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# A Maximum Power Point Tracking Control Algorithms for a PMSG-based WECS for Isolated Applications: Critical Review

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Karim Belmokhtar, Hussein Ibrahim and  
Mamadou Lamine Doumbia

Additional information is available at the end of the chapter

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## Abstract

This chapter deals with a comprehensive overview study of the direct-driven (DD) permanent magnet synchronous generator (PMSG) for wind-energy generation system for stand-alone applications. The dynamic model of PMSG is presented, and different maximum power point tracking (MPPT) algorithms have been realized in the aim to compare their performance. A comparison of performances of the conventional P&O MPPT and the fuzzy logic P&O (FLC P&O) MPPT is presented. Control technique for the presented system is presented and analyzed for the generator side converter. The simulation results carried out using Matlab/Simulink software show the effectiveness of the wind turbine control system.

**Keywords:** wind-energy conversion system, PMSG, MPPT, energy storage, direct-drive, direct torque control.

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## 1. Introduction

Wind power is an important renewable energy resource, which has known a great growth in the last two decades [1-4]. This had led to reduced cost comparative to the conventional fossil energy resources. Nowadays, diesel generators are still the main source of energy in remote areas [5-9]. In stand-alone applications, small wind turbines provide a very attractive source of renewable energy. Wind turbines contribute to decrease stress on the grid, reduce pollution [10], and save on fuel costs by reducing or eliminating the need for diesel generators. These diesel generators consume a lot of polluting fuel, and their high operation and maintenance

costs can result in substantial additional costs if installed in a remote location, where the fuel transport and refueling is a complex mission [6, 8, 11, 12]. In addition, wind turbine in autonomous applications can be installed anywhere the wind resource is abundant and there is no access to the grid, while the grid connection is very expensive [13-17] or is not authorized or is difficult due to the different official approvals [18]. Nevertheless, in case of hybrid wind-diesel systems, a more complex control is required to accomplish an effective power management [18, 19].

Several structures of wind turbine systems are proposed in the literature, and their classification can be based on point of view of the type of generators, or a rotational speed, and the type of power control techniques which is used. Comparatively to the fixed speed type, the variable speed operation type permits to reach a high energy gain (20–30% more energy than the fixed speed operation [20]), reduce stresses, and increase efficiency and power quality [21-24]. In the variable speed wind turbine, to achieve a power flow control, a high efficiency through a maximum power point tracking (MPPT) techniques or a high quality of a delivered power, a (partial or full scale) power converters are needed [18]. In the fixed speed wind turbine, the squirrel-cage induction machine is commonly used, and no electronic interface is required [25, 26]. Asynchronous and synchronous machines are the most common generators used in variable speed wind turbine systems, where it is possible to operate in wide range of rotation speed with respect to the used generators and power converters types [18].

In the other hand, when considering the drive system, and when the generator is coupled to the turbine's shafts via a gearbox, the turbine is classified into the geared systems. The turbine is classified into direct-drive (DD) or gearless systems when the generator is directly coupled to the turbine's shaft [18, 22, 27]. The cost, weight, and maintenance of mechanical transmission needs give a serious limitation on the pursuit of increased power [22, 28]. Indeed, the DD type has many advantages such as a lower maintenance cost, noise reduction, and smaller size [22]. As a consequence, the correct selection of type of generator with regard to the wind conditions is essential to capture the maximum wind energy [18]. Typically, the geared generators cover a speed range of much lower about 20 to 60 rpm and much higher poles, (*e.g.*, about 50 to 300 poles) [28]. In order to avoid the excitation requirement of the generators in remote locations, it has been established that the permanent magnet (PM) machines are more suitable [18, 29-31]. The key technologies of small-scale wind turbine are listed in [32], where the PM machine is addressed as the competitive solution for stand-alone applications [33, 34].

This work focuses on overview study of a DD PMSG used in remote areas power systems, since it is the most usually used generator in small-scale wind turbines [18, 32]. PMSG has many advantages such as its high efficiency, improved thermal characteristics due to the absence of magnetic losses, a solid structure of its field, a high power per weight ratio, and an improved dynamic stability [35-39]. The PM generators can easily provide power without undergoing the process of voltage accumulation, and there is no risk of loss of excitation. In addition, the application of PM machines as wind turbine generators has grown rapidly due to the development of power electronics and permanent magnet materials [22, 40]. An overall configuration of the wind-energy conversion system (WECS) based on DD PMSG is shown in **Figure 1**. It contains the mechanical part (aerodynamics, gearless drive train) and the electrical

