Generalized Predictive Control of Standalone Wind Energy Generation System

BOUZID Mohamed Amine*‡, MASSOUM Ahmed*, ZINE Souhila**

*Department of Electrical Engineering, Faculty of Technology, Djillali Liabes University, Sidi Bel Abbes, Algeria

**Department of Electrical Engineering, University of Sciences and Technology, Oran, Algeria

(bouzid_mohamedamine@yahoo.com, ahmassoum@yahoo.fr, souracha2005@yahoo.fr)

‡ Corresponding Author; BOUZID Mohamed Amine, Department of Electrical Engineering, Faculty of Technology, Djillali Liabes University, Sidi Bel Abbes, Algeria, Tel: +213 773 643 795, bouzid_mohamedamine@yahoo.com

Received: 20.01.2016 Accepted: 24.02.2016

Abstract- The irregularity of the generated power from wind turbines is caused by the stochastic nature of the wind. It can affect the quality of power and plan of the power supply system. The purpose of control is to adjust the inverter voltage's amplitude and frequency at a variable speed of the wind. This article presents a Generalized Predictive Control application to a wind power converting system with emphasis on the Maximum Power Point Tracking (MPPT). The controller developed consists RST regulator obtained GPC. This equivalent polynomial structure is needed to convert the GPC parameters to be monitored to its RST equivalent parameters. The obtained results have shown that the Generalized Predictive Controller performances were largely better than the PI ones.

Keywords Generalized Predictive Control, PMSG, standalone wind turbine, voltage and frequency control.

1. Introduction

With the increasing concern about environment, many people look for clean, renewable and inexhaustible energy resources [1-3].

Wind energy can be seen as sustainable attractive source of electricity. Rising from 6100 Megawatts of generating capacity in 1996 to 369597 Megawatts at the end of 2014, wind energy has been the source that has the highest growth of electrical energy from renewable sources in the world [4].

Standalone wind energy conversion systems are electric energy alternative sources for isolated area. They usually supplies air conditioning mechanical loads, ventilation and water pumps [5]. For remote communities, the generator voltage stability is the main concern for any regulation scheme [6, 7].

Batteries are critical elements for an autonomous power supply system to keep the balance between the generated power and the power requested by the load [8]. The battery bank is attached to the DC bus via a buck-boost converter. The control purpose of the DC converter is maintaining the DC voltage at a consistent level.

During the last twenty years, GPC strategy has benefited from a growing concern in numerous control applications [9]. Compared to conventional control methods, GPC is an efficient method for applications that request high performances with good properties in both time and frequency domains [10]. GPC algorithms are largely used because of his prominent characteristics like stability and robustness [9, 11].

In Ref. [12], Hui et al has established a neural network controller to estimate the wind velocity. They used a PI for extracting the maximum of energy from the wind.

Kamel Ouari et al developed a Nonlinear Generalized Predictive Controller with nonlinear Observer for a DFIG based variable speed wind turbine [13]. QIU et al present a wind energy system equipped with PMSG, but the use of the diode rectifier decrease the efficiency of the control system [14].

In [15], a Generalized Predictive RST regulator is used for controlling the output voltage of wound rotor synchronous generator.

In this study, a generalized predictive controller is suggested for the PMSG speed control. The results of simulation are presented to show the advantage of the proposed control strategy.

The proposed system comprises: wind turbine; PMSG; stator side converter; battery; buck-boost converter; DC/AC converter. The obtained electrical power is delivered to a local AC load.

A rectifier is employed in the MPPT control to achieve a maximum level of wind energy extraction. It gives the possibility to the PMSG to reach high performances by delivering sinusoidal currents contrary to diode rectifier. The buck-boost converter is used for controlling the DC link voltage and the battery current during the charging and discharging cycles. In the load side, the inverter is used to control the voltage amplitude and frequency. The system topology used in this work is illustrated in Fig 1.

