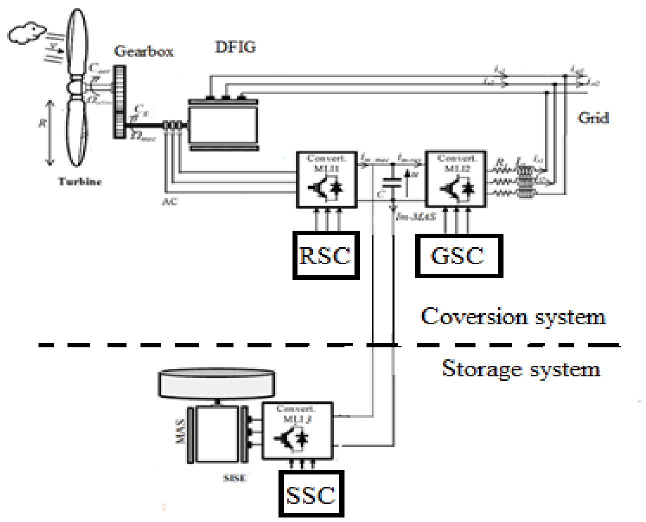


Fig. 1. Wind energy conversion and storage system (WECSS)

In order to analyze the behavior of VSWG associated to the FESS, the model of this global system is developed and simulated (fig.1).

The wind turbine, gearbox, DFIG, AC-DC-AC converter, grid connexion and FESS are modeled. The maximum power point tracking (MPPT) algorithm to maximize the generated power is presented.

In order to study the power transfer between the wind generator and the network, we applied a control independent power. The storage system considered in this study consists of an electronic converter; an induction machine which operates in flux weakening region and a flywheel. The field oriented control will be considered here for the induction machine.

2. Wind Conversion System

2.1. Wind Turbine Model

The turbine is characterized by its power coefficient C_p which is function of the tip speed ration and the pitch angle of specific wind turbine blades. In our case, it is given by the following mathematical approximation [12]:

$$C_p = 0.5 - 0.167.(\beta - 2).\sin\left[\frac{\pi.(\lambda + 0.1)}{18.5 - 0.3.(\beta - 2)}\right] - 0.00184.(\lambda - 3).(\beta - 2) \quad (1)$$

This relationship is shown on fig.2.

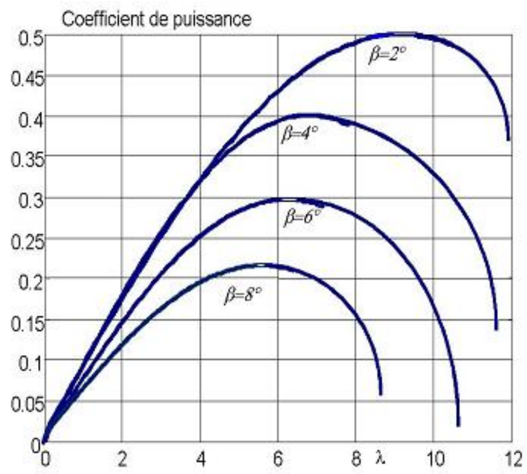


Fig. 2. Power coefficient [12]

This graph is a key element in the characterization of wind energy converters [10, 11]. The tip speed ration is dependent on the wind speed and the turbine angular velocity:

$$\lambda = \frac{\Omega_{turbine}.R}{\upsilon} \quad (2)$$

A power available on the shaft of the turbine is given by:

$$P_{aer} = C_p(\lambda, \beta).\frac{\rho.S.\upsilon^3}{2} \quad (3)$$

The turbine torque is given by:

$$C_{aer} = \frac{P_{aer}}{\Omega_{turbine}} = C_p.\frac{\rho.S.\upsilon^3}{2}.\frac{1}{\Omega_{turbine}} \quad (4)$$