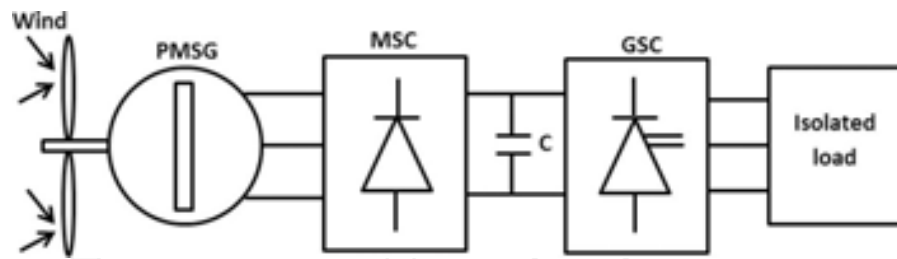


Figure 1. Configuration of the direct-driven PMSG wind-energy conversion system.

part (PM generator, full-scale converters). In this work, each element of the WECS is presented and detailed. The power converters topologies for the direct-driven PM generator system are widely discussed in the literature [18, 22, 41, 42] and highlighted in this chapter.

A field orientation control (FOC) algorithm, which is the advanced scheme, is the most used technique in AC machine control applications such as a PMSG wind-generation system [43, 44]. However, FOC technique has many drawbacks, such as high parameter dependence, and requires much computational resources. Furthermore, using mechanical speed sensors or observers is required to achieve FOC applications. Indeed, the rotor position is needed to give both current and voltage coordinates transformation [45]. On the other hand, a direct torque control (DTC), which is introduced in the mid-1980s [46, 47], is the new concept in WECSs and has many improvements in comparison with the FOC, such as the elimination of the current

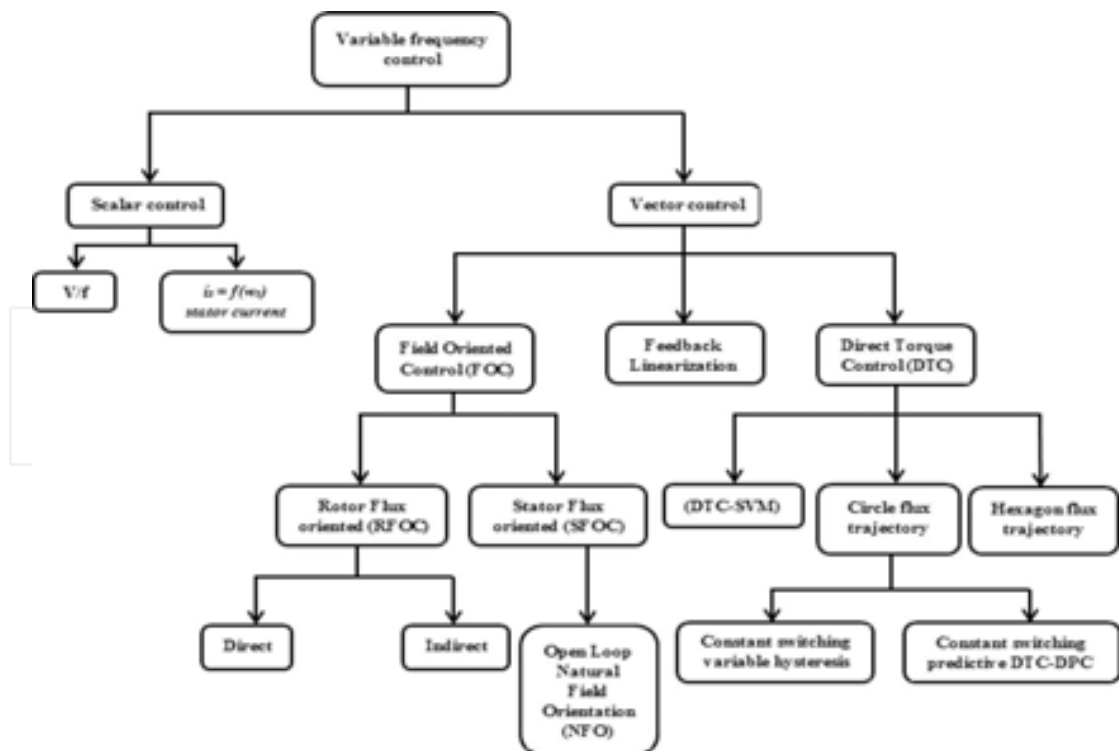


Figure 2. Classification of the PMSG control techniques [54, 55].

control loops, reduce the physical parameters sensitivity, intrinsic sensorless operation, and it is easy to implement in variable speed strategies [48]. Then, the DTC is more appropriate in WECS applications than the conventional FOC technique [49, 50]. The standard DTC technique based on switching table is already employed in commercial wind power generation systems using PMSG products. Some works have used a different DTC techniques such as space vector modulation (DTC-SVM) and a standard DTC in wind-energy systems, and the conclusion is that a DTC is very well appropriated [49, 51-53]. The different variable frequency control techniques of PMSG can be classified as shown in **Figure 2**. However, DTC presents some drawbacks such as the difficulty to control both torque and flux at very low speed, variable switching frequency operation and high torque and current ripple, and high noise level at very low speed [48].