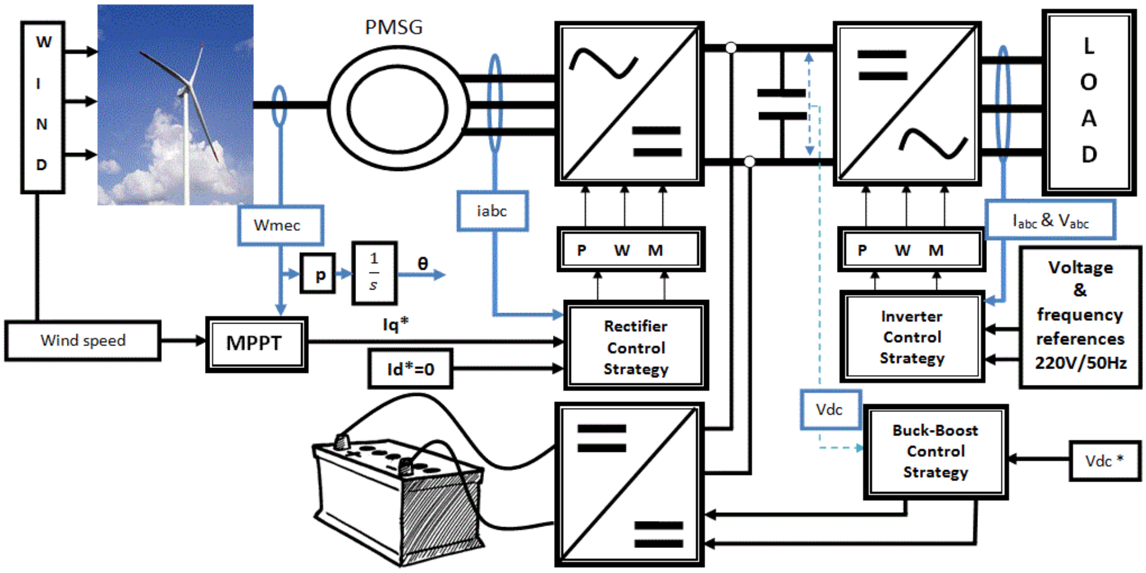

Fig. 1. Block diagram of the studied configuration

2. Wind Turbine Model

The wind profile used in simulation is represented in Fig.2. This profile presents a random variation of the wind speed. It is modelled by an addition of a number of harmonics as: [16-18]

$$V_w(t) = 6.5 + (0.2\ \sin(0.1074\ t) + 2\ \sin(0.2665\ t) + \sin(1.2930\ t) + 0.2\sin(3.6645\ t)) \tag{1}$$

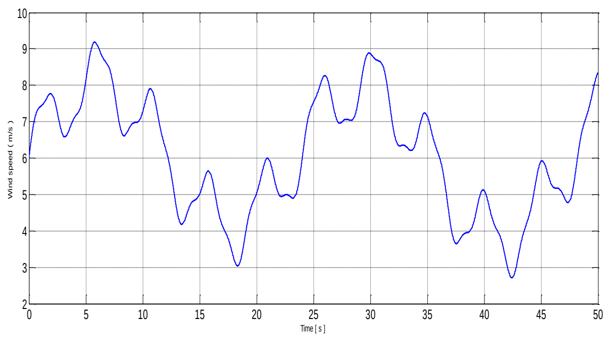

Fig. 2. Wind profile

Extracting mechanical power from the wind can be expressed as: [19]

$$P_m = C_P(\lambda,\beta).P_w = C_p(\lambda,\beta).\frac{\rho.A V_w^3}{2} \tag{2}$$

P_w: extracted power from wind, ρ: density of air, V_w: wind velocity, A: area swept by the blades, Cp: power coefficient which is a function of β and λ as given by: [20]

$$\lambda = \frac{R \times \omega_m}{V_w} \tag{3}$$

ωm is the rotor turbine speed, and R is the radius of the turbine blades.

The power coefficient is given by: [21, 22]

$$C_P(\lambda,\beta) = 0.5176.(116.\frac{1}{\lambda_i} - 0,4.\beta - 5)\exp^{(-21.\frac{1}{\lambda_i})} + 0.0068.\lambda \tag{4}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1})$$

The torque of the wind turbine is expressed as:

$$T = C_p(\lambda,\beta).\frac{\rho.A V_w^3}{2.\lambda} \tag{5}$$

Fig. 3 presents Cp according to λ. There is only one optimal point, known by λ_{opt}, where the Cp value is maximum. The continuous operation of the wind turbine at this level guarantees that provide maximum available power in the wind at any speed.

When β=0, the Tip Speed Ratio (TSR) λ can be set to its optimal value (λ_{opt} = 8.1) and Cp can attain his maximum (Cpmax = 0.48), the MPPT control aim is achieved.

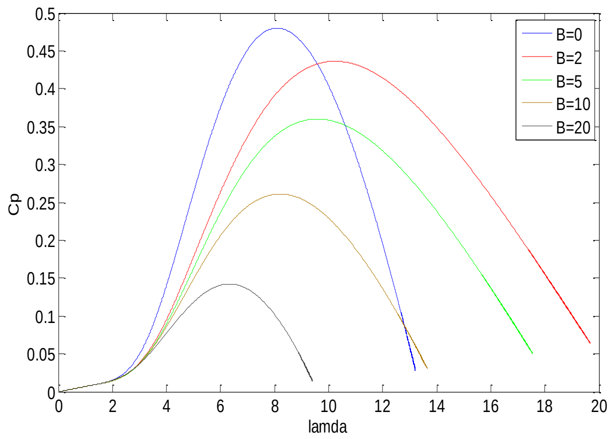

Fig. 3. The power coefficient characteristic

3. Generalized Predictive Control

When the wind power is less than the nominal value, the pitch angle is held constant and Cp becomes function of λ.

For every wind velocity, the optimal speed achieved is the reference for the closed loop.

GPC is a method based on a model that uses receding horizon approach for predicting future outputs. By minimizing the quadratic cost function, an appropriate sequence of control signals is calculated to minimize the tracking error. Once the first element of the control signal is applied to the system, the process is repeated every sampling time. Information is updated for every sample interval [23].

