Sliding Mode MPPT Control of a Dual Stator Induction Generator for Wind Power Generation

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Abstract

This paper proposes a robust sliding mode controller based on an indirect vector control of Dual stator Induction Generator (DSIG) for a variable speed wind integrated into the network. The main goal of this paper is to improve and to optimize the performances of power system using a wind energy conversion system based on DSIG. In first step, The modeling of variable-speed wind energy conversion system is presented. In second step, a field-oriented control of a DSIG is proposed. In the last step, in order to ensure an optimum operating point and a Maximum Power Point Track (MPPT) giving online a maximum production of electric power for different wind speeds, a sliding mode controller have been suggested . The efficiency and validity of the proposed control strategy are illustrated by simulation results.

Keywords: Dual stator Induction Generator, Variable Speed Wind Turbine, Three-phase converters, Field oriented control, Variable structure systems, Sliding control.

1. Introduction

With exhausting of traditional energy resources and increasing concern of environment, renewable and clean energy is attracting more attention over the last few decades to overcome the increasing power demand. Wind energy is one of the most important and promising source of renewable energy all over the world, mainly because it is considered to be nonpolluting and economically viable. At the same time there has been a rapid development of related wind energy technology [1], [2].An induction generator, with its lower maintenance demands and simplified controls, appears to be an effective solution for small hydro and wind power plants [3].

To increase the power rating of an AC drive system a multi-phase induction machine is seemed an ultimate solution. In fact the advantages of multi-phase drive systems over conventional three-phase drives are : the total rating of system is multiplied, the torque pulsations will be smoothed, reducing the rotor harmonic currents, reducing the current per phase without increasing the voltage per voltage, power segmentation and high reliability [3]. A common type of multi-phase machine is a dual stator induction machine (DSIM), also known as the six phase induction machine

However, a variable speed wind energy conversion system with the DSIG require both wide operating range of speed and fast torque response, regardless of any disturbances and uncertainties (turbine torque variation, parameters variation and un-modeled dynamics). This leads to more advanced control methods to meet the real demand [4].

The motivation of this work is to design a suitable control scheme to confront the uncertainties existed in the wind energy conversion systems based on DSIG. One of the possible approaches to the robust control of the uncertain systems has been found in variable structure systems and sliding mode control [5],[6].

The sliding mode controller has been suggested to achieve robust performance against parameter variations and load disturbances. It also offers a fast dynamic response, stable control system and easy hardware-software implementation.

On the other hand, this control method offers some drawbacks associated with the large torque chattering that appears in steady state. Chattering involves high-frequency control switching and may lead to excitation of unmodelled high frequency system dynamics. Chattering also causes high heat losses in electronic systems and undue wear in mechanical. In order to reduce the chattering phenomenon, a sign function is used.

The special merit of the suggested sliding mode controller is a): To search the optimum operating point for wind power generation in speed control mode. b) To improve the performance of wind energy conversion systems especially the power coefficient of the turbine and which allows the optimization of the efficiency of the maximum power extraction.

This paper is constructed as follows: in Section II, the modeling of the wind generator and the MPPT are presented. Section III deals with the field oriented control (FOC) of a DSIG. The design of a SMC for speed regulation of a DSIG is presented in Section IV. In Section V the performances of the proposed control are illustrated by some simulation results. Finally some concluding remarks are given in Section VI.

2. MODELING OF THE WIND GENERATOR

2.1. Modeling of the Wind Turbine and Gearbox

Wind turbine mechanical power is expressed as follows [7] and [8]:

$$P_t = C_p\left(\lambda\right)\rho S V^3 \tag{1}$$

where C_p the power coefficient of the turbine, ρ is the air density, R is the blade length and V is the wind velocity.

The turbine torque is the ratio of the out power to the shaft speed Ω_t, given by:

$$T_t = \frac{P_t}{\Omega_t} \tag{2}$$

The turbine is normally coupled to the generator shaft through a gearbox whose gear ratio G is chosen in order to set the generator shaft speed within a desired speed range. Neglecting the transmission losses, the torque and shaft speed of the wind turbine, referred to the generator side of the gearbox, are obtained as follows:

$$T_g = \frac{T_t}{G}, \Omega_t = \frac{\Omega_r}{G} \tag{3}$$

where the T_g driving is torque of the generator and Ω_r is the generator shaft speed.

The captured wind power is not converted totally by the wind turbine. $C_p(\lambda)$ Give us the percentage converted which is function of the wind speed, the turbine speed and the pith angle of specific wind turbine blades [9] and [10].