The gearbox is modeled by these two equations:

$$C_g = \frac{C_{aer}}{G} \quad (5)$$

$$\Omega_{turbine} = \frac{\Omega_{mec}}{G} \quad (6)$$

It is clear that the power extracted from the wind is maximized when C_P is maximal. This optimal value of C_P occurs at a defined value of the tip speed ratio λ. For each wind speed, there is an optimum rotor speed where maximum power is extracted from the wind. Therefore, if wind speed is assumed to be constant, the value of C_P depends only on the rotor speed of the wind turbine. The variability of the output power from the wind generator implies that, without special interface measures, the turbine will often operate away from its maximum power point. The associated losses can be avoided by the use of maximum power point tracker (MPPT) which ensures that there is always maximum energy transfer from the wind turbine to the grid. In this paper we develop the MPPT algorithm named “Perturbation and Observation Method”. It is more accurate since it doesn’t need the turbine characteristic measurement,[6,7].

This algorithm can be summarizd by five several steps, which are:

1. Choose the initial reference rotor speed and measure the output power of the generator;

2. Increase or decrease the reference rotor speed by one step (Ω_{step}) and measure the output power again;

3. Calculate Sign (ΔP) and Sign ($\Delta\Omega$);

4. $\Omega_{ref}(n) = \Omega_{ref}(n-1) + \text{Sign}(\Delta P)\,\text{Sign}(\Delta\Omega)\,\Omega_{step}$;

5. Repeat from step 3 to reach optimum operating point.

2.2. DFIG Model

The electrical equations in the PARK reference frame are given by:

$$\begin{cases} V_{ds} = R_s I_{dr} + \dfrac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \dfrac{d}{dt}\psi_{qs} + \omega_s \psi_{ds} \end{cases} \tag{7}$$

$$\begin{cases} V_{dr} = R_r I_{dr} + \dfrac{d}{dt}\psi_{dr} - (\omega_s - \omega)\psi_{qr} \\ V_{qr} = R_r I_{qr} + \dfrac{d}{dt}\psi_{qr} + (\omega_s - \omega)\psi_{dr} \end{cases} \tag{8}$$

The stator and rotor flux are written as follows:

$$\begin{cases} \psi_{ds} = L_s I_{ds} + M_{sr} I_{dr} \\ \psi_{qs} = L_s I_{qs} + M_{sr} I_{qr} \end{cases} \tag{9}$$

$$\begin{cases} \psi_{dr} = L_r I_{dr} + M_{sr} I_{ds} \\ \psi_{qr} = L_r I_{qr} + M_{sr} I_{qs} \end{cases} \tag{10}$$

The electromagnetic torque is defined as:

$$C_{em} = P\left(\psi_{ds} I_{qs} - \psi_{qs} I_{ds}\right) \tag{11}$$

The active and reactive powers at the stator are defined as:

$$\begin{cases} P_s = V_{ds} I_{ds} + V_{qs} I_{qs} \\ Q_s = V_{qs} I_{ds} - V_{ds} I_{qs} \end{cases} \tag{12}$$

PWM are employed with each respective converter (three converters) in order to produce a controlled output voltage vector [19].

3. Conversion System Control

3.1. Rotor Side Converter Control

The control of rotor side converter is based on an active and reactive DFIG power control. It controls independently the active and reactive powers generated by the DFIG by controlling independently the rotor currents of the DFIG (Fig. 3). Rotor current vector components are controlled by controlling the inverter voltage vector.

A d-q reference frame synchronized with the stator flux is employed. By setting the quadratic component of the stator to the null value as follows:

$$\{\psi_{ds} = \psi_s \quad et \quad \psi_{qs} = 0 \tag{13}$$

Simplified expression of the electromagnetic torque is obtained:

$$C_{em} = -p\frac{M}{L_s}.\psi_s I_{qr} \tag{14}$$

Assuming that the resistance of the stator winding Rs is neglected, the voltage equations and the flux equations of the stator windings can be simplified in steady state as:

$$\begin{cases} V_{ds} = 0 \\ V_{qs} = \omega_s.\psi_s = V_s \end{cases} \tag{15}$$

$$\begin{cases} \psi_{ds} = \psi_s = L_s I_{ds} + M_{sr} I_{dr} \\ \psi_{qs} = 0 = L_s I_{qs} + M_{sr} I_{qr} \end{cases} \tag{16}$$

