Mustapha MEKKI[1], **Tayeb ALLAOUI**[1], **Belkacem BELABBAS**[1], **Mouloud DENAI**[2]

Laboratory of Energy Engineering and Computer Engineering, University of Tiaret, Algeria(1)
School of Engineering and Computer Science, University of Hertfordshire, Hatfield, UK (2)

doi:10.15199/48.2020.08.22

Decoupling Vector Control and Optimisation of PMSG-Based Wind Energy System Using Adaptive Type-1 and Type-2 Fuzzy Logic Control

***Abstract**. Variable-speed wind energy conversion systems based on permanent magnet synchronous generators (PMSG) are becoming increasingly popular over the recent years and PMSGs are being adopted by many wind turbine manufacturers especially due to several advantages such as high energy density, low maintenance, self-excitation and direct-drive operation. Vector control is currently the most widely used control strategyin PMSGs to achieve decoupling between the magnetic flux and torguqe via the direct and quadrature components of the current respectively.The major disadvantage of this method is the use of current sensors to ensure accurate decoupling. In this work, a decoupling vector control strategy based on Type-1 and Type-2 fuzzy logic is proposed eliminating the use of current sensors. In addition, a maximum power point tracking (MPPT) technique is proposed to optimise the power extracted from the wind turbine system. Two speed control methodes based on adaptive Type-1 and Type-2 fuzzy logic fractional proportional and integral (PI) controllers. Several simulations are presented to demonstrated the effectiveness of the proposed control schemes for the PMSG-based wind energy conversion system.*

Streszczenie.** Generator synchroniczny z magnesem trwałym PMSG odgrywa kluczową rolę w konwersji energii wiatru (WECS). Sterowanie wektorowe było najczęściej stosowane jako strategia sterowania dla tego generatora w celu zapewnienia oddzielenia prądu stałego od kwadratury. Wadą tej metody jest to, że potrzebuje czujników prądu, aby zapewnić oddzielenie. Artykuł koncentruje się na sterowaniu wektorem oddzielającym opartym na logice rozmytej typu 1 (DFLC1_VC) i logice rozmytej typu 2 (DFLC2_VC). Możemy zapewnić kontrolę systemu, a oddzielenie bez użycia czujników prądu zapewnia kontrolę i odsprzęgnięcie w tym samym czasie. Wyniki symulacji wykazały skuteczność proponowanych strategii kontroli WECS w oparciu o PMSG. **Odsprzęgnięte sterowanie wektorowe systemu energii wiatrowej z generatorem MSG wykorzystujące logikę rozmytą

Keywords: WECS; PMSG; MPPT; Vector Control; Decoupling Vector Control; FOPI, type-1 fuzzy logic, type-2 fuzzy logic.
Słowa kluczowe: WECS; PMSG; MPPT; Kontrola wektorowa; FOPI, logika rozmyta typu 1, logika rozmyta typu 2.

Introduction

In recent years, there has been a global trend towards the adoption of renewable energy sources as conventional sources of energy based on fossil fuels are limited and demand for such sources increases every year [1-2]. Today, wind energy is the fastest growing renewable energy technology worldwide.

The permanent magnet synchronous generator (PMSG) has recently begun to attract the attention of wind turbine manufacturers due to its superior features. This generator is an interesting solution which is based on variable-speed operation. Since the speed of wind turbine is variable, the generator is controlled by power electronic devices. The generator is self-excited by the permanent magnets there is no need for an external DC excitation system. With a multipole synchronous generator it is possible to operate at low speeds and without gearbox. Therefore eliminating losses and avoiding maintenance of the gearbox. The generator is directly connected to the grid through a full scale back-to-back power converter. The power converter provides the interface between the generator and the grid. With a full scale power converter, there are more losses which may be a drawback but it allows a full controllability of the system. With the use of the power converter it is possible to comply with the grid connection requirements [3-4].

The structure of the control system is very important not only for extracting the maximum wind power with the best performance, but also to improve the decoupling between the torque and the flux and avoid degradation of the quality of the electrical energy injected into the grid. The most frequent control methodology used in the literature is vector control. The main objective of this technique is to separate the rotor currents into two components, one controls the torque and the other controls the flux independently in order to emulate the simple regulation of a separately excited DC machine. Vector control based on conventional Proportional-Integral (PI) controllers has been adopted for a long time. However, this type of controllers have some limitations and are less effective under variable operating conditions. Furthermore, current sensors are required to ensure accurate decoupling. Several works have shown that the fuzzy logic controllers (FLC) are able to out-perform conventional controllers under such operating conditions. FLCs provide better transient response tracking and are less sensitive to parametric variations and disturbances as compared to PI controllers. In this technique, the PI controller is replaced by the FLC controller but it requires a decoupling block similar to that of a PI where current sensors are still needed [5, 9].