3.1. Model(CARIMA)

The predictive control method needs the definition of the numerical model. The process model is supposed to be in Controlled Auto Regressive Integrated Moving Average (CARIMA) form: [24-26]

$$A(q^{-1})y(t) = B(q^{-1})\ u(t-1) + \frac{\xi(t)}{\Delta(q^{-1})} \tag{6}$$

Where the expressions of the polynomials A and B are given as follow:

$$\begin{aligned} A(q^{-1}) &= 1 + a_1 q^{-1} + ...+ a_{na} q^{-na} \\ B(q^{-1}) &= b_0 + b_1 q^{-1} + ...+ a_{nb} q^{-nb} \end{aligned} \tag{7}$$

u, y: Process input and output

q^{-1}: delay operator.

n_a, n_b: A and B polynomial degree.

Δ (q-1) =1-q^{-1}: operator that ensures an integral control law.

ξ (t): zero mean white noise.

3.2. Definition of the Quadratic Function Cost

The criterion that is minimized, is a weighted sum of squares predicted futures errors and increments control values: [25]

$$J = \sum_{j=N_1}^{N_2} [w(t+j) - y(t+j)]^2 + \lambda_1 \sum_{j=1}^{N_u} \Delta u(t+j-1)^2 \tag{8}$$

N_1: minimum costing horizon,

N_2: maximum costing horizon,

N_u: control horizon,

λ_1: ponderation factor on the control.

3.3. Optimal Predictor Structure

The purpose of the method is to find an optimal predictor as: [27]

$$\begin{aligned} \hat{y}(t+j) &= F_j(q^{-1})y(t) + H_j(q^{-1})\Delta u(t-1) \\ &+ G_j(q^{-1})\Delta u(t+j-1) \end{aligned} \tag{9}$$

Where Hj, Fj and Gj represent respectively the past, the present and the future.

3.4. Equivalent *Regulator RST Synthesis*

RST polynomial form is summarized as depicted in Fig.4: [28, 29]

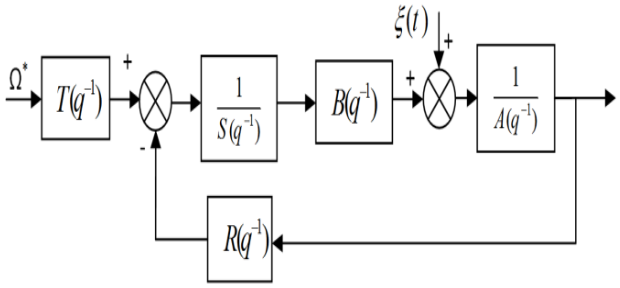

Fig. 4. RST polynomial controller equivalent of GPC

The polynomial form of Generalized Predictive Controller requires adjustment of parameters N1, N2, Nu and λ_1 to ensure good stability.

In the literature, we can find some recommendations: [30]

$$N_1 = \frac{dead - time\ of\ the\ system}{Sampling\ Period} = 1$$

$$N_2 \leq \frac{response\ time\ of\ the\ system}{Sampling\ Period}$$

Usually, Nu is chosen so that Nu << N2

The GPC parameters were chosen to design robust controller as shown in Table 1.

Table 1. GPC Parameters

N1	N2	Nu	λ_1
1	10	3	25

3.5. Result Analysis

Here, the results obtained from the GPC controller are compared with those found using PI controller.