This chapter is organized as follows. A dynamic model of WECS based on axial flux (AF) PMSG and its control are presented in Section 2. In Section 3, a simulation results are presented and analyzed. Finally, a conclusion based on the analysis of performance of different MPPT algorithms is given in Section 4.

## 2. PMSG Modeling Control system

### 2.1. Modeling of Wind Turbine

Generally, wind turbines are characterized by two parameters: tip speed ratio ( $\lambda$ ) and power coefficient ( $C_p$ ). The tip speed ratio is defined as follows:

$$\lambda = \frac{R \Omega}{v} \quad (1)$$

where  $R$  is the radius of the wind turbine aerodynamic rotor in meters  $\Omega$  is rotational speed of rotor in rad/s, and  $v$  presents wind linear velocity in m/s.

The mechanical power harvested by the wind turbine, which is given by the usual cube law, can be calculated as follows:

$$p_{mec} = \frac{1}{2} \rho \pi R^2 C_p (\lambda, \beta) v^3 \quad (2)$$

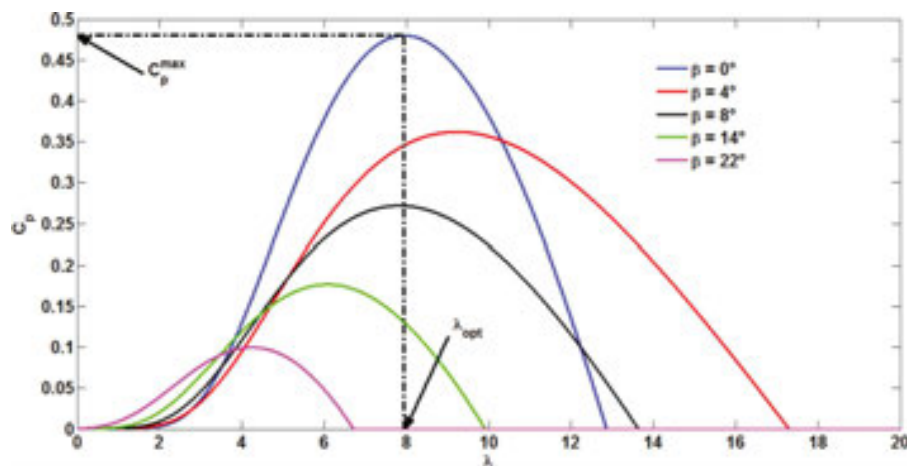
where  $\rho$  is the air density at the turbine in  $\text{kg/m}^3$ , and  $C_p$  designates the fraction of power available in the wind that is converted into mechanical power.  $C_p$  has a theoretical maximum value of 0.593, the Betz limit [56, 57], and basically, it depends on the tip speed ratio  $\lambda$ , and the blade pitch angle,  $\beta$ , can be expressed as follows [58]:

$$C_p(\lambda, \beta) = 0.5 \left( \frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{-\frac{21}{\lambda_i}} \quad (3)$$

with

$$\lambda_i = \left( \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right)^{-1} \quad (4)$$

**Figure 3.** illustrates the characteristic curves of the power coefficient obtained from (3). In the aim to extract the maximum available wind power by the wind turbine at a certain speed, the operating point of the turbine must be kept in the  $\lambda_{opt}$  area. Consequently, a maximum power point tracking (MPPT) algorithm, which is detailed below, is needed to control the rotational rotor velocity of the turbine and maintains it at the maximum power.



**Figure 3.** Power coefficient curves versus tip speed ratio for different blade angles.

## 2.2. Modeling of PMSG

In the aim to define the PMSG control system, its dynamic model is required. The model of the generator is derived by the projection of its equations on a reference coordinate system rotating synchronously with the magnet flux. In order to reach a synchronization between the  $dq$  rotating reference frame and the  $abc$  three-phase frame, a phase-locked loop (PLL) is used [59]. Then, a dynamic model of the surface mounted PMSG is expressed as follows:

$$\begin{cases} v_{ds} = R_s i_{ds} + L_s \frac{di_{ds}}{dt} - \omega \psi_{qs} \\ v_{qs} = R_s i_{qs} + L_s \frac{di_{qs}}{dt} + \omega \psi_{ds} \end{cases} \quad (5)$$

where  $L_s$  and  $R_s$  are, respectively, the generator inductance and resistance,  $\omega$  is the electrical generator speed, and  $\Psi_{ds}$  and  $\Psi_{qs}$  are d-axis and q-axis magnet flux, respectively, which are expressed as follows:

$$\begin{cases} \Psi_{ds} = L_s i_{ds} + \Phi \\ \Psi_{qs} = L_s i_{qs} \end{cases} \quad (6)$$

where  $\Phi$  is the magnet flux. Then, the electrical model of PMSG in the synchronous reference frame can be expressed as follows:

$$\begin{cases} \frac{di_{ds}}{dt} = \frac{1}{L_s} (-R_s i_{ds} + \omega L_s i_{qs} + v_{ds}) \\ \frac{di_{qs}}{dt} = \frac{1}{L_s} (-R_s i_{qs} - \omega L_s i_{ds} - \omega \Phi + v_{qs}) \end{cases} \quad (7)$$