In this study, a decoupling vector control scheme based on Type-1 fuzzy logic (DFLC1_VC) and Type-2 fuzzy logic (DFLC2_VC) are proposed. These controllers are designed to simultaneously to perform speed regulation and decoupling.

To optimize the power supplied by wind power system, the proposed control strategies for the PMSG wind energy conversion system include a full proportional (PI), on adaptive type-1 fuzzy logic fractional PI regulator (AFLC1_FOPI) and on adaptive type-2 fuzzy logic fractional PI regulator (AFLC2_FOPI). A comparison of these controllers is also presented to demonstrate the superior performance and robustness of the proposed controllers and the limitations of the traditional fixed parameter PI controllers for this application.

The remaining of the paper is organized as follows: The description and modelling of the wind generatoar system are presented in Section 2. In Section 3, the proposed optimization and control scheme is described. The results of the simulation are presented in Section 4. The conclusion of the paper are summarised in Section 5.

Description of the wind generator system

The overall system is shown in Fig.1. The wind generator consists of a variable speed turbine coupled directly to a permanent magnet synchronous generator (PMSG) connected to a DC bus through a PWM power converter.

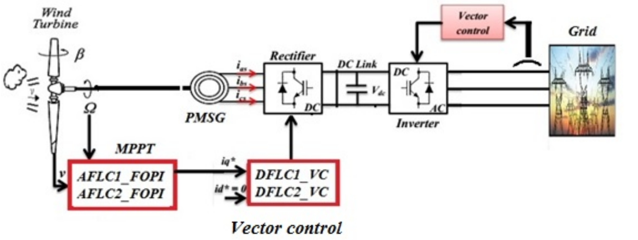


Fig.1. Configuration of PMSG-based wind turbine water pumping system

Wind turbine model

The turbine power and torque developed are given by the following relation [10,12]:

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda) \tag{1}$$

$$T_m = \frac{P_m}{\Omega} = \frac{1}{2\lambda}\rho\pi R^3 v^2 C_p(\lambda) \tag{2}$$

Where λ denotes the ratio between the turbine angular speed and the wind speed. This ratio is defined as the tip speed ratio and is given as:

$$\lambda = \frac{\Omega R}{v} \tag{3}$$

Where ρ is the air density, R is the blade length, v is the wind speed, Cp is the power coefficient, Ω is the turbine angular speed.

The power coefficient (Cp) represents the aerodynamic efficiency of the turbine and depends on the specific speed λ and the angle of attack of the blades. It differs from one turbine to another, and is usually provided by the manufacturer [13,14].

Permanent magnetic synchronous generator

A detailed model of the PMSG generator drive system is required for a complete and proper simulation of the system [6]. The dynamic model of the PMSG can be represented in the rotating reference frame with the following equations:

$$\begin{cases} Vq = -R_s.I_q - L_q.\dfrac{dI_q}{dt} - w.L_d.I_d + w.\phi_m \\ Vd = -R_s.I_d - L_d.\dfrac{dI_d}{dt} + w.L_q.I_q \end{cases} \tag{4}$$

The electromagnetic torque in the rotor can be written as:

$$Cem = P.\frac{3}{2}.[(L_d - L_q).I_d.I_q + \phi_m.I_q] \tag{5}$$

In a cylindrical rotor is assumed then $L_d \approx L_q$ and hence the above equation reduces to:

$$Cem = P.\frac{3}{2}.\phi_m.I_q \tag{6}$$

Where P is the number of poles, Φ_m is the magnetic flux, L_d is the direct axis inductance, L_q is the quadrature inductance, R_s is the resistance and w is the rotor speed of the generator [7].

Controllers design

The control of the WECS system consists of two control parts: optimization of wind energy conversion system and vector control of PMSG generator.

MPPT Algorithms: Extracting Maximum Power from Wind Turbines

Two different Maximum Power Point Traching (MPPT) techniques used to extract the maximum power from wind energy conversion system. In this study, the proposed MPPTs methods are based on an adaptive Type-1 fuzzy logic controller (AFLC1_FOPID) and an adaptive Type-2 fuzzy logic controller (AFLC2_FOPID).

Adaptive Type-1 fuzzy logic controller (AFLC1_FOPID)

The purpose of the AFLC1_FOPID adjusts the parameters of the FOPID in order to improve the performances of the system as illustrated in Fig. 2.