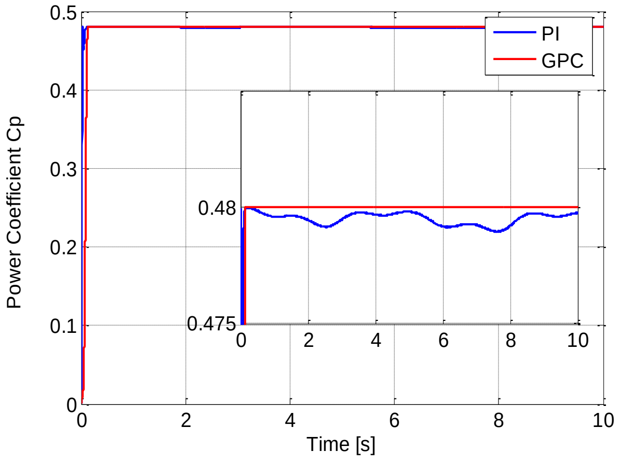

Fig. 5. Power Coefficient

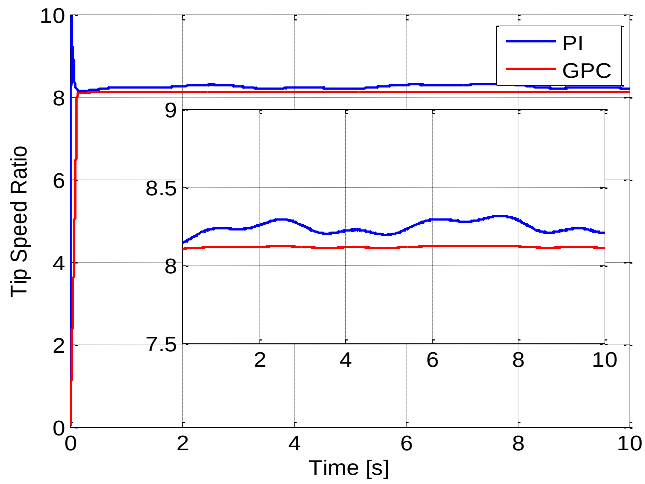

Fig. 6. Tip Speed Ratio

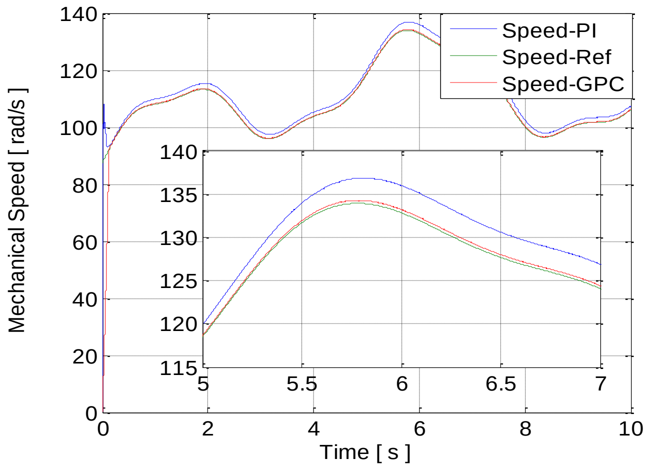

Fig. 7. Generator Speed

The power coefficient and the Tip Speed Ratio for each control strategy are presented in Fig.5 and Fig.6.

Compared with those from the PI control, which stay oscillating around the maximum value, power coefficient and the tip speed ratio are fixed at their optimum values Cp = 0.48 and λ = 8.1 with varying wind speed.

Fig. 7 shows the difference between the use of a PI controller and GPC controller in speed tracking. By using PI controller, the generator speed can follow the speed reference but not fully coincide. It can be observed that the GPC has a good effect on speed tracking. The generator measured speed coincides with the optimum speed reference.

4. Modelling and Control of PMSG

In the PMSG, the rotor excitation is supposed constant [31]. The electric model in the synchronous referential is determined by: [14, 32]

$$\begin{cases} \dfrac{dI_d}{dt} = -R_s I_d + V_d + \omega I_q L_q \\ \dfrac{dI_q}{dt} = -R_s I_q + V_q - \omega I_d L_d + \omega \Phi_f \end{cases} \quad (10)$$

Rs: stator resistance; Ld and Lq: components of stator inductances; Vd and Vq: stator voltage components; Id and Iq: components of stator current; Φf: permanent magnet flux. The electrical rotation speed ωe is given by:

$$\omega_e = n_p . \omega \quad (11)$$

n_p is the pole pair number. Power equations are provided by:

$$\begin{aligned} P &= \frac{3}{2}(V_d . I_d - V_q . I_q) \\ Q &= \frac{3}{2}(V_q . I_d - V_d . I_q) \end{aligned} \quad (12)$$

P and Q are active and reactive power output. The electromagnetic torque Te is calculated as follows:

$$T_e = \frac{3}{2} n_p \Phi_f i_q \quad (13)$$

The control scheme is represented in Fig.8. The quadratic current is used to control the speed of the generator through the MPPT control reference. The direct axis current is set to zero.

