SPEED CONTROL OF PMSG SUPPLIED CLOSED LOOP PMSM DRIVE FOR WATER PUMPING SYSTEM

NAIMA RAHOUA(1), RACHID ABDESSEMED(2)

(1) Department of electrical engineering University Mohamed Khider Biskra, Algeria

(2) Department of electrical engineering University Batna 2, Algeria

ABSTRACT

This paper introduces a standalone variable speed wind energy conversion system(WECS) based on permanent magnet synchronous Generator (PMSG) supplied permanent magnet synchronous Motor (PMSM) drive for water pumping system. Pumping water is a worldwide need that is necessary for agriculture and the usage of wind energy conversion is a choice that is considered natural for that kind of applications. The Permanent magnet synchronous motor (PMSM) drive that is powered by high speed wind energy conversion system is investigated. The WECS application is inquired, in order to high light the wind speed effect on the WECS feeding the PMSM, where the speed of a PMSM drive is a function of wind speed. The proposed system consists of WECS using PMSG, a rectifier converter, a three phase VSI (Voltage Source Inverter) and a PMSM coupled with a centrifugal water pump. The suggested control strategies are focused on Maximum Power Point Tracking (MPPT) for PMSG speed control, and DC-bus voltage management. Three phase VSI (Voltage Source Inverter) is also controlled to supply PMSM under change in wind speed in vector oriented mode. Some simulations are done using Matlab / Simulink software in order to show the control strategies performances.

KEYWORDS: PMSG ;WECS ;PMSM drive ; Speed control ; FOC ; DC-bus voltage control; Maximum Power Point Tracking (MPPT) ;water pumping system .

1 INTRODUCTION

These days, there is a variety of renewable energy forms, those that are more frequently used are: solar, wind and hydraulic. In this paper, the focus will be on Wind Energy Conversion System (WECS) which is an important and popular renewable energy technology[1] ; it is free, inexhaustible, and clean. The use of wind energy in the isolated zones and the rural sectors is a better solution to produce the needed electric energy for such applications as the pumping systems [2,3]; where connection to the grid is technically impossible or expensive. Different types of generators are used in WECS such as induction machines, double fed induction machines and PMSG. Nowadays, the permanent magnet synchronous generator (PMSG) has earned much attention in wind pumping systems because of its variety of advantages like high efficiency, small size, less cost, less maintenance, high energy generation capability, non requirement of external excitation and its easiness to control[4,5,6,7]. A variable WECS including a PMSG offers advantages over the constant speed approach such as maximum power point tracking capability and reduced acoustic noise at lower wind speeds [8,9]. This paper presents a standalone wind turbine that supplies PMSM drive for water pumping system. Pumping water is a worldwide need that is necessary for agriculture and the usage of wind energy conversion is a choice that is considered natural for that kind of applications. In our study, the water pumping system used a wind turbine based on PMSG which supplies PMSM motor to generate the torque required to the centrifugal hydraulic pump. In the proposed system, a direct searching Maximum Power Point Tracking (MPPT) controller is designed for PMSG speed control and preferred for its efficient operation ; and a duty cycle of rectifier converter is controlled to maintain the DC link voltage at constant value inspite of the changes in the wind generator voltage, due to the changes in the wind speed. The speed of a PMSM drive is a function of wind speed. Three phase VSI (Voltage Source Inverter) is controlled to supply PMSM under change in wind speed using field oriented control (FOC) that manages the motor’s speed to attain maximum power point operation .

2 OVERVIEW OF PERMANENT MAGNET WIND POWER GENERATION

The system studied is presented in Fig.1. It includes a turbine connected to a permanent magnet synchronous generator (PMSG), a gearbox, a static converter side of the generator acting as a rectifier (GSC), a static converter load side playing the role of an inverter (LSC), and a load represented by a permanent magnet synchronous motor

(PMSM) which is coupled to a centrifugal pump.