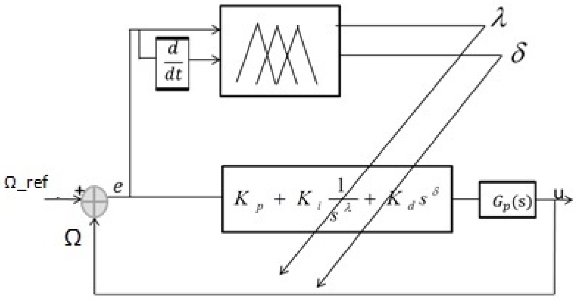


Fig.2. Adaptive Type-1 fuzzy logic fractional PID regulator

As shown in Fig. 2, the PID parameters λ and δ can affect the error e and the change of error Δ e.

For this purpose, the designed (AFLC1_FOPID) has two inputs variables are e and of Δe, and the two outputs variables are λ and δ parameters (Figs. 3 and 4).

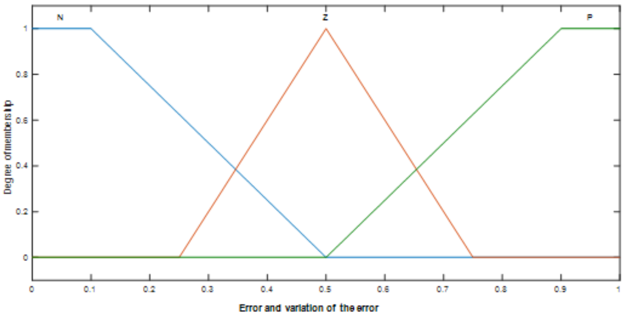


Fig. 3. Membership functions of e and of Δ e

The fractional PID regulator strategy with type-1 FLC is performed by the rule base matrix given by Table 1.

Table 1 Representation of inference rules

e	Δe		λ	δ
N	N		GP	GP
N	Z		GP	PM
N	P		GP	GN
N	N		GP	GP
N	Z		GP	PM
Z	P		NM	GN
Z	N	–	PM	GP
Z	Z		Z	Z
Z	P		NM	GN
Z	N		Z	Z
P	Z		GN	NM
P	P		GN	GN
P	N		GN	GP
P	Z		GN	NM
P	P		GN	GN

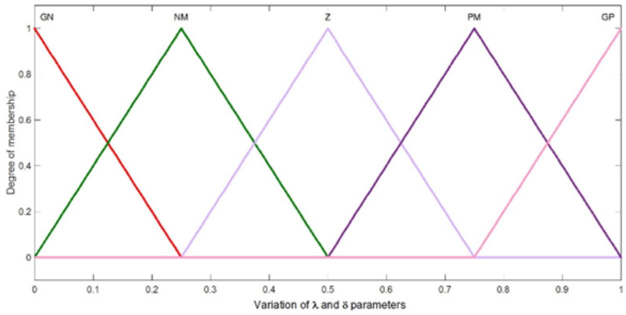


Fig. 4. Membership functions of λ and δ parameters.

Adaptive Type-2 fuzzy logic controller (AFLC2_FOPID)

In this case, the proposed control scheme for the speed is based on Interval Type 2 adaptive FOPID fuzzy logic controller and is applied to this regulation to optimize the power supplied by the PMSG generator for variable wind speed [18][19].

The structure of the fuzzy logic type 2 adaptive FOPID control combines a FOPID controller with Type-2 FLC. On the one hand, it has adaptive ability, which enables it to automatically identify the controlled process parameters, set control parameters, and adapt to the changes of process parameters. On the other hand, it also has the advantages of the FOPID controller, such as simple structure, and familiarity to practical engineering-design personnel [15,17].

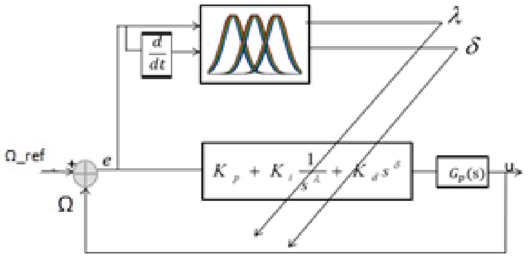


Fig. 5. An adaptive type-2 fuzzy logic fractional PID regulator

The membership functions for the inputs and outputs variables are represented in Fig. 6 and Fig. 7, respectively.