Although this equation seems simple, C_p is dependent on the ratio λ between the turbine angular velocity Ω_t and the wind speed V. this ratio is called the tip speed ratio expressed by:

$$\lambda = \frac{\Omega_t R}{V} \tag{4}$$

The areodynamique torque (wind) is determined the following equation [9]:

$$T_t = \frac{P_t}{\Omega_t} = C_p(\lambda) S \rho\, V^3 / 2\Omega_t \tag{5}$$

From the previous equations, a functional block diagram model of the turbine is established. It shows that the turbine rotation speed is controlled by acting on the electromagnetic torque of the generator. The wind speed is considered an entry disruptive to this system (see Fig.1)
The wind speed varies over time, and to ensure maximum capture of wind energy incident, the speed of the wind turbine should be adjustable permanently with that of the wind [9].

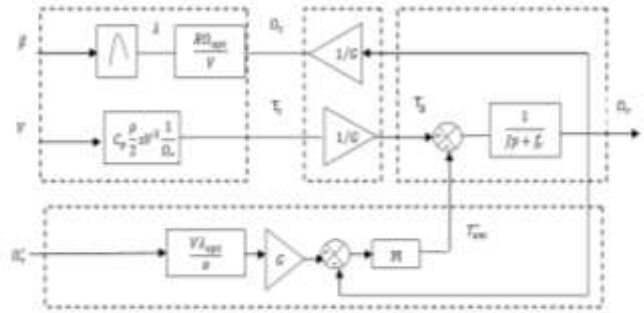

Figure 1. Control of turbine.

2.2. Induction generator Model

The model of dual stator induction generator is composed of a stator with two identical phase windings shifted by an electric angle $\alpha = 30°$, and a squirrel cage rotor. [11],[12][13][14].

Under the assumptions of magnetic circuits linearity, and assuming sinusoidal distributed air-gap flux density, the equivalent two-phase model of dual stator induction machine, represented in asynchronous frame (d, q) and expressed in state-space form, is a fourth-order model [8]-[10]:

$$[\dot{I}] = [L]^{-1}\left\{[B][U] - \omega_{gl}[C][I] - [D][I]\right\} \tag{6}$$

Where:

$[U] = \left[V_{qs1} V_{ds1}\ V_{qs2} V_{ds2} V_{qr} V_{dr}\right]^t$;

$[I] = \left[I_{qs1} I_{ds1}\ I_{qs2} I_{ds2}\ I_{qr}\ I_{dr}\right]^t$;

$[\dot{I}] = \dfrac{d[I]}{dt}$

$[B] = diag\,[1\ \ 1\ \ 1\ \ 1\ \ 0\ \ 0]$

$$[C] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ L_m & 0 & L_m & 0 & 0 & L_r + L_m \\ 0 & L_m & 0 & L_m & -(L_r + L_m) & 0 \end{bmatrix}$$

Where: $\tau_r = \dfrac{L_r}{R_r}$

$$[L] = \begin{bmatrix} L_{s1} + L_m & 0 & L_m & 0 & L_m & 0 \\ 0 & L_{s1} + L_m & 0 & L_m & 0 & L_m \\ L_m & 0 & L_{s2} + L_m & 0 & L_m & 0 \\ 0 & L_m & 0 & L_{s2} + L_m & 0 & L_m \\ L_m & 0 & L_m & 0 & L_r + L_m & 0 \\ 0 & L_m & 0 & L_m & 0 & L_r + L_m \end{bmatrix}$$

The mechanical modeling part of the system is given by [10]

$$J\frac{d\Omega_r}{dt} = T_r - T_{em} - f_r \Omega_r \tag{7}$$

With :

$$T_{em} = \left(\frac{p}{2}\right)\left(\frac{L_m}{L_{md} + L_r}\right)\left[\left(i_{qs1} + i_{qs2}\right)\varphi_{dr} - \left(i_{ds1} + i_{ds2}\right)\varphi_{qr}\right] \tag{8}$$

$$[D]=\begin{bmatrix} R_{s1} & -\omega_s(L_{s1}+L_m) & 0 & -\omega_s L_m & 0 & -\omega_s L_m \\ \omega_s(L_{s1}+L_m) & R_{s1} & \omega_s L_m & 0 & \omega_s L_m & 0 \\ 0 & -\omega_s L_m & R_{s2} & -\omega_s(L_{s1}+L_m) & 0 & -\omega_s L_m \\ \omega_s L_m & 0 & \omega_s(L_{s1}+L_m) & R_{s2} & 0 & 0 \\ 0 & 0 & 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & 0 & 0 & R_r \end{bmatrix}$$

2.3. Grid Side Power Control

In grid-connected control mode, is used injects the generated power into the grid. By using vector control techniques the currents in the ac side of the converter are controlled with very high bandwidth. The orientation of the reference frame is done along the supply voltage vector to obtain a decoupled control of the active and reactive power.