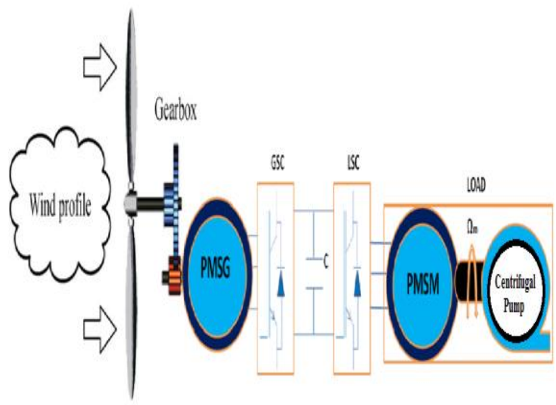

Figure 01: Permanent magnet wind power generation system

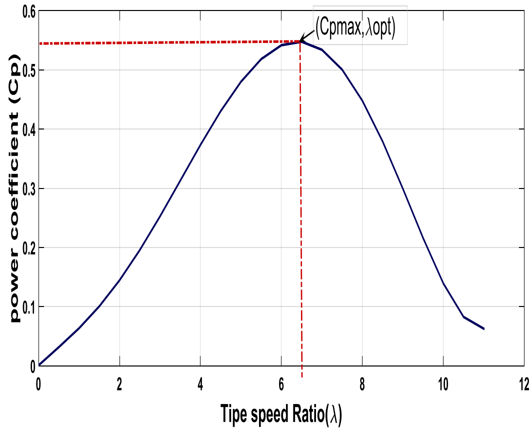

Figure 02: Wind turbine power coefficient versus tip speed

3 DESCRIPTION OF SOME COMPONENTS OF THE SYSTEM

3.1 Wind Turbine Model

The mechanical output power of a variable speed wind turbine is given by [10,11]:

$$P_t = C_p(\lambda, \beta) . \frac{\rho . S . V^3}{2} \tag{1}$$

where C_p is a power coefficient, ρ is an air density (kg/m^3), S is a turbine swept area (m^2)($S = \pi R^2$), v is a wind speed (m/s), β is a blade pitch angle (degree), and λ is a tip speed ratio and can be expressed as [11] :

$$\lambda = \frac{\Omega_t . R}{V} \tag{2}$$

Where Ω_t is the wind turbine speed (rad/s) and R is the blade radius in meters.

The turbine power coefficient $C_p(\lambda, \beta)$ is modeled based on the turbine characteristics. For a fixed-pitch wind turbine, C_p is only a function of the tip-speed-ratio λ, which is determined by [12] :

$$cp(\lambda) = a_5 . \lambda^5 + a_4 . \lambda^4 + a_3 . \lambda^3 + a_2 . \lambda^2 + a_1 . \lambda + a_0 \tag{3}$$

Where : the constants a_i(i=0 …5) are given in appendix.

Fig. 2 shows the power coefficient characteristic, that is an optimum value of tip speed ratio (λ_{opt}= 6.5) corresponding to a maximum value of the power coefficient(C_{pmax}= 0.547)

3.2 PMSG Model

The electrical model of a synchronous machine with permanent magnet generator mode is reproduced from the machine in motor operation, by reversing the direction of the stator current using Park transformation. The model of PMSG, expressed in d-q frame Fig.3, is given by voltage system Eqs. (4)-(5) [13, 14, 15].

$$V_d = -R_s . i_d - L_d \frac{di_d}{dt} + \omega_g . L_q . i_q \tag{4}$$

$$V_q = -R_s . i_q - L_q \frac{di_q}{dt} - \omega_g . L_d . i_d + \omega_g . \Psi_f \tag{5}$$

Where d and q are the synchronous rotating reference frame; R_s is the armature resistance; L_d , L_q are the generator inductances on the d-q axis; i_d , i_q are, respectively, the d and q axis components of current; V_d , V_q are the d- and q-axis voltage components, respectively.