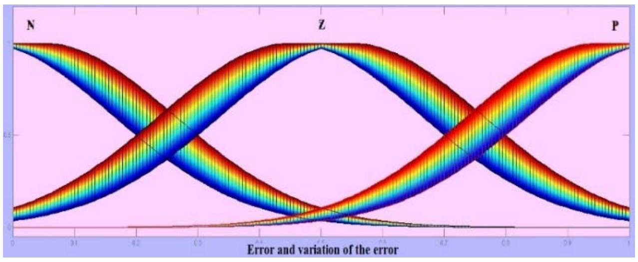


Fig. 6. Membership functions of e and of Δ e

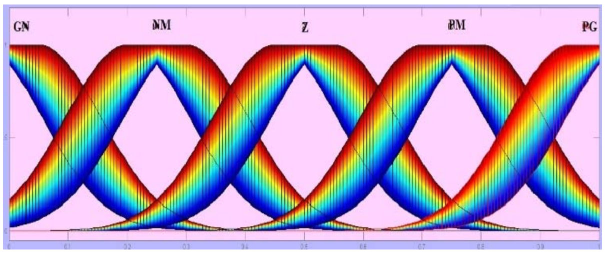


Fig. 7. Membership functions of λ and δ parameters.

The fractional PID regulator strategy with type-1 FLC is performed by the rule base matrix given by Table 1.

Table 1 Representation of inference rules

e	Δe		λ	δ
N	N	–	GP	GP
N	Z		GP	PM
N	P		GP	GN
N	N		GP	GP
N	Z		GP	PM
Z	P		NM	GN
Z	N		PM	GP
Z	Z		Z	Z
Z	P		NM	GN
Z	N		Z	Z
P	Z		GN	NM
P	P		GN	GN
P	N		GN	GP
P	Z		GN	NM
P	P		GN	GN

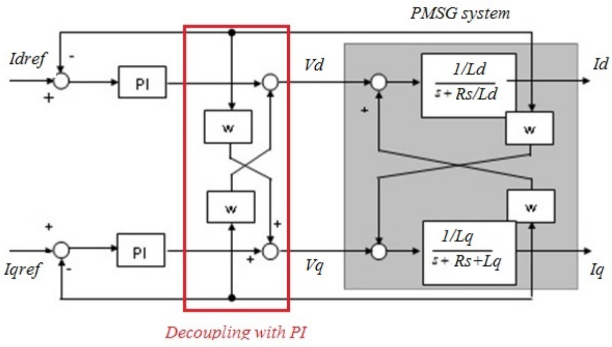


Fig. 8. Decoupling vector control with PI of PMSG system.

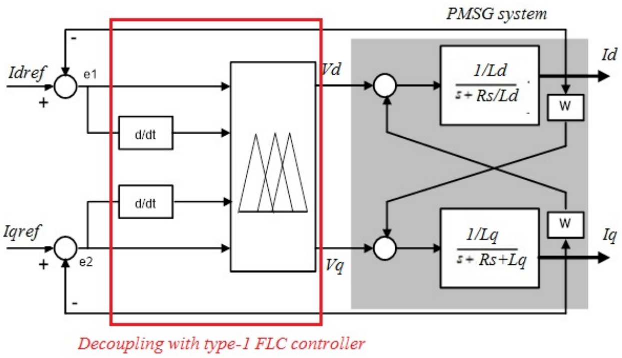


Fig. 9 .Decoupling vector control with type-1 FLC of PMSG system.

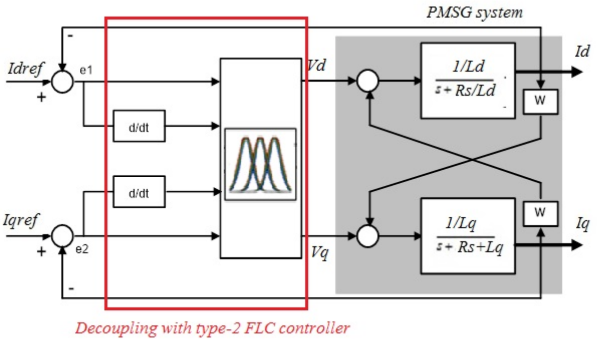


Fig.10. Decoupling vector control with type-2 FLC of PMSG system.

Decoupling vector control of PMSG generator

Three different decoupling vector control of PMSG are proposed based on PI, Type-1 fuzzy logic (DFLC1_VC) and Type-2 fuzzy logic (DFLC2_VC).

Figures. 8, 9 and 10 depict the decoupling vector control for the PMSG using PI, a type-1 FLC and type-2 FLC respectively [12], [13].

The FLC inputs are the errors signals (e1=Idref- Id) and (*e2=Iqref- Iq*). The outputs are *Vd* and *Vq*.

The universe of discourse for the input variables (error and error change) are defined by two fuzzy subsets {N, P} where N (Negative) and P (Positive) are linguistic variables. The universe of discourses for *Vd* and *Vq* voltages are defined by the fuzzy subsets {N, Z, P}.

The membership functions for the input and output variables are of DFLC1_VC strategy are represented in Figs. 11 and 12 respectively.