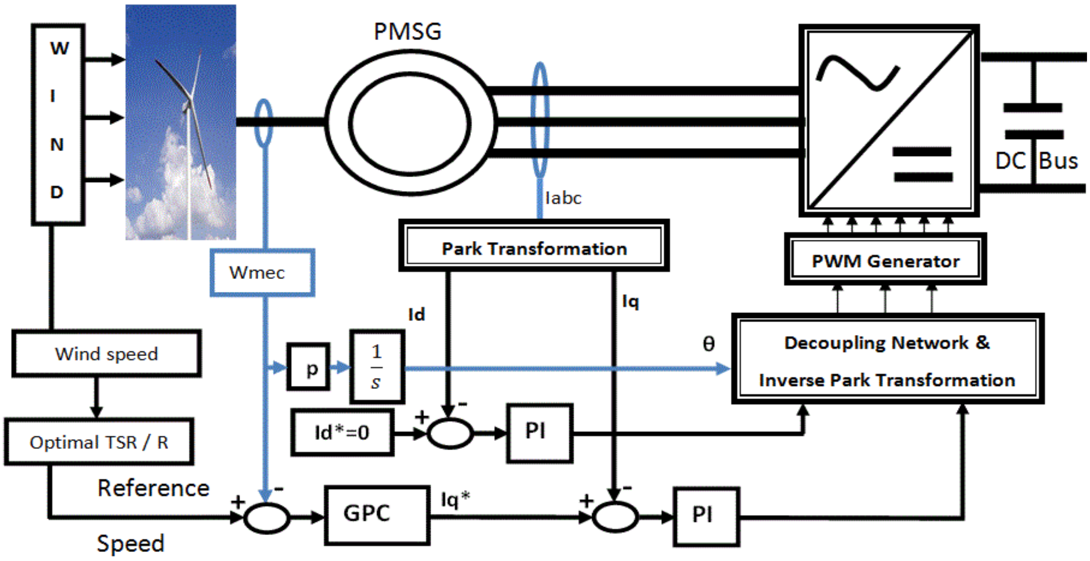

Fig. 8. Overall diagram of proposed control system of PMSG

5. Control of the Storage System

The converter is controlled to keep the DC bus voltage near the reference. The capacitor reference voltage was set to 500V.

The lead acid battery is considered as a storage element in the studied system. The battery is coupled to the DC bus via a bidirectional power converter as shown in Fig. 9.

When charging the battery, the converter is considered as unidirectional buck converter. The energy circulates from the DC bus to the battery via the switch S1 and S2 diode. The battery discharges through switch S2 and S1 diode to provide energy to the DC bus. The converter operates as a boost converter.

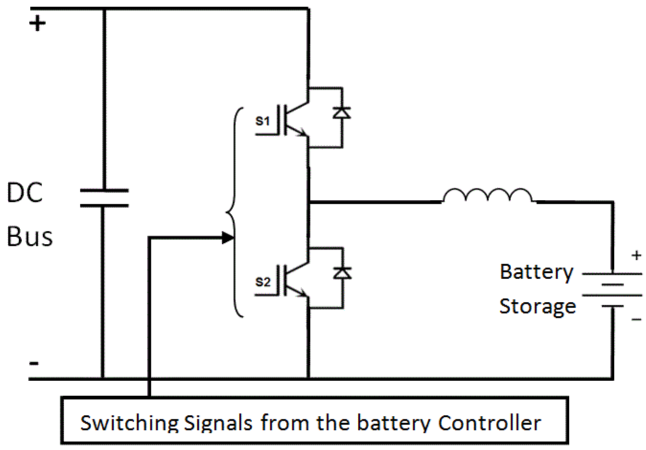

Fig. 9. DC/DC battery power converter

As illustrated in Figure 10, the voltage reference is compared to the actual measurement. The error is treated by the PI controller. The output signal is used to control the switches S1 or S2 depending on the case of charge or discharge.

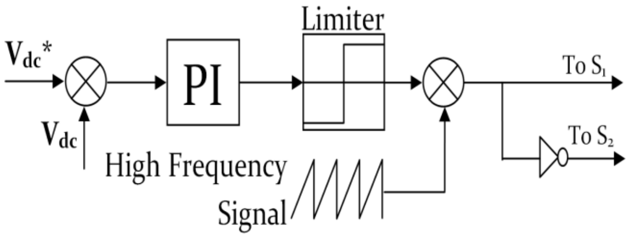

Fig. 10. Control Scheme of dc–dc buck-boost

6. Load Side Control

The voltage and frequency control is the main purpose of controlling the load side converter. A three-phase inverter is introduced between the DC bus and the user load. Output voltages are controlled in terms of frequency and amplitude, upon variation of the load and / or wind speed, because of the absence of the network in the autonomous systems [33, 34]. In our study, the frequency of the charging voltage is 50 Hz and the RMS value of the phase voltage is fixed at 220V.

The equations of the voltage in the rotating frame are given as follows:

$$\begin{cases} V_d = V_{di} - L_f \dfrac{dI_d}{dt} + \omega I_q L_f \\ V_q = V_{qi} - L_f \dfrac{dI_q}{dt} - \omega I_q L_f \end{cases} \tag{14}$$

Active and reactive powers are given in the dq coordinate by:

$$\begin{aligned} P &= \frac{3}{2}(V_d.I_d + V_q.I_q) \\ Q &= \frac{3}{2}(V_q.I_d + V_d.I_q) \end{aligned} \tag{15}$$

The equations of active and reactive power in the rotating frame, assuming Vq= 0 and Vd= |V|, will be as follows:

$$\begin{aligned} P &= \frac{3}{2}V_d.I_d = \frac{3}{2}|V|I_d \\ Q &= \frac{3}{2}V_d.I_q = \frac{3}{2}|V|I_q \end{aligned} \tag{16}$$

Active and reactive power can be ordered systematically via the direct and quadrature current elements. For resistive load, Vd * can be given by:

$$V_d{}^* = \sqrt{2}V^*_{RMS} \tag{17}$$

Where V^*_{RMS} is the output RMS phase voltage reference value. In this control technique, both of internal and external control loops are governed by the PI controllers. The load side converter control technique is shown in Fig 11.