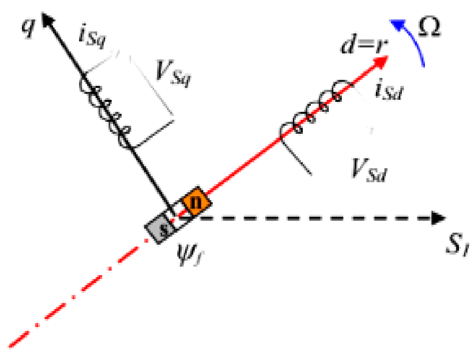

Figure 03: Frame of PMSG

V_q are the d- and q-axis voltage components, respectively.

Ψ_f is the permanent magnet flux and the electrical rotating speed ω_e isgiven by:

$$\omega_e = P\Omega \tag{6}$$

Where: P is the number of pole pairs and Ω is the mechanical angular velocity of the generator (rad/s).

The expression of the mechanical speed of the generator is given by :

$$\Omega = G\Omega_t \tag{7}$$

Where, the gear ratio G is chosen in order to adjust the slow speed of the turbine to the speed of the generator.

In the d-q synchronously rotating reference frame, the electromagnetic torque is represented by [13]:

$$C_{em} = \frac{3}{2}P[(\mathrm{Lq}-\mathrm{Ld})\mathrm{id.iq}+\mathrm{iq}\Psi\mathrm{f}] \tag{8}$$

The mechanical equation of PMSG is given by:

$$J\frac{d\Omega}{dt} = C_m - C_{em} - f\Omega \tag{9}$$

Where: C_m is the mechanical torque input from the wind turbine, C_{em} is the electromagnetic torque of PMSG, J the moment of inertia, f the friction coefficient.

3.3 Modelling of load

The model of the load contains the motor and the pump. The motor is a PMSM and it has been already discussed above. And the pump is a centrifugal model that can be described by Knowing the mechanical characteristics 'h' illustrated in relation (10) [16,17]:

$$\mathrm{h} = A_0\Omega_m^2 - A_1\Omega_m Q - A_2 Q^2 \tag{10}$$

Where: A0, A1, A2 and Q are manufacture pump coefficients.

The hydraulic power P_h and the torque of the centrifugal pump can be given respectively by Eqs (11) and (12):

$$P_h = \rho g h Q \tag{11}$$

$$C_{rp} = K_{ch}\Omega_m^2 + C_s \tag{12}$$

Where: K_{ch} ,C_s are constants depend on hydraulic part.

The mechanical model of the electric motor and the centrifugal pump can be described by Eq (13).

$$J_{mp}\frac{d\Omega_m}{dt} = C_M - C_{rp} - f_{mp}\Omega_m \tag{13}$$

Where, J_{mp} is the total inertia of the motor and the pump

f_{mp} friction of motor with pump.

C_M and C_{rp} represent respectively the motor torque and the hydraulic load torque of the pump.

4 WIND ENERGY SYSTEM CONTROL STRATEGIES

The control strategy used in this paper includes the control of PMSG speed, the control of DC bus voltage, and the control of PMSM speed.

4.1 Control strategy of PMSG speed

The control strategy of the PMSG speed is illustrated in Fig. 4 where optimum speed reference has been pulled from the MPPT technique expressed by (14).

$$\Omega_{ref} = \left(\frac{\lambda_{opt}.V}{R}\right) \tag{14}$$

The PI controller coefficients obtained from closed loop analysis are shown in (15), where w_{nd} presents the dynamics of the system, ξ is the damping factor and t_{sd} is the control loop time constant [18, 19].