The membership functions for the input and output variables are of DFLC12_VC strategy are represented in Figs. 13 and 14 respectively.

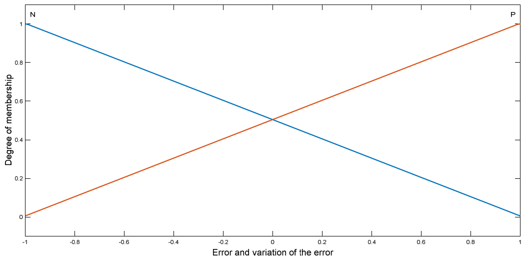


Fig. 11. Membership functions of e and of Δe

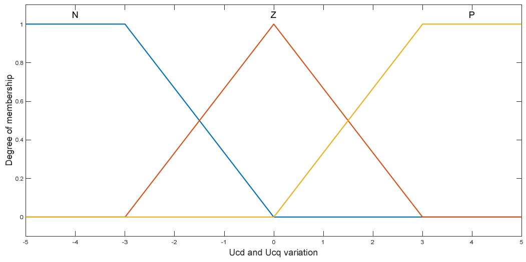


Fig. 12. Membership functions of *Vd* and of *Vq*.

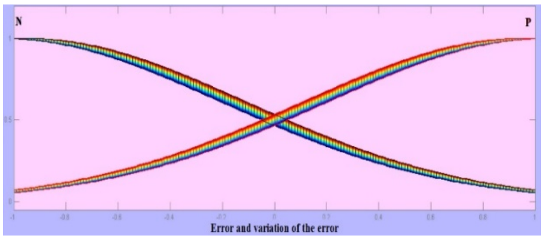


Fig. 13. Membership functions of e and of Δ e.

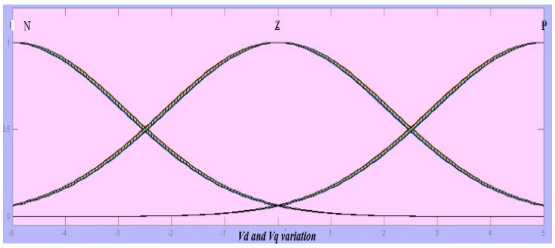


Fig. 14. Membership functions of *Vd* and of *Vq*.

The decoupling vector strategy with type-1 FLC and type-2 FLC is performed by the rule base matrix given by Table 2.

Table 1 Representation of inference rules

e_1	Δe_1	e_2	Δe_2		*Vd*	*Vq*
N	N	N	N		P	P
N	N	N	P		P	Z
N	N	P	N		P	Z
N	N	P	P		P	N
N	P	N	N		Z	P
N	P	N	P		Z	Z
N	P	P	N	–	Z	Z
N	P	P	P		Z	N
P	N	N	N		Z	P
P	N	N	P		Z	Z
P	N	P	N		Z	Z
P	N	P	P		Z	N
P	P	N	N		N	P
P	P	N	P		N	Z
P	P	P	N		N	Z
P	P	P	P		N	N

Control of the bus voltage Vdc and the active and reactive powers injected into the network:

We know that the active and reactive powers in the network are given by [1]:

$$\begin{cases} P_r = \frac{3}{2}(V_{rd}.I_{rd} + V_{rq}.I_{rq}) \\ Q_r = \frac{3}{2}(V_{rq}.I_{rd} - V_{rd}.I_{rq}) \end{cases} \tag{07}$$

The control scheme is as follows:

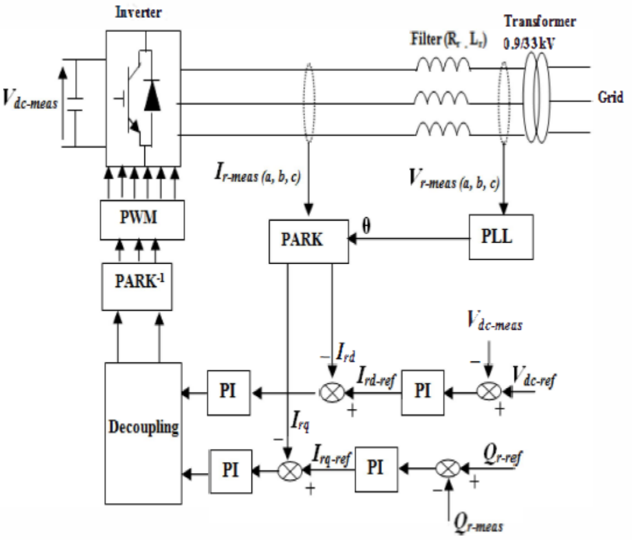


Fig. 15. Control strategy between the PMSG and the grid.