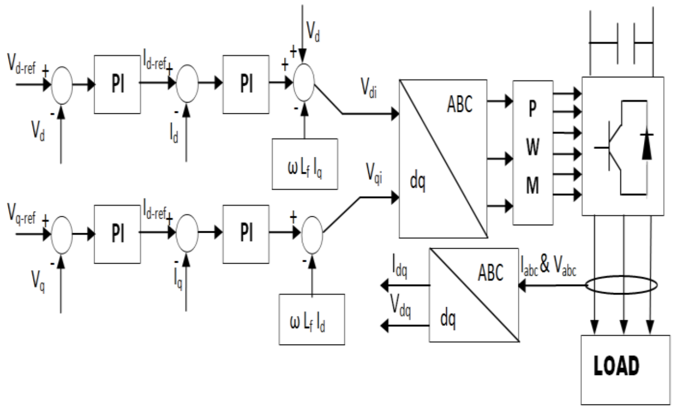

Fig. 11. Load side converter control scheme

7. Simulation Results and Discussions

The effectiveness of the suggested control strategy has been simulated using MATLAB/Simulink with parameters given in Table 2.

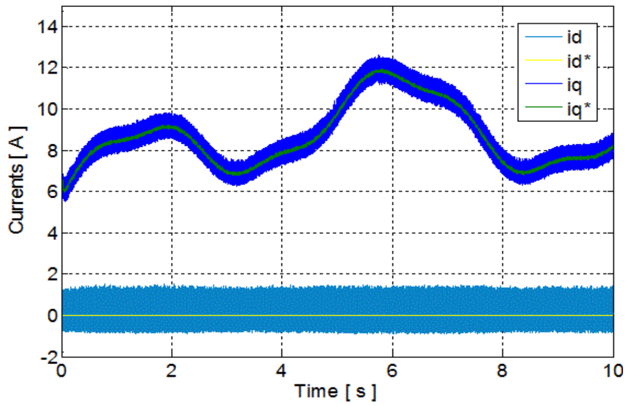

Fig. 12. Stator current regulation

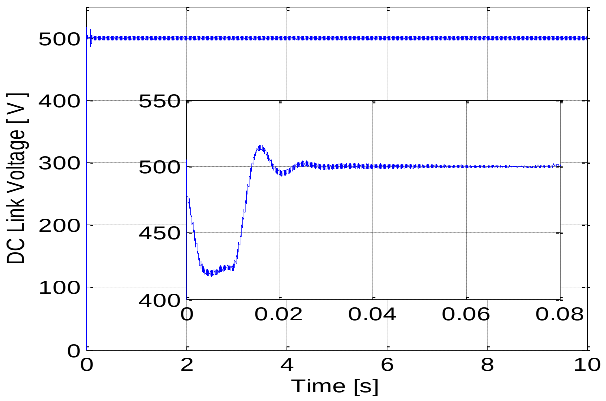

Fig. 13. DC Link Voltage

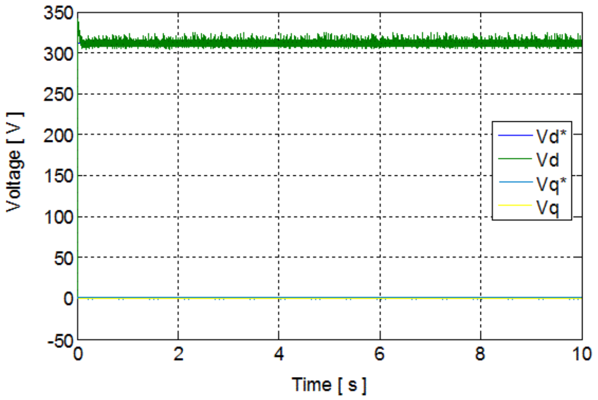

Fig. 14. d-and q-axis output voltages

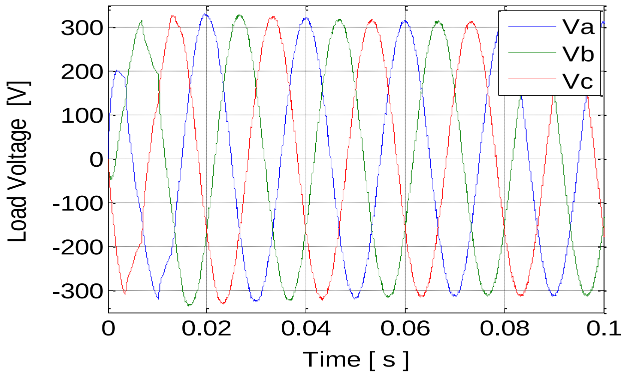

Fig. 15. Load Voltage

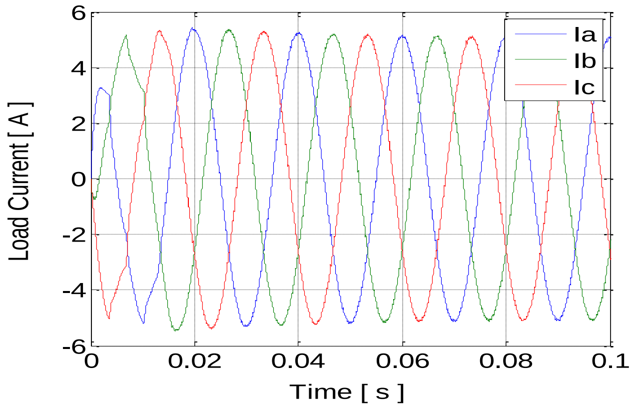

Fig. 16. Load Current

Fig. 12 shows the stator currents of synchronous generator. It is seen that the controller regulates the d-and q-axis stator currents in order maintain a high efficiency operation of the generator.