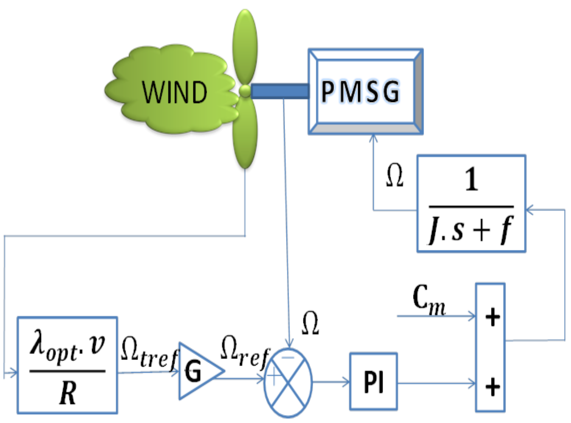

Figure 04: Speed control loop of PMSG

$$\begin{cases} K_p = 2.\xi .\ w_{nd}\ .J \\ K_i = w_{nd}^2\ .J \end{cases} \quad ,w_{nd} = \frac{5.8}{t_{sd}} \qquad (15)$$

4.2 DC-bus voltage control method

A Field Oriented Control (FOC) strategy with hysteresis current control (HBCC) is applied to the PMSG-side converter Fig.5, to keep the DC link voltage constant when the rotor speed is varied, where the reference current in q axis I_{qref} is obtained from DC-bus voltage control loop. Idref is fixed to zero to obtain a power factor of 1. PI controller is used for DC-bus voltage management. The coefficients of this controller are expressed in Eq(16), where w_n and t_{sdc} are respectively the dynamics of the system, and system time constant.

$$\begin{cases} K_{pdc} = 2.\xi.C\ .\ w_n \\ K_{idc} = C\ .w_n^2 \end{cases} \quad ,w_n = \frac{5.8}{t_{sdc}} \qquad (16)$$

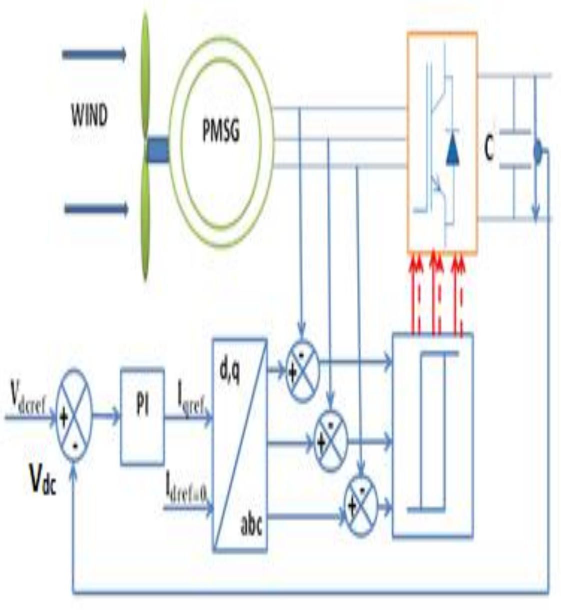

Figure 05: DC-bus voltage control strategy

4.3 Control strategy of PMSM speed

For the load-side converter, a FOC (Field Oriented Control) scheme is used Fig.6. Reference motor speed (Ωref) is the function of wind speed and is used to track the maximum power, where (Ωref) is obtained from MPPT technique expressed by Eq (14). Reference speed is compared with the measured rotor speed (Ωm) and the error is fed as input to the PI controller which output will be proportional to torque producing component of stator current (i_{qref}).

This current is compared with q-axis component of stator current (i_q) and error is fed to another PI controller to find q-axis reference voltage component V_{qref}. The d-axis component of stator reference current which is the flux producing component (i_{dref}) is taken equal to zero to satisfy maximum torque. This current is compared with motor d-axis current component and the error is fed to PI controller to find V_{dref}. The voltage reference (V_{qref},) is processed into the inverse Park transformation.

The outputs of this are Vαref and Vβref, which are the components of the stator vector voltage in the α, β orthogonal reference frame. These voltage blocks feed the SVM module, which creates command signals for the inverter'sgates