The DC bus voltage and the active power exchanged with the network are given by the following equation:

$$V_{dc}.I_{dc} = \frac{3}{2}.V_{rd}.I_{rd} \tag{08}$$

The parameters of the DC bus voltage regulator are given as follows [1]:

$$\begin{cases} k_{p-v_{dc}} = \sqrt{2}.\omega_n.C \\ k_{i-v_{dc}} = C.\omega_n{}^2 \end{cases} \tag{09}$$

The parameters of the power regulation:

$$\begin{cases} k_p = \sqrt{2}.\omega_n.L_f - R_f \\ k_i = L_f.\omega_n{}^2 \end{cases} \tag{10}$$

Simulation results

The variable wind speed profile used in these simulations is shown in Fig. 16. It varies between a minimum value of 7m/s and a maximum value of 14,8 m/s.

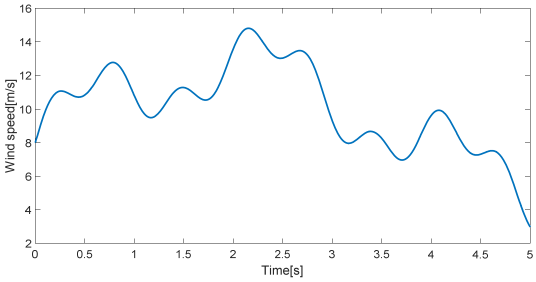


Fig.16. Wind speed profile.

The proposed system is simulated in MATLAB/Simulink environment using SimPowerSystem (SPS) blockset.

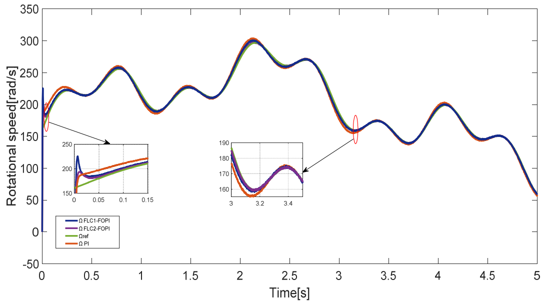


Fig. 17. Rotational speed (rad / s).

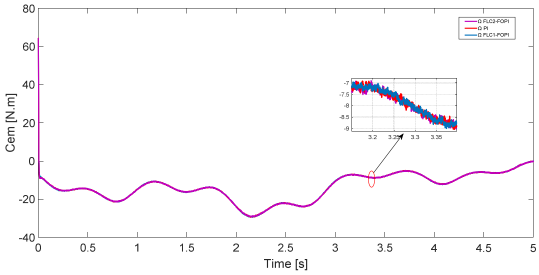
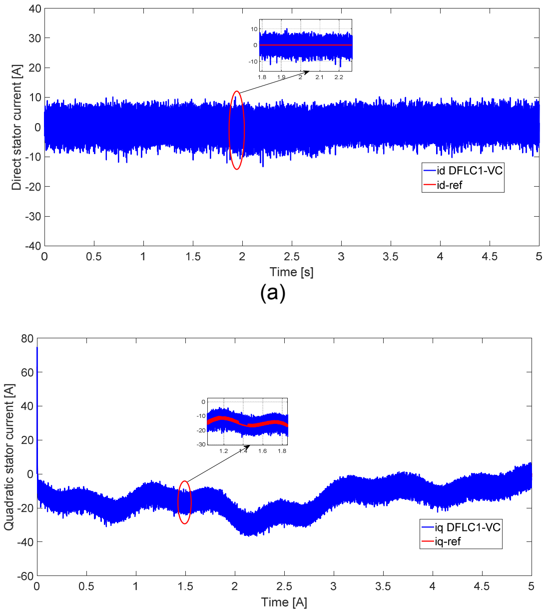


Fig. 18. Electromagnetic torque (N. m),

electromagnetic torque of the PMSG, with the three MPPT algorithm (PI, AFLC1_FOPI, AFLC2_FOPI) respectively.

It can be observed that, initially, the speed of rotation diverges from its the desired reference speed for a very short time for the three MPPT algorithms. The variations of the speed of the generator are adapted to the variation of the speed of the wind.