Since the stator voltage frequency is set by the grid, the rotor speed is deduced from:

$$\omega_r = \omega_s - P\Omega_{mec} \tag{17}$$

The angle θ_r is obtained by integrating the previous equation:

$$\theta_r = \theta_{r0} + \int_0^t \omega_r.dt \tag{18}$$

The stator active and reactive power and the rotor voltages can be written according to the rotor currents as:

$$\begin{cases} P_s = -V_s \dfrac{M_{sr}}{L_s} I_{qr} \\ Q_s = V_s \dfrac{\psi_s}{L_s} - V_s \dfrac{M_{sr}}{L_s} I_{dr} \end{cases} \tag{19}$$

$$\begin{cases} V_{dr} = R_r I_{dr} - g\omega_s \left(L_r - \dfrac{M_{sr}^2}{L_s}\right) I_{qr} \\ V_{qr} = R_r I_{qr} + g\omega_s \left(L_r - \dfrac{M_{sr}^2}{L_s}\right) I_{dr} + g\dfrac{M_{sr} V_s}{L_s} \end{cases} \tag{20}$$

Where g generator slip: $g = (\omega_s - \omega)/\omega_s$

3.2. Grid Side Converter Control (GSC)

The grid side converter is charged to regulate the direct current link voltage [13]. The grid-side reference frame is oriented and synchronized with the grid voltage vector. Resultantly, active and reactive power is independently controlled by independently controlling the grid current vector dq components (I_{td}, I_{tq}) [14]. Grid current vector components are controlled by the inverter voltage vector.

By looking fig.3, grid side converter control is based on three functionalities:

- DC bus control

The active power reference is derived from the DC bus voltage error. This power is obtained after being added to the active power which is necessary to charge the capacitor (to the desired value), the DFIG active power generated.

- Power control

The active and reactive powers exchanged with a grid can be expressed by:

$$P_t = v_{sd} i_{td} + v_{sq} i_{tq} \tag{21}$$

$$Q_t = v_{sq} i_{td} - v_{sd} i_{tq} \tag{22}$$

We can find the reference currents i_{td_ref}, i_{tq_ref}, which allows setting the desired reference active and reactive powers P_{t_ref}, Q_{t_ref}, as follows:

$$i_{td-ref} = \frac{P_{t-ref} v_{sd} + Q_{t-ref} v_{sq}}{v_{sd}^2 + v_{sq}^2} \tag{23}$$

$$i_{tq-ref} = \frac{P_{t-ref} v_{sq} - Q_{t-ref} v_{sd}}{v_{sd}^2 + v_{sq}^2} \tag{24}$$

In our case, the reference reactive power is chosen in order to study different operating mode where we can generate or absorb the reactive power (Q_{t_ref}<0 or Q_{t_ref} >0).

- Current control

Two fast PI current control loops are used to control the grid current vector dq components (i_{td}, i_{tq}) by using the synchronized reference with the grid voltage.

The electric equations of the filter (R_t, L_t) connected to the grid are given as:

$$V_{md} = R_t i_{td} + L_t \frac{di_{td}}{dt} - L_t \omega_s i_{tq} + v_{sd} \tag{25}$$

$$V_{mq} = R_t i_{tq} + L_t \frac{di_{tq}}{dt} + L_t \omega_s i_{td} + v_{sq} \tag{26}$$

The grid currents (i_{td}, i_{tq}) can be expressed by the following equations:

$$\frac{di_{td}}{dt} = \frac{1}{L_t}(V_{bd} - R_t i_{td}) \tag{27}$$

$$\frac{di_{tq}}{dt} = \frac{1}{L_t}(V_{bq} - R_t i_{tq}) \tag{28}$$

Where V_{bd} and V_{bq} are filter voltages in Park reference frame given by:

$$\begin{aligned} V_{bd} &= L_t \omega_s i_{tq} + v_{sd} \\ V_{bq} &= L_t \omega_s i_{td} + v_{sq} \end{aligned} \tag{29}$$

3.3. Storage System Control

The third controller which is charged to control the energy storage in the flywheel. It is designed to smooth wind power fluctuations by releasing or absorbing stored energy during wind speed fluctuations.