As indicated above, the buck boost converter was controlled to keep the DC bus voltage at the nominal value. As shown in Fig 13, It was achieved an adequate control of the DC bus voltage. The capacitor voltage is kept constant even with variations of wind speed. It is noted that the load currents are sinusoidal, which increased the efficiency of control. Fig. 14 presents the regulation of the load side output voltage. The actual and the target of the d-and q-axis output voltages are practically coincident for most of the considered time interval.

Fig. 15 and 16 shows respectively voltage and the current of the load. We can deduce that the inverter's voltage control is working well in a variable wind speed.

Table 2. Parameters used in Simulations

Symbol	Quantity	Values
Rs	Stator phase resistance	2.8750 Ω
Ls	Stator phase inductance	8.5e-3 H
Φf	Permanent magnetic flux	0.175 Wb
J	Inertia moment	0.0008 kg·m^2
f	Friction coefficient	0.001 Nm/rad/s
n_p	Pole pairs number	4
R	the radius of the turbine blades	3 m
ρ	The air density	1.225 kg/m^3
Cp_{max}	Power Coefficient (optimal value)	0.48
λ_{opt}	Tip Speed Ratio (optimal value)	8.1

8. Conclusion

The control of standalone wind energy conversion system is presented in this article. The system is comprises a PMSG, a wind turbine and a lead-acid battery as storage element.

The objective of this work is to apply a Generalized Predictive Controller to wind energy conversion system with particular attention on MPPT. A comparison between performances of the proposed GPC method and conventional Proportional Integral (PI) controller is performed.

The GPC regulator was synthesized under the RST form. This method obtained the optimal value of Cp and keeps it at maximum even in the presence of changes in wind velocity. The output voltage of inverter is maintained constant at its rated value by keeping the DC-link voltage at the desired value.

The results of simulation are very satisfactory because it gets good tracking performances. The comparison between GPC and PI control methods is given. The results indicate that the GPC method shortens transient time clearly.

References

[1] V. Nelson, Wind Energy: Renewable Energy and the Environment, Second Edition, Florida: CRC Press, 2013.

[2] R. Saidur, N. A. Rahim, M. R. Islam, et K. H. Solangi, “Environmental impact of wind energy”, Renew.

Sustain. Energy Rev., vol. 15, no 5, pp. 2423‑2430, juin 2011

[3] D. Y. C. Leung et Y. Yang, “Wind energy development and its environmental impact: A review”, Renew. Sustain. Energy Rev, Vol.16, pp. 1031-1039, Janvier, 2012

[4] Steve Sawyer and Klaus Rave, Global wind report, Global Wind Energy Council (GWEC), 2014.

[5] O. Badran, “Wind turbine utilization for water pumping in Jordan”, J. Wind Eng. Ind. Aerodyn., Vol. 91, pp. 1203-1214, October,2003.

[6] M. E. Haque, M. Negnevitsky, et K. M. Muttaqi, “A Novel Control Strategy for a Variable Speed Wind Turbine with a Permanent Magnet Synchronous Generator”, in IEEE Industry Applications Society Annual Meeting IAS ’08 Edmonton, Canada, pp. 1-8, 5-9 October 2008.

[7] A. M. O. Haruni, A. Gargoom, M. E. Haque, et M. Negnevitsky, “Voltage and frequency stabilization of wind-diesel hybrid remote area power systems”, in Australasian Universities Power Engineering Conference AUPEC Adelaide, Australia, pp. 1-6, 27-30 September 2009.

[8] A. M. O. Haruni, M. Negnevitsky, M. E. Haque, et A. Gargoom, “Control strategy of a stand-alone variable speed wind turbine with integrated energy storage system using NPC converter”, in IEEE Power and Energy Society General Meeting, Detroit, USA, pp. 1-8, 24-29 July 2011,.

[9] J. H. Lee, “Model predictive control: Review of the three decades of development”, Int. J. Control Autom. Syst., Vol. 9, no.3, 415-424, juin 2011.

[10] D. Uduehi, A. Ordys, and M. J. Grimble, “A generalized predictive control benchmark index for MIMO systems”, in Proceedings of the 2002 International Conference on Control Applications, Glasgow, UK, pp. 1213-1218, 18-20 September 2002.

[11] cike J. Grimble and A. W. Ordys, “Predictive control for industrial applications”, Annu. Rev. Control, Vol. 25, 13-24, 2001.