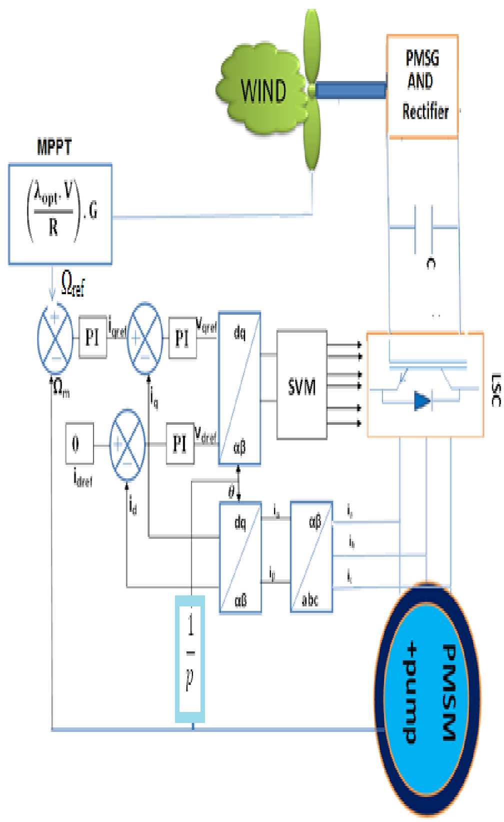

Figure 06: Block Diagram of field oriented control of PMSM and the WECS

5 SIMULATION RESULTS AND DISCUSSIONS

Results of the proposed strategy for the stand-alone wind energy conversion system for pumping water are presented in this section. The simulations were carried out using the Matlab/Simulink environment, which parameters are indicated in Appendix.

The figures show the wind speed step change, PMSG speed, power coefficient, DC link voltage, the output voltage of PMSG (phase ‘a’ voltage), PMSM speed, Electromagnetic torque of PMSM, d-q component of stator current and the pump flow.

In Fig.7, the wind speed is varied as follows: 12 m/s from 0 s to 0.25 s, and 14 m/s from 0.25 s to 0.5 s onwards. We can show the performance of the whole system for a step change of wind speed.

Fig. 8. This curve shows that the proposed control strategy is satisfactory. The measured speed of PMSG is almost identical to the reference obtained by the MPPT technique.

From Fig.9 it is seen that the output voltage of PMSG for phase ‘a’ is 150 V until 0.25 s. The output voltage increases to 350 V as the wind speed increases from 12 m/s. to 14 m/s.

Fig.10 shows the power coefficient variation Cp which is kept around its maximum value Cp= 0.5475. It is clear that the MPPT algorithm is fulfilled during the wind speed changes.

Fig.11 presents the wave form of the voltage V_{dc} in the DC link of the rectifier converter system. The voltage V_{dc} is maintained constant at 380V even though the generated voltage varies with the variation in the wind speed due to the PI based voltage controller. It shows good performance of control circuits.

In Fig.12, the speed of PMSM follows its reference with very small overshoot at startup and without static error despite the variation of the wind.

In Fig.13, the electromagnetic torque starts at 15.6.Nm and stabilizes at the value of the load torque. We notice that if the wind speed increases, the speed of the motor also increases. So, the value of the load torque increases according to the speed of the motor.

The corresponding dq component of current is given in fig. 14 in which the value of the direct current id is zero, since field oriented control is used despite the variation of the wind. Then, the quadratic current response goes towards the nominal value of the motor current as an image of the torque.

In Fig.15 we show, the variation of the centrifugal pump flow. During the variation of the wind we notice that, when the wind speed increases the pump flow also increases, which proves that the water pumping system operates at its optimal conditions.

These results demonstrate the good performances of the regulation.