It is well known that the wind speed is fluctuant and, because of this, the wind generator delivers a variable electrical power. To overcome this drawback, an auxiliary energy storage system is to be installed in order to produce an additional energy and regulate the electric power delivered to the grid [2].

The reference active power applied to the FESS is obtained by:

$$P_{f-ref} = P_{g-ref} - P_{eol} \tag{30}$$

Where P_{g_ref} the reference grid active power and P_{eol} is the optimal power generated by the DFIG.

3.3.1. Induction machine model

The IM modeled in the Park reference frame [6,7], is described by:

$$\frac{d}{dt}\begin{pmatrix} \varphi_{rd} \\ \varphi_{rq} \\ i_{sd} \\ i_{sq} \end{pmatrix} = \begin{pmatrix} -\frac{R_{r-IM}}{L_{r-MAS}} & (\omega_s - p\Omega_f) & \frac{M.R_{r-IM}}{L_{r-IM}} & 0 \\ -(\omega_s - p\Omega_f) & -\frac{R_{r-IM}}{L_{r-IM}} & 0 & \frac{M.R_{r-IM}}{L_{r-IM}} \\ \frac{M.R_{r-IM}}{\sigma L_{s-IM} L_{r-IM}^2} & \frac{M.p\Omega_f}{\sigma L_{s-IM} L_{r-IM}} & -\frac{R_{sr}}{\sigma L_{s-IM}} & \omega_s \\ -\frac{M.p\Omega_f}{\sigma L_{s-IM} L_{r-IM}} & \frac{M.R_{r-IM}}{\sigma L_{s-IM} L_{r-IM}^2} & -\omega_s & -\frac{R_{sr}}{\sigma L_{s-IM}} \end{pmatrix} \begin{pmatrix} \varphi_{rd} \\ \varphi_{rq} \\ i_{sd} \\ i_{sq} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{\sigma L_{s-IM}} & 0 \\ 0 & \frac{1}{\sigma L_{s-IM}} \end{pmatrix} \begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} \tag{31}$$

The rotor flux oriented control is applied to the IM, the system (31) becomes:

$$\frac{d}{dt}\begin{pmatrix} \varphi_{rd} \\ i_{sd} \\ i_{sq} \end{pmatrix} = \begin{pmatrix} -\frac{R_{r-IM}}{L_{r-IM}} & \frac{M.R_{r-IM}}{L_{r-IM}} & 0 \\ \frac{M.R_{r-IM}}{\sigma L_{s-IM} L_{r-IM}^2} & -\frac{R_{sr}}{\sigma L_{s-IM}} & \omega \\ -\frac{M.p\Omega_f}{\sigma L_{s-IM} L_{r-IM}} & -\omega & -\frac{R_{sr}}{\sigma L_{s-IM}} \end{pmatrix} \begin{pmatrix} \varphi_{rd} \\ i_{sd} \\ i_{sq} \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ \frac{1}{\sigma L_{s-IM}} & 0 \\ 0 & \frac{1}{\sigma L_{s-IM}} \end{pmatrix} \begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} \tag{32}$$

The rotor-flux reference value can be computed using the flux weakening algorithm. It is determined by:

$$\varphi_{r-ref}(\Omega_f) = \begin{cases} \varphi_{rn} & \text{if } |\Omega_f| \le \Omega_{fn} \\ \varphi_{rn} \cdot \frac{\Omega_{fn}}{|\Omega_f|} & \text{if } |\Omega_f| > \Omega_{fn} \end{cases} \tag{33}$$

The reference power of the FESS, P_{f_ref}, must be limited to the rated value of the IM power in order to avoid the IM overheating.