Usually the reactive power component current is set to zero for near unity power factor operation. The main aim of the front-end converter control strategy is to keep the DC link voltage E constant. It can be shown that the dynamic for the DC link voltage E, The dc link voltage is given by [9]:

$$\frac{du_{dc}}{dt}=\frac{1}{C_{dc}}(i_{dc}-i_{ond}) \tag{9}$$

where,

$$i_c^*=i_{dc}-i_{ond} \tag{10}$$

The reference active power injected to the electrical supply network is given by:

$$P_g^*=u_{dc}i_{dc}-u_{dc}i_c^* \tag{11}$$

The reference voltages are expressed by [9]:

$$\begin{aligned} v_{d\_ond}^* &= v_{dg}^*+v_{dg}-\omega_s L_t i_{qg} \\ v_{q\_ond}^* &= v_{qg}^*+v_{qg}+\omega_s L_t i_{dg} \end{aligned} \tag{12}$$

To maintain constant the dc link voltage, we have recourse to use a proportional integral corrector. It is parameterized according to the capacitor value and the dynamics of the regulation loop. Network reference currents, expressed in d–q frame, are given by:

$$\begin{aligned} i_{dg}^* &= \frac{P_g^* v_{dg}+Q_g^* v_{qg}}{v_{dg}^2+v_{qg}^2} \\ i_{qg}^* &= \frac{P_g^* v_{qg}-Q_g^* v_{dg}}{v_{dg}^2+v_{qg}^2} \end{aligned} \tag{13}$$

3. FIELD ORIENTED CONTROL OF A DSIG

According to the field orientation theory [15], the machine currents are decomposed into ids and iqs components, which are respectively, flux and torque components. The key feature of this technique is to keep namely $\varphi_{dr}=\varphi_r$ and $\varphi_{qr}=0$.

Hence, the flux and the electromagnetic torque are decoupled from each other, and can be separately controlled as desired. Then the drive behavior can be adequately described by a simplified model expressed by the following equations [9]:

$$i_{dr}=\frac{\varphi_r^*}{L_m+L_r}-\frac{L_m}{L_m+L_r}(i_{ds1}+i_{ds2}) \tag{14}$$

$$i_{qr}=-\frac{L_m}{L_m+L_r}(i_{qs1}+i_{qs2}) \tag{15}$$

$$\omega_{sl}^*=\frac{r_r L_m}{(L_m+L_r)}\frac{(i_{qs1}+i_{qs2})}{\varphi_r^*} \tag{16}$$

Finally the electromagnetic expression can be represented by:

$$T_{em}^*=P\frac{L_m}{L_m+L_r}(i_{qs1}+i_{qs2}).\varphi_r^* \tag{17}$$

4. DESIGN OF SLIDING MODE CONTROLER FOR DUAL STATOR INDUCTION GENERATOR

The basic principle of the sliding mode control consists in moving the state trajectory of the system toward a surface S(X) = 0 and maintaining it around this surface with the switching logic function U_n. The basic sliding mode control law is expressed as [5]:

$$U = U_{eq} + U_n \tag{18}$$

This expression uses two terms, U_{eq} and U_n. Where U_{eq} : is determined off line with a model that represents the plant as accurately as possible.

In this study, the proposed control scheme is shown in Fig. 2, in which five surfaces are required. The'd' axis, has two stator current component (i_{ds1}, i_{ds2}) loops and the 'q' axis, the internal loops allow the control stator current components (i_{qs1}, i_{qs2}), where as the external loop provide the regulation of the speed. So, six sliding surfaces are used and taken as follows since a first order is defined as [9]:

$$\begin{aligned} &S(\Omega_r) = \Omega_r^* - \Omega_r, S(\varphi_r) = \varphi_r^* - \varphi_r \\ &S(i_{ds1}) = i_{ds1}^* - i_{ds1}, S(i_{qs1}) = i_{qs1}^* - i_{qs1} \\ &S(i_{ds2}) = i_{ds2}^* - i_{ds2}, S(i_{qs2}) = i_{qs2}^* - i_{qs2} \end{aligned} \tag{19}$$

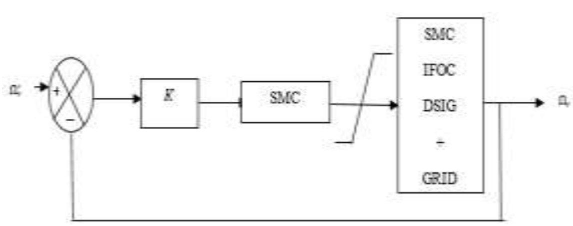

Figure 2. Basic structure of the sliding mode controller for indirect field oriented control of DSIG.