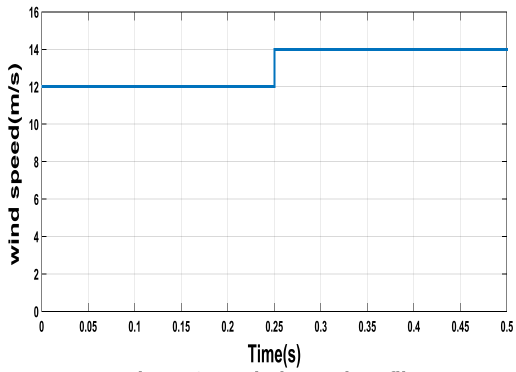

Figure 07: Wind speed profil

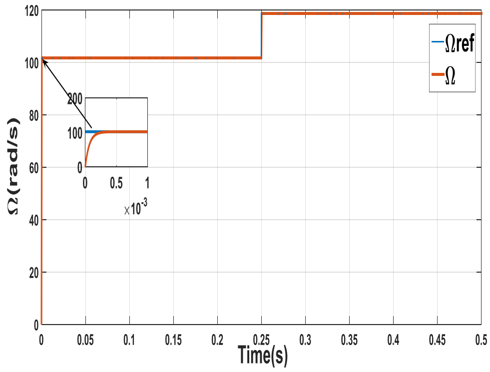

Figure 08: PMSG speed control result

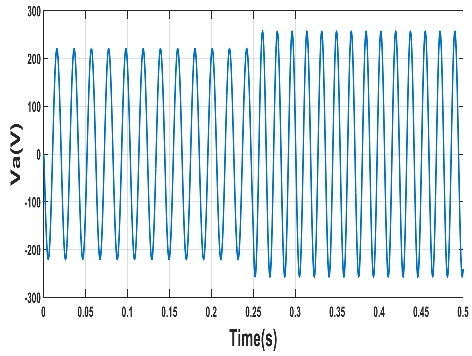

Figure 09: output voltage of PMSG(phase ‘a’)