The torque reference is given by:

$$T_{em-IM-ref} = \frac{P_{f-ref}}{\Omega_f} \quad (34)$$

The quadratic reference current becomes:

$$i_{sq-ref} = \frac{T_{em-IM-ref} . L_{r-IM}}{p.M.\varphi_{rd-ref}} \quad (35)$$

A complete RSC, GSC and SSC controller is depicted in Fig.3

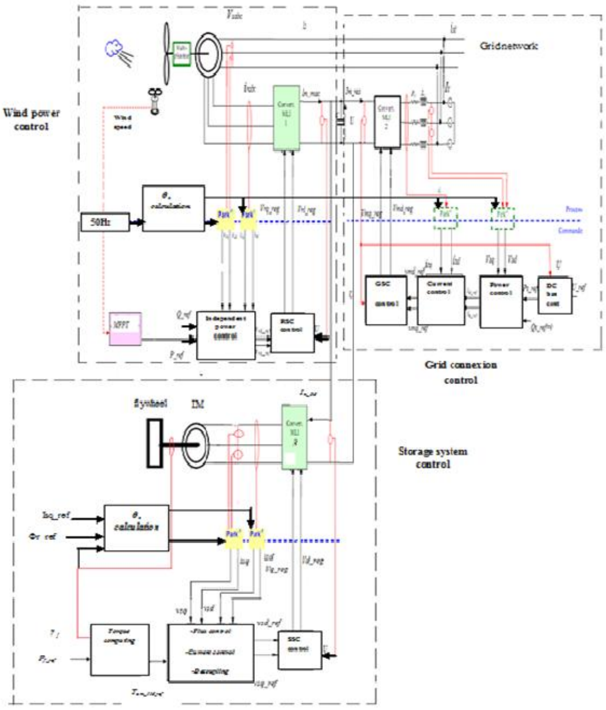


Fig. 3. A completed conversion system control schematic.

4. Simulation Results

To study the final control solution, both storage controller and the wind power conversion system have been tested and all simulations were carried out using Matlab/Simulink. The DFIG was rated at 1.5MW and its parameters are given in appendix.

The DC link voltage was set at 2000V and the capacitor is 4400µF.

The wind profile applied in all these simulations is given in figure 4.