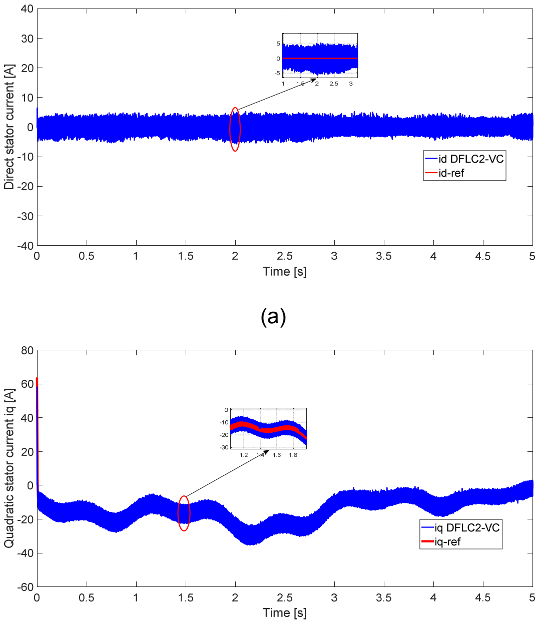
As depicted from these figures, the proposed MPPT strategy "AFLC2_FOPI" leads to a better and enhanced response. The overshoot in the system states have been considerably reduced with a better accuracy as compared to both the PI [20] and the AFLC1_FOPI strategies, respectively.



(a)

(b)

Fig. 19. System performance under random wind speed using a decoupling vector control based on type-1 fuzzy logic (DFLC1_VC). (a) direct stator current (A) and (b) quadratic stator current (A).



(a)

(b)

Fig. 20. System performance under random wind speed using a decoupling vector control based on type-1 fuzzy logic (DFLC2_VC). (a) direct stator current (A) and (b) quadratic stator current (A).

Figs. 19 and 20 show the direct and quadratic stator current and the quadratic stator current of the PMSG, for the a decoupling vector control based on type-1 fuzzy logic (DFLC1_VC) and type-2 fuzzy logic (DFLC2_VC). It can be noted that the two current components exhibit better performance with a significant reduction in the amplitudes of the oscillations, as compared to those obtained with PI [20].

It can be seen the current iq the image of the torque and the current id assumes a value close to zero. Thus the decoupling is assured and therefore a good operation of the of the two proposed vector controls DFLC1_VC and DFLC2_VC).

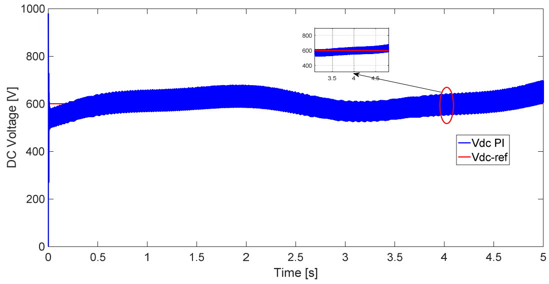


Fig. 21. DC Voltage.

Figure 21 illustrates the curve of the DC voltage, one can notice well that the measured value of the tension follows its reference with a good dynamics, nevertheless some fluctuations which are due to the variation of the wind speed.

Conclusion

The aim of this work was to propose an effective control scheme for a wind energy conversion system based on a permanent magnet synchronous generator to ensure both good tracking of the generator speed for different wind variations and achieve a maximum power extraction from the wind. Two control strategies based on Type-1 and Type-2 fuzzy logic control are designed and evaluated under different operating conditions of the wind energy system using MATLAB/Simulink. The results demonstrate improved performance and robustness of the proposed control schemes AFLC1_FOPI and AFLC2_FOPI as compared to to conventional MPPT algorithms.

Decoupling without sensors of the current by the two proposed strategies DFLC1_VC and DFLC2_VC is perfect with a significant reduction in the amplitudes of the oscillations compared to classic vector control strategies using a classic PI regulator that requires current sensors.

Authors

Mekki mustapha, Faculty of Science, He is Ph.D. in Renewable Energy. His research interests are renewable energy and applications of intelligence technique in power systems; He is a member in Energetic Engineering and Computer Engineering Laboratory at the Ibn Khaldoun University of Tiaret, Algeria. Email: mustamekki@ymail.com

Allaoui Tayeb, Professor of Electrical Engineering, Electrical Engineering Department, He is a Director of Energetic Engineering and Computer Engineering Laboratory at the Ibn Khaldoun University of Tiaret, Algeria. Email: allaoui_tb@yahoo.fr

Belkacem BELABBAS, is a lecturer in the Department of Electrical Engineering, His research activities include the Renewable Energies and the Control of Electrical Systems. He is a member in Energetic Engineering and Computer Engineering Laboratory at the Ibn Khaldoun University of Tiaret, Algeria. Email: belabbas.belkacem@yahoo.fr

Denai Mouloud, is a Senior Lecturer in Electric Power and Control. He graduated from the University of Science and Technology of Algiers and Ecole Nationale polythechnique of Algiers, Algeria in Electrical Engineering, and received his PhD in Control Engineering from the University of Sheffield, UK, He is currently with the School of Engineering & Technology, University of Hertfordshire, UK. Email: m.denai@herts.ac.uk

REFERENCES

[1] Huenteler, J.; Niebuhr, C.; Schmidt, T.S. The effect of local and global learning on the cost of renewable energy in developing countries. J. Clean. Prod. 2016, 128, 6–21.