Development Of The Control Laws

For the speed regulator [9]:

$$S(\omega_r)S(\omega_r) < 0 \Rightarrow i_q^* = i_{qeq} + i_{qn}$$

With: $i_q = i_{q1} + i_{q2}$

$$i_{qeq} = \frac{J}{P^2}\frac{L_r + L_m}{L_m \varphi_r^*}\left[P\omega_r^* + \frac{f}{J}\omega_r + \frac{P}{J}T_g\right] \tag{20}$$

$$i_{qn} = \begin{cases} \dfrac{K_{\omega r}}{\varepsilon_{\omega r}} S(\omega_r) & si\ |S(\omega_r)| < \varepsilon_{\omega r} \neq 0 \\ K_{\omega r} sign(S(\omega_r)) & si\ |S(\omega_r) > \varepsilon_{\omega r}| \end{cases} \tag{21}$$

For the flux regulator:

$$S(\varphi_r)S(\varphi_r) < 0 \Rightarrow i_d^* = i_{deq} + i_{dn}$$

With: $i_d = i_{d1} + i_{d2}$

$$i_{deq} = \frac{L_r + L_m}{r_r L_m}\left[P\varphi_r^* + \frac{r_r}{L_r + L_m}\varphi_r\right] \tag{22}$$

$$i_{dn} = \begin{cases} \dfrac{K_{\varphi r}}{\varepsilon_{\varphi r}} S(\varphi_r) & si\ |S(\varphi_r)| < \varepsilon_{\varphi r} \neq 0 \\ K_{\varphi r} sign(S(\varphi_r)) & si\ |S(\varphi_r) > \varepsilon_{\varphi r}| \end{cases} \tag{23}$$

For the stator currents regulators:

$$S(i_{ds1})S(i_{ds1})<0 \Rightarrow V_{d1}^{*}=V_{d1eq}+V_{d1n}$$
$$S(i_{qs1})S(i_{qs1})<0 \Rightarrow V_{q1}^{*}=V_{q1eq}+V_{q1n}$$
$$S(i_{ds2})S(i_{ds2})<0 \Rightarrow V_{d2}^{*}=V_{d2eq}+V_{d2n}$$
$$S(i_{qs2})S(i_{qs2})<0 \Rightarrow V_{q2}^{*}=V_{q2eq}+V_{q2n}$$

With:

$$\begin{aligned}
V_{d1eq} &= r_1 i_{ds1} + L_1 p i_{ds1} - \omega_s^{*}(L_1 i_{qs1} + \tau_r \varphi_r^{*} \omega_{gl}^{*}) \\
V_{q1eq} &= r_1 i_{qs1} + L_1 p i_{qs1} + \omega_s^{*}(L_1 i_{ds1} + \varphi_r^{*}) \\
V_{d2eq} &= r_2 i_{ds2} + L_2 p i_{ds2} - \omega_s^{*}(L_2 i_{qs2} + \tau_r \varphi_r^{*} \omega_{gl}^{*}) \\
V_{q2eq} &= r_2 i_{qs2} + L_2 p i_{qs2} + \omega_s^{*}(L_2 i_{ds2} + \varphi_r^{*})
\end{aligned} \quad (24)$$