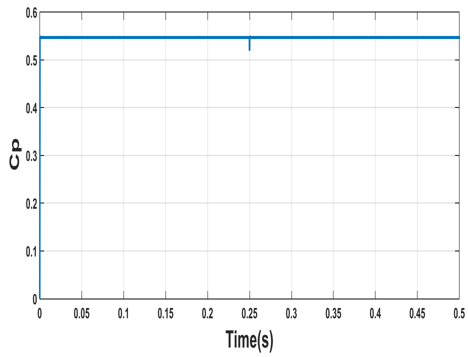

Figure 10: Power conversion coefficient

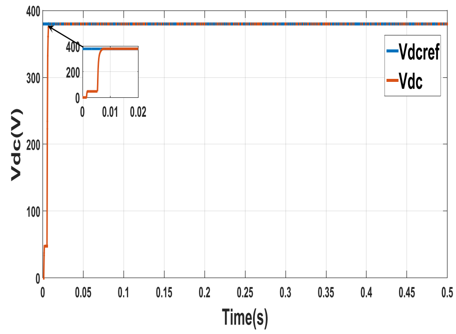

Figure 11: Dc-bus voltage control result

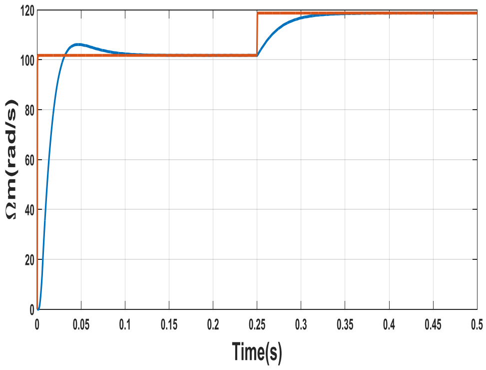

Figure 12: PMSM speed control result

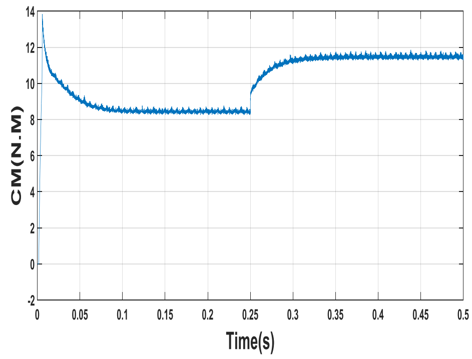

Figure 13: Electromagnetic torque of PMSM

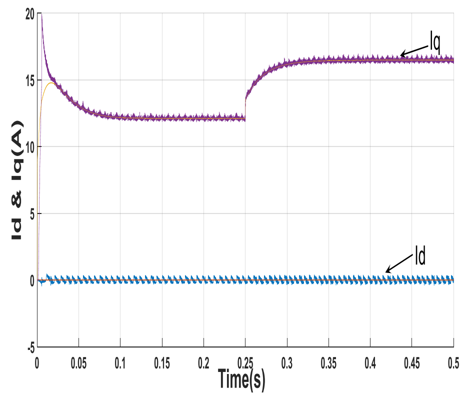

Figure 14: d-q component current

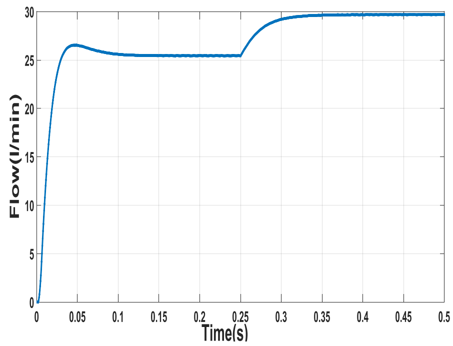

Figure 15: the pump Flow

6 CONCLUSION

A control strategy of stand-alone variable speed wind turbine based on PMSG that supplies PMSM for water pumping system has been presented in this paper. The performance of this system is verified using matlab simulation. The results of the simulation are satisfying and it can be seen that the three goals of the target control system have been achieved. These control strategies are focused on generator's speeds control, DC-bus voltage management, and the motor's speed control. The main goal of this study is to design a controller that adjusts the motor speed reference in order to reach the maximum power point operation of the wind turbine, thanks to the implementation of an MPPT scheme when the wind varies. To reach this goal, a controller was designed based on PI controller and field oriented control. We observed that an increase of the flow of water is reached by the proposed approach. As perspective, then, we will verify it by experimental work.

APPENDIX

Parameters of wind turbine

ρ = 1.25 kg/m3; R = 4.6 m; G = 6

a_0=0.001,a_1=6.38.10^{-2},a_2=-9.4.10^{-3},a_3=9.86.10^{-3},

a_4=-17.375.10^{-4},a_5=7.9563.10^{-5}

Parameters of PMSG

Rs= 0.895 Ω; Ld = 0.012 H ; Lq = 0.0211 H; J = 0.00141

N.m; f = 0.001(N.m.s)/rad; p = 3; Ψf = 0.9 Wb.

Parameters of PMSM

Rs= 1.4 Ω; Ld = 6.6e-3 H ; Lq = 5.8e-3 H; J = 0.00176

N.m; f = 0.0003881 (N.m.s)/rad; p = 3; Ψf = 0.1546Wb.

REFERENCES

[1] F. Blaabjerg, M. Liserre and KeMa, "Power

Electronics Converters for Wind Turbine Systems" , IEEE Transaction on Industry Application, Vol. 48, No. 2,pp.708-719, 2012.

[2] S. Hammadi,N.Hidouri,L.Sbita ,"A DTC- PMSG-PMSM Drive Scheme for an Isolated Wind turbine water Pumping System", International Journal of Research and Reviews in Electrical and Computer Engineering, Vol. 1, No. 1,pp. 1-10, 2011.

[3] P. Camorcadi, P. Battaiotto, R. Mantz, "BDFIG-Based Wind Electric Pumping System with a Variable Structure Control Strategy", International Journal of Systems Control, Vol.1, No.2, pp. 38-47, 2010.

[4] A. Knight and G. Peters, "Simple wind Energy Controller for an Expanded Operating Range" , IEEE Transaction on Energy Conversion., Vol. 20, No. 2, pp. 459–466, 2005.

[5] L.-R. Chang-Chien and Y.-C. Yin, "Strategies for Operating Wind Power in a Similar Manner of Conventional Power Plant " , IEEE Transactions on Energy Conversation,Vol. 24, No. 4, pp. 926–934, 2009.