[12] H. Li, K. L. Shi, et P. G. McLaren, “Neural-network-based sensorless maximum wind energy capture with compensated power coefficient”, IEEE Trans. On Ind. Appl., Vol. 41, 1548-1556, 2005.

[13] K. Ouari, T. Rekioua, and M. Ouhrouche, “Real time simulation of nonlinear generalized predictive control for wind energy conversion system with nonlinear observer”, ISA Trans., Vol. 53, 76-84, Janvier, 2014.

[14] H.-W. Kim, S.-S. Kim, et H.-S. Ko, “Modeling and control of PMSG-based variable-speed wind turbine”, Electr. Power Syst. Res.,Vol. 80, 46-52, 2010.

[15] E. Mouni, S. Tnani, et G. Champenois, « Synchronous generator output voltage control via a generalized predictive R S T controller », in IEEE International Symposium on Industrial Electronics ISIE , Cambridge, United Kingdom, pp. 718-723, 30 Jun - 02 Jul 2008.

[16] A. Mirecki, X. Roboam, and F. Richardeau, “Architecture complexity and energy efficiency of small wind turbines”, IEEE Trans. On Ind. Electron. Vol. 54, 660-667, 2007.

[17] A. Abdelli, B. Sareni, et X. Roboam, “Optimization of a small passive wind turbine generator with multiobjective genetic algorithms”, Int. J. Appl. Electromagn. Mech., Vol. 26, 175-182, 2007.

[18] D.-H. Tran, B. Sareni, X. Roboam, et C. Espanet, “Integrated optimal design of a passive wind turbine system: an experimental validation”, IEEE Trans. On Sustain. Energy, Vol. 1, 48-56, 2010.

[19] C.-H. Lin, “Recurrent modified Elman neural network control of PM synchronous generator system using wind turbine emulator of PM synchronous servo motor drive”, Int. J. Electr. Power Energy Syst., Vol. 52, 143-160, 2013.

[20] S. M. Muyeen, A. Al-Durra, and J. Tamura, “Variable speed wind turbine generator system with current controlled voltage source inverter”, Energy Convers. Manag., Vol. 52, 2688-2694, 2011.

[21] R. Gasch and J. Twele, Wind power plants: fundamentals, design, construction and operation. Berlin: Springer-Verlag, 2011

[22] L. Peng, F. Colas, B. Francois, and Y. Li, “A modified vector control strategy for DFIG based wind turbines to ride-through voltage dips”, 13th European Conference on Power Electronics and Applications EPE’09 Barcelona, pp. 1–10, 8-10 September 2009.

[23] S. Chidrawar and B. Patre, “Generalized predictive control and neural generalized predictive control”, Leonardo J. Sci., Vol. 13, 133-152, 2008.

[24] D. W. Clarke, C. Mohtadi, and P. S. Tuffs, “Generalized predictive control—Part I. The basic algorithm”, Automatica, Vol. 23, 137-148, Mars1987.

[25] E. F. Camacho and C. B. Alba, Model Predictive Control. Berlin: Springer-Verlag, 2013.

[26] J. A. Rossiter, Model-Based Predictive Control: A Practical Approach. Florida: CRC Press, 2013.

[27] D. W. Clarke, C. Mohtadi, and P. S. Tuffs, “Generalized Predictive Control—Part II Extensions and interpretations”, Automatica, 23, 149-160, Mars 1987.

[28] Maaziz, M.K.; Boucher, P.; Dumur, D., “A new RST cascaded predictive control scheme for induction machines”, the IEEE International Conference on Control Applications, Kohala Coast, pp.927-932, 22-27 August 1999.

[29] D. Dumur, P. Boucher, and J. Röder, “Advantages of an Open Architecture Structure for the Design of Predictive Controllers for Motor Drives”, Annals of the CIRP. Vol. 47, 291-294, 1998.

[30] D. Dumur, P. Boucher, and J. Röder, "Design of an open architecture structure for implementation of predictive controllers for motor drives," in Proceedings of the 1998 IEEE International Conference on Control Applications, Trieste, pp. 1307-1311, 1-4 September 1998.

[31] Jayalakshmi N. S, D. N. Gaonkar, "Maximum Power Point Tracking for Grid Integrated Variable Speed Wind based Distributed Generation System with Dynamic Load" International Journal of Renewable Energy Research, Vol. 4, No.2, 464-470, 2014.

[32] M. Chinchilla, S. Arnaltes, and J. C. Burgos, "Control of permanent-magnet generators applied to variable-speed wind-energy systems connected to the grid," IEEE Trans. On Energy Convers., Vol. 21,No. 1, 130-135, 2006.

[33] Z. Alnasir and M. Kazerani, "An analytical literature review of stand-alone wind energy conversion systems from generator viewpoint," Renew. Sustain. Energy Rev., Vol. 28, 597-615, December 2013.

[34] Kenneth E. Okedu, "Hybrid Control Strategy for Variable Speed Wind Turbine Power Converters" International Journal of Renewable Energy Research, Vol. 3, No.2, 283-288, 2013.