And

$$V_{d1n} = \begin{cases} \dfrac{K_{ids1}}{\varepsilon_{ids1}} S(i_{ds1}) & si\ |S(i_{ds1})| < \varepsilon_{ids1} \neq 0 \\ K_{ids1} sign(S(i_{ds1})) & si\ |S(i_{ds1}) > \varepsilon_{ids1}| \end{cases}$$

$$V_{q1n} = \begin{cases} \dfrac{K_{iqs1}}{\varepsilon_{iqs1}} S(i_{qs1}) & si\ |S(i_{qs1})| < \varepsilon_{iqs1} \neq 0 \\ K_{iqs1} sign(S(i_{qs1})) & si\ |S(i_{qs1}) > \varepsilon_{iqs1}| \end{cases}$$

$$V_{d2n} = \begin{cases} \dfrac{K_{ids2}}{\varepsilon_{ids2}} S(i_{ds2}) & si\ |S(i_{ds2})| < \varepsilon_{ids2} \neq 0 \\ K_{ids2} sign(S(i_{ds2})) & si\ |S(i_{ds2}) > \varepsilon_{ids2}| \end{cases}$$

$$V_{q2n} = \begin{cases} \dfrac{K_{iqs2}}{\varepsilon_{iqs2}} S(i_{qs2}) & si\ |S(i_{qs2})| < \varepsilon_{iqs2} \neq 0 \\ K_{iqs2} sign(S(i_{qs2})) & si\ |S(i_{qs2}) > \varepsilon_{iqs2}| \end{cases}$$

(25)

I. SIMULATION RESULTS AND DISCUSSION

In order to investigate the performance and accuracy of the proposed method control, simulation tests were performed for a 1 .5 MW DSIG using a sliding mode controller. The parameters of the test DSIG used in the simulation are given in Table II and Table III. The results of simulations are obtained for reactive power Q = 0 for a unity power factor.

From figure.4 the DSIG speed follow properly it optimal reference and has the same waveform as applied wind profile. The electromagnetic torque converges quickly to its reference see figure.5. The feature of vector control is shown in figure.6. From figures 7 and 8, it is easily shown that the use of Sliding mode controller improve very well the performance of wind energy conversion systems especially the power coefficient Cp

and λ. In fact, the coefficient Cp close to its maximum value during the whole wind speed profile, same for tip speed ratio. Hence the efficiency of the maximum power extraction can be clearly observed as the power coefficient is fixed at the optimum value Cp =0.52 and λ= 9.

The DC link voltage is maintained at a constant level (1130V) see figure.9; hence that the real power extracted from the wind energy conversion systems can pass through the grid. The grid active power tracks quite well its set-point up to the rated speed, when the reactive grid power is fixed to 0 VAR see figure.1.

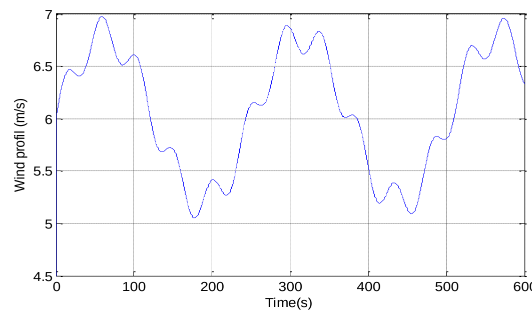

Figure 3. Wind profile.

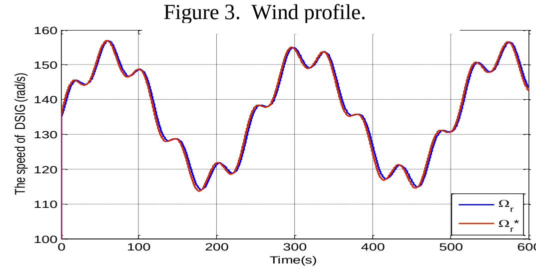

Figure 4. DSIG speed and its reference.

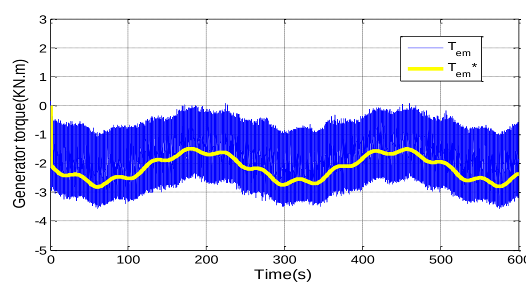

Figure 5. DSIG Torque and its reference.

Figure 5. DSIG Torque and its reference.

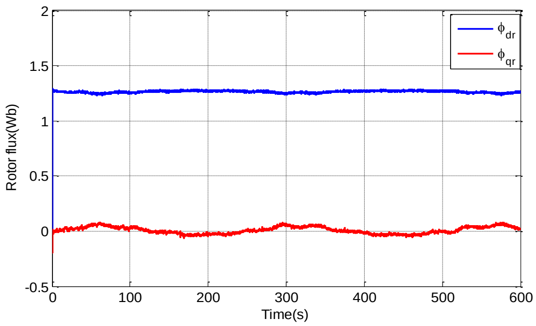

Figure 6. Direct and quadratic rotor flux.