[2] Singaravel, M.M.R.; Daniel, S.A. MPPT with Single DC-DC Converter and Inverter for Grid Connected Hybrid Wind-Driven PMSG-PV System. IEEE Trans. Ind. Electron 2015, 62, 4849–4857.

[3] Abdelrahem, M.; Hackl, M.C.; Kennel, R. Simplified model predictive current control without mechanical sensors for variable-speed wind energy conversion systems. Electr. Eng. 2017, 99, 367–377.

[4] Gencer, A. Analysis and control of low-voltage ride-through capability improvement for PMSG based on an NPC converter using an interval type-2 fuzzy logic system. Elektron. Elektrotech. 2019, 25, 63–70.

[5] Putri R.I., Jasa L., Pujiantara M., Priyadi A., Hery M., "Tuning PI controller based on multiobjective optimization approaches for speed control of PMSG wind turbine", International Review of Automatic Control, Vol.8, No.4, pp.315-321, July 2015.

[6] Y. Zhao, C. Wei, Z. Zhang, W. Qiao, "A review on position/speed sensorless control for permanent-magnet synchronous machine-based wind energy conversion systems", IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol.1, No.4, pp.203–216, Dec. 2013.

[7] J. Ivanqui, H. Voltolini, R. Carlson and E. H. Watanabe, "pq theory" control applied to wind turbine trapezoidal PMSG under symmetrical fault,IEEE International Electric Machines & Drives Conference (IEMDC):534-540, 2013.

[8] A.G. Sanchez, M.G. Molina, A.M. Rizzato Lede, "Dynamic model of wind energy conversion systems with PMSG-based variable-speed wind turbines for power system studies", International Journal of Hydrogen Energy, Vol.37, 2012, pp.10064-10069.

[9] S. Li ., T.A. Haskew, L. Xu, "Conventional and novel control designs for direct driven PMSG wind turbines", Electric Power Systems Research, Vol.80, 2010, pp.328–338.

[10] S. Chekkal, N. A. Lahaçani, D. Aouzellag, K. Ghedamsi, Fuzzy logic control strategy of wind generator based on the dual-stator induction generator, *International Journal of Electrical Power & Energy Systems,* vol. 59:166-175, July. 2014.

[11] Baroudi JA, Dinavahi V, Knight AM. A review of power converter topologies for wind generators. *Renew Energy* 2007;32:2369–85

[12] Abdin ES, Xu W. Control design and dynamic performance analysis of a wind turbine-induction generator unit. *IEEE Trans Energy Convers* 2000;15(1):5–8

[13] M. Singh, A. Chandra, Power maximization and voltage sag/swell ride-through capability of PMSG based variable speed wind energy conversion system, *Industrial Electronics, 34th Annual Conference of IEEE:*2206-2211, 2008.

[14] Poitiers F. Study and control of induction generators for wind energy conversion systems. *PhD thesis, University of Nantes;* 2003.

[15] Kumar, R.; Daya, M.L. A novel self-tuning fuzzy based PID controller for speed control of induction motor drive. In Proceedings of the International Conference on Control Communication.

[16] Gopala-Rao, K.A.; Amarendra-Reddy, B.; Durga-Bhavani, P. Fuzzy Pi and integrating type fuzzy PID controllers of linear, nonlinear and time-delay systems. IJCA 2010, 1, 41–47.

[17] Gnanavadivel, J., Senthil Kumar, N., Yogalakshmi, P.: Comparative study of PI, fuzzy and fuzzy tuned PI controllers for single-Phase AC–DC three-level converter. J Electr. Eng. Technol. 12, 78–90 (2017)

[18] El-Bardini, M., El-Nagar, A.M.: Direct adaptive interval type-2fuzzy logic controller for the multivariable anaesthesia system.Ain Shams Eng. J. 2, 149–160 (2011)

[19] Mendel, J.M., John, R.I., Liu, F.: Interval type-2 fuzzy logic systems made simple. IEEE Trans. Fuzzy Syst. 14,808–821 (2006).

[20] Ibrahim BENGUERGOUR , Tayeb ALLAOUI, Abdeldjabbar Mohamed KOUADRIA , Mouloud DENAI, Optimization and Adaptive Control of Wind water Pumping System based on fuzzy RST and genetic RST, PRZEGLĄD ELEKTROTECHNICZNY, ISSN 0033-2097, R. 96 NR 2/2020.