[6] M.Edwinlawrance,R.M.Sasiraja,V.Suresh Kumar "Permanent Magnet Synchronous Generator Voltage Control Using Fuzzy Logic Controller", Internationnal Journal of Innovative Resaearch & Development, Vol. 2, No. 5,pp. 1182- 1195, 2013.

[7] V. Yaramasu and W. Bin, "Predictive Control of a Three-Level Boost Converter and an NPC Inverter for High-Power PMSG-Based Medium Voltage Wind Energy Conversion Systems " , IEEE Transaction on Power Electronics., Vol. 29, No. 10, pp. 5308–5322, 2014.

[8] C.E.A. Silva, D.S. Oliveira, L.H.S.C. Barreto, R.P.T. Bascopé, "A Novel Three-Phase Rectifier With High Power Factor for Wind Energy Conversion Systems" , Power Electronics Conf, pp. 985- 992, 2009.

[9] C. Sasi and G. Mohan, "Performance Analysis of Grid Connected Wind Energy Conversion System with a PMSG during Fault Conditions" , International Journal of Engineering and Advanced Technology, pp. 2249 – 8958, Vol.2, No.4, 2013.

[10] W. Xiaoyu, Y. Meng, E. Muljadi, and G. Wenzhong, "Probabilistic Approach for Power Capacity Specification of Wind Energy Storage Systems", IEEE Transaction on Industry Application, Vol. 50, No. 2, pp. 1215-1224, 2014.

[11] A. Tamaarat and A. Benakcha, "Performance of PI Controller for Control of Active and Reactive Power in DFIG Operating in a Grid-Connected Variable Speed Wind Energy Conversion System", Frontiers in Energy , Vol. 8, No. 3, pp. 371–378, 2014.

[12] A. Guettaf, A. Bettka, O. Bennis, F. Benchabane, and A. Ali, "Direct Field Oriented Control of Induction Motor Fed by Wind Turbine Generator Under Saturation Effect" , Mediterranean Journal of Measurement and Control, Vol. 17, No. 1, pp. 190–196, 2011.

[13] Shuhui Li, Timothy A. Haskew, Richard P. Swatloskis,and William Gathings, "Optimal and Direct-Current Vector Control of Direct-Driven PMSG Wind Turbines" , IEEE Transactions on Power Electronics, Vol.27, No.5,pp.2325-2337, 2012.

[14] A. Uehara, A. Pratap, T. Goya, T. Senjyu, A. Yona, N. Urasaki and T. Funabashi, "A Coordinated Control Method to Smooth Wind Power Fluctuations of a PMSG-Based WECS" , IEEE Transaction on Energy Conversion, Vol. 26, No. 2, pp. 550-558, 2011.

[15] E. Haque, M. Negnevitsky, and K. M. Muttaqi, "A Novel Control Strategy for a Variable-Speed Wind Turbine With a Permanent-Magnet Synchronous Generator" , IEEE Transaction on Industry Application,Vol.46, No.1, pp. 331-339 , 2010.

[16] H. Jedli, N. Hidouri, "A Power Drive Scheme for an Isolated Pitched Wind Turbine Water Pumping System Based on DC Machine" , Journal of Advances in Mechanical Engineering and its Applications, Vol. 1, No. 1, 2012.

[17] N. Hidouri,L. Sbita, "An IRFOC Drive Scheme for a SEIG-Wind Turbine Water Pumping System" ,13th International Conference on Control, Engineering & Information Technology, Vol.1,pp.93-98, 2013.

[18] M. S. Camara, M. B. Camara, B. Dakyo, and H. Gualous, "Permanent Magnet Synchronous Generator for Offshore Wind Energy System Connected to Grid and Battery-Modeling and Control Strategies" , International Journal Of Renewable Energy Research, Vol. 5, No. 2, 2015.

[19] L. Fateh, O. Ahmed, O. Amar, D. Abdelhak, and B. Lakhdar,"Modeling and Control of a Permanent Magnet Synchronous Generator Dedicated to Standalone Wind Energy Conversion System" , Frontiers in Energy, Vol.10, No. 2,pp. 155–163, 2016.