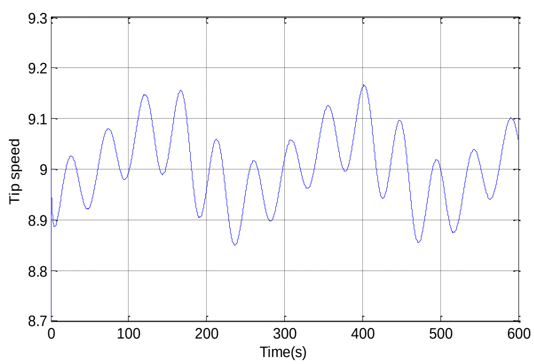

Figure 7. The tip speed.

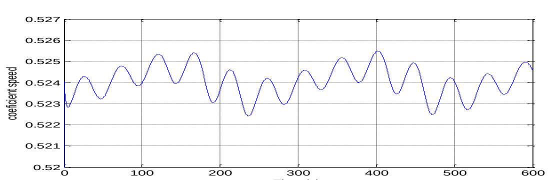

Figure.8 The power coefficient.

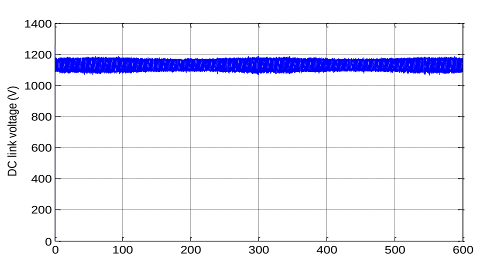

Figure 9. DC link voltage

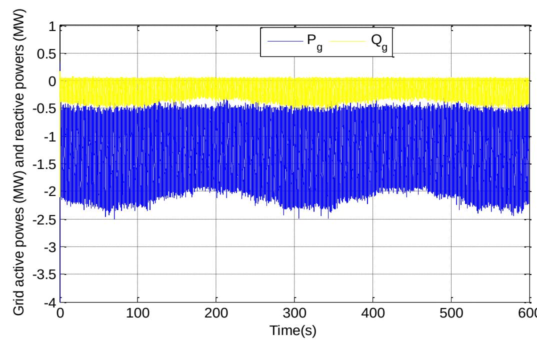

Figure10. Grid active and reactive power.

5. CONCLUSION

In this paper, a sliding mode MPPT control system for searching the optimum operating point for wind energy conversion system based on a dual stator induction generator has been presented. The performance of the proposed scheme has been simulated under several changes in wind. It is determined from simulation results, that the sliding mode control can greatly improve the power system performances. Besides the suggested sliding mode controller achieves:

Good pursuit of reference speed;

Good support for changes of the turbine and the generator as well as to electric grid disturbances.

Appendix

A. Parameters

Turbine: Diameter = 60 m, Number of blades = 3, Hub height =85 m, Gearbox = 90.

DSIG: 1.5 MW, 400 V, 50 Hz, 2 pole pairs, Rs1=Rs2=0.008 X, L1=L2=0.134 mH, Lm= 0.0045 H, Rr = 0.007 X, Lr = 0.067 mH, J = 104 kg m2 (turbine + DSIG), *f*r= 2.5 N m s/rd: (turbine + DSIG).

B. Nomenclature

G	Gear ratio
V	Wind velocity
P_n	Nominal power
λ	Tip speed ratio
S	Area of the rotor
C_p	Power coefficient
Ω_r , Ω_t	Mechanical speed of the DSIG, Turbine speed
T_t , T_g	Aerodynamic torque, Generator torque
R_{s1} , R_{s2}	Per phase stators resistances
L_1 , L_2	Per phase stators leakages inductances
L_m	Magnetizing inductance
R_r , L_r	Per phase rotor resistance and leakage inductance
J	Inertia (turbine + DSIG),
f_r	Viscous coefficient
P, p	Number of pole pairs, and Derivative operator
ω_s , ω_r	Synchronous speed ,and Rotor speed
T_{em}^*	Electromagnetic torque reference
$V_{qs1} V_{ds1}$ V_{qs2} , V_{ds2}	"d–q" stators voltages
$I_{qs1} I_{ds1}$ $I_{qs2} I_{ds2}$	"q" stators currents
V_{qr} V_{dr}	"d–q" rotor voltages
I_{qr} I_{dr}	"d–q" rotor currents

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