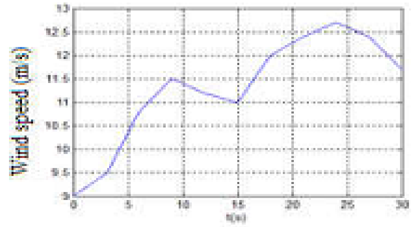


Fig. 4. Wind velocity

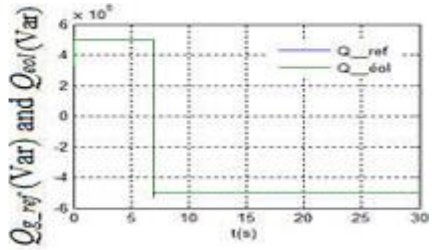


Fig. 5. Reference grid and DFIG reactive powers

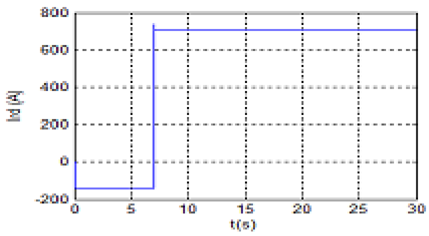


Fig. 6. Direct rotor current component

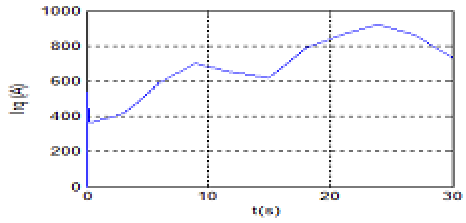


Fig. 7. Quadratic rotor current component

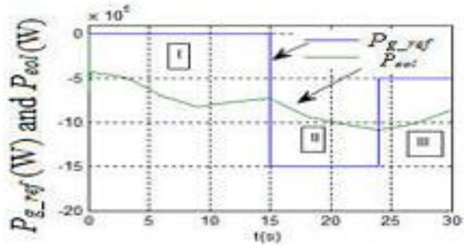
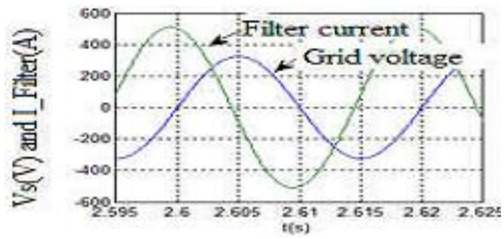
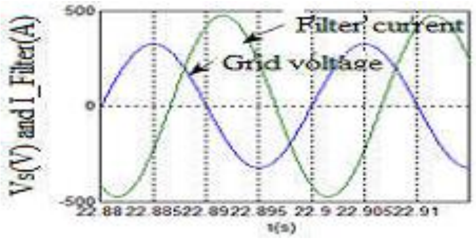


Fig. 8. Grid reference and DFIG active powers

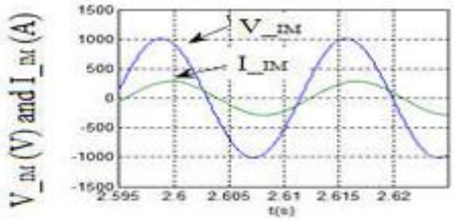


(a)

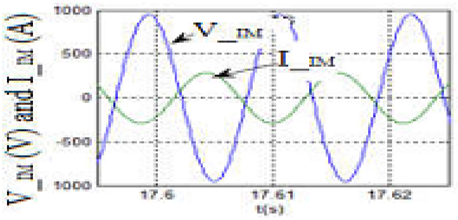


(b)

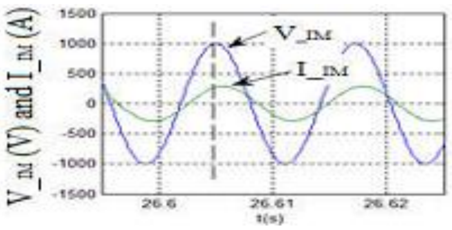
Fig. 9. (a) Grid voltage and filter current for Q>0, (b) Grid voltage and filter current for Q<0



(a)



(b)



(c)

Fig. 10. (A), (B) and (C) IM stator voltage and current corresponding respectively to regions I, II and III current

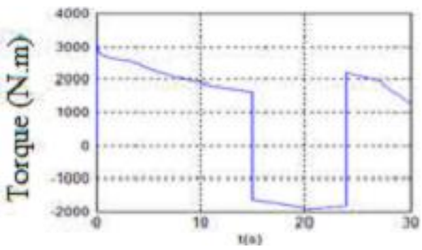


Fig. 11. IM electromagnetic torque

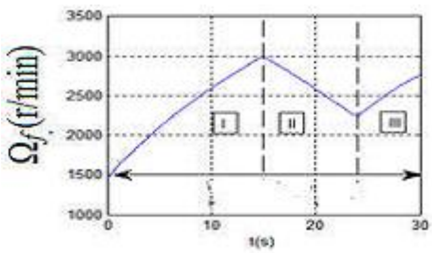


Fig. 12. FESS speed

The results shown here are for the conditions where reactive power reference changes from 0.5 to -0.5MVAR where we can study the possibility to generate or absorb the reactive power. The active power references are 0, -1.5 and -0.5MW respectively as shown in figures 8 and 5.

The figures 6 and 7 show the direct and quadratic rotor current components where we can see the concordance between the active power and quadratic rotor component on the one hand and the reactive power and direct rotor current on the other hand.

The conversion system operates in two operating modes. For Q>0, the grid voltage is advanced in phase comparing with a current filter wave form, which means that we absorb (the wind power generator) a reactive power. For Q<0, the system supplies the grid with reactive power, in fact, the current filter is in phase advanced (fig9.a and b). So, we can say that the compensation of reactive power is possible.

According to the reference active power applied in this study, the IM stator current and voltage wave form and these zoom are presented in figure 10.A-C. When $P_{g\_ref} < P_{\_eol}$, the IM operates in motor mode for storing the power gain. The FESS speed acceleration explains this case (fig12). Then, $P_{g\_ref} > P_{\_eol}$, the FESS speed start to decreasing which means that the IM operates in generator mode for covering the power deficit. Figure 11 presents the IM electromagnetic torque.

5. Conclusion

In this study, a control of a variable speed wind generator system based on a doubly fed induction generator connected to the network associated to a flywheel energy storage system is considered. Firstly, the doubly fed induction generator is modeled and simulated. A decoupled dq control is adopted for both GSC and RSC. In the second part, the FESS including an IM is proposed and studied.

In all DFIG operating modes, the machine supplies the grid with active power and compensates the reactive power. When $P_{g\_ref} < P_{\_eol}$ (in algebraic value), DFIG operates in super-synchronous and the FESS cover the deficit and the IM operates in generator mode. For $Pg_{\_ref} > P_{\_eol}$, DFIG operates in sub-synchronous and the FESS stores the energy surplus and the IM operates in motor mode.

The FESS associated to a VSWG is validated by simulation results.

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Appendix

Parameters

Blades number: 3, R=35.25 m, G=90, J (Turbine+DFIG) = 1000 g/m^2, ρ =1.22Kg/m^3, P_{DFIG}=1.5MW, R_s =0.012Ω, R_r =0.021Ω, M_{sr} =0.035 H, L_s =0.035+2.037.10^{-4} H, L_r =0.035+1.75.10^{-4} H, P=2, f=0.0024 N.m.s/rd, V_s=690V. IM and FESS parameters: v_s=690V, P_f =450kW, R_{s-IM} =0.051 Ω, R_{r-IM} =0.051 Ω, L_{s-IM} = 40.71.10^{-3} H, L_{r-IM} =40.71.10^{-3} H, M =40.1.10^{-3}H, p=2, f_v=0.008 N.m.s/rd, J_v =250 kg/m^2

Nomenclature

Turbine

$\Omega_{turbine}$: Turbine speed
Ω_{mec} : Generator chaft speed
υ : Wind velocity
R: Rotor radius.
ρ: Air density
S: Area swept by the blades.
C_g: Driven torque of the generator,
G: Gear ratio.

DFIG

V_{ds}, V_{qs}, V_{dr}, V_{qr}: Two-phase stator and rotor voltages
Ψ_{ds}, Ψ_{qs}, Ψ_{dr}, Ψ_{qr}: Two-phase stator and rotor fluxes
R_s, R_r: Stator and rotor phase resistances
L_s, L_r: Stator and rotor phase inductances
I_{ds}, I_{qs}, I_{dr}, I_{qr} : Two-phasestator and rotor currents
s: Generator slip
P: Number of pole pairs
f: Viscous friction

IM and flywheel

v_{sd}, v_{sq}: Two-phase stator voltages
φ_{rd}, φ_{rq}: Two-phase rotor fluxes
R_{s-IM}, R_{r-IM}: Stator and rotor phase resistances
L_{s-IM}, L_{r-IM}: Stator and rotor phase inductances
I_{sd}, i_{sq}: Two-phasestator and rotor currents
σ: Dispersion ratio
p: Number of pole pairs
Ω_f: FESS angular speed
φ_{rn}: Nominal rotor flux
Ω_{fn}: Nominal FESS speed
P_f: FESS active power
T_{em-IM} : FESS electromagnetic torque