The electromagnetic torque of the nonsalient poles of PMSG is written as follows:

$$T_{em} = \frac{3}{2} p \Phi i_{qs} \quad (8)$$

where  $p$  is the number of pole pairs of the generator. Eq. (8) shows that the generator torque can be controlled directly via the q-axis current of the stator.

The mechanical dynamics model of the considered wind turbine system can be defined by the following expression:

$$J_T \frac{d\omega_r}{dt} + f \omega_r = T_T - T_{em} \quad (9)$$

where  $T_T$  represents the mechanical torque,  $J_T$  is the moment of inertia,  $f$  is the coefficient of friction, and  $\omega_r$  is the mechanical speed, which is related to the electrical rotating  $\omega$  as follows:

$$\omega = p \omega_r \quad (10)$$

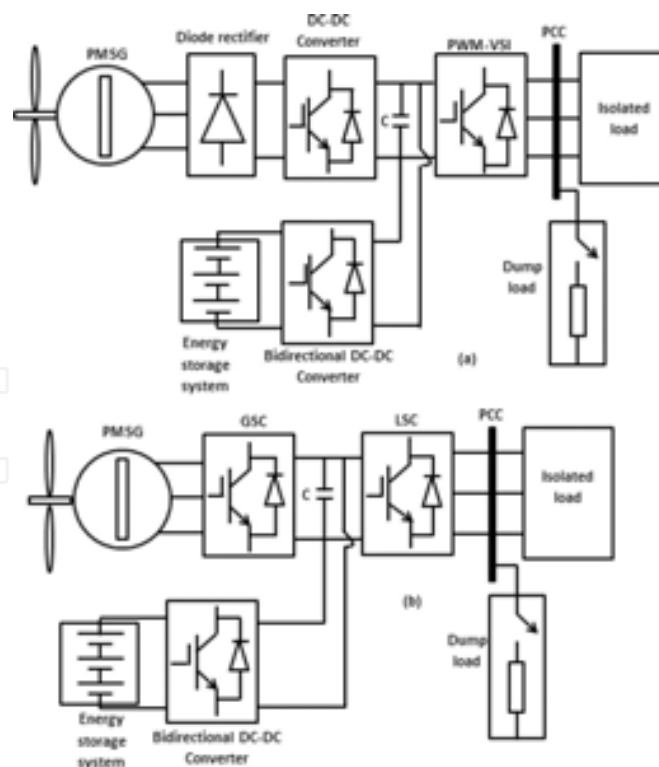
### 2.3. Different structures of DD PMSG-based wind turbine system

For remote area applications, different topologies of PMSG-based WECS and their control techniques are presented in order to demonstrate their efficient performance [18]. In [60], a diode bridge rectifier and boost DC-DC converter is controlled in order to extract the maximum power by controlling the duty cycle of the IGBT switch. In addition, a controlled voltage source



inverter (VSI) is used to control both voltage amplitude and frequency on the load side. The results have shown that the proposed control strategy gives a good performance in both transient and steady-state cases. However, these performances can be enhanced by taking into account the use of energy storage systems. An experimental study of a voltage control strategy focused only to compensate harmonic due the using a nonlinear load in autonomous application are presented and analyzed in [61]. In [62], the same structure studied in [60] is analyzed under unbalanced load, with the addition of battery as energy storage device and its DC-DC reversible converter, with an addition of hydrogen storage in [63]. A dump load is used to balance power between wind generator, battery, and primary load through a controllable switch such as IGBT. Hysteresis band current control (HBCC), voltage-oriented control (VOC), and flux-oriented control (FOC) are used to control machine side converter, in order to regulate DC-link voltage in [64]. It has demonstrated that VOC and FOC control strategies give a small THD in comparison with the HBCC. Therefore, the estimation of the field improves the performance of VOC, making FOC better compared to VOC. However, in this work, the optimization of wind power generation, such as MPPT strategy, has not been taken into account. After presentation and discussion of some works dealing with autonomous PMSG-based WECSs, we present in the next section their typical topologies.

**Figure 4(a).** illustrates the PMSG wind turbine system used three-phase bridge diode rectifier as generator side converter (GSC) and a voltage source converter as GSC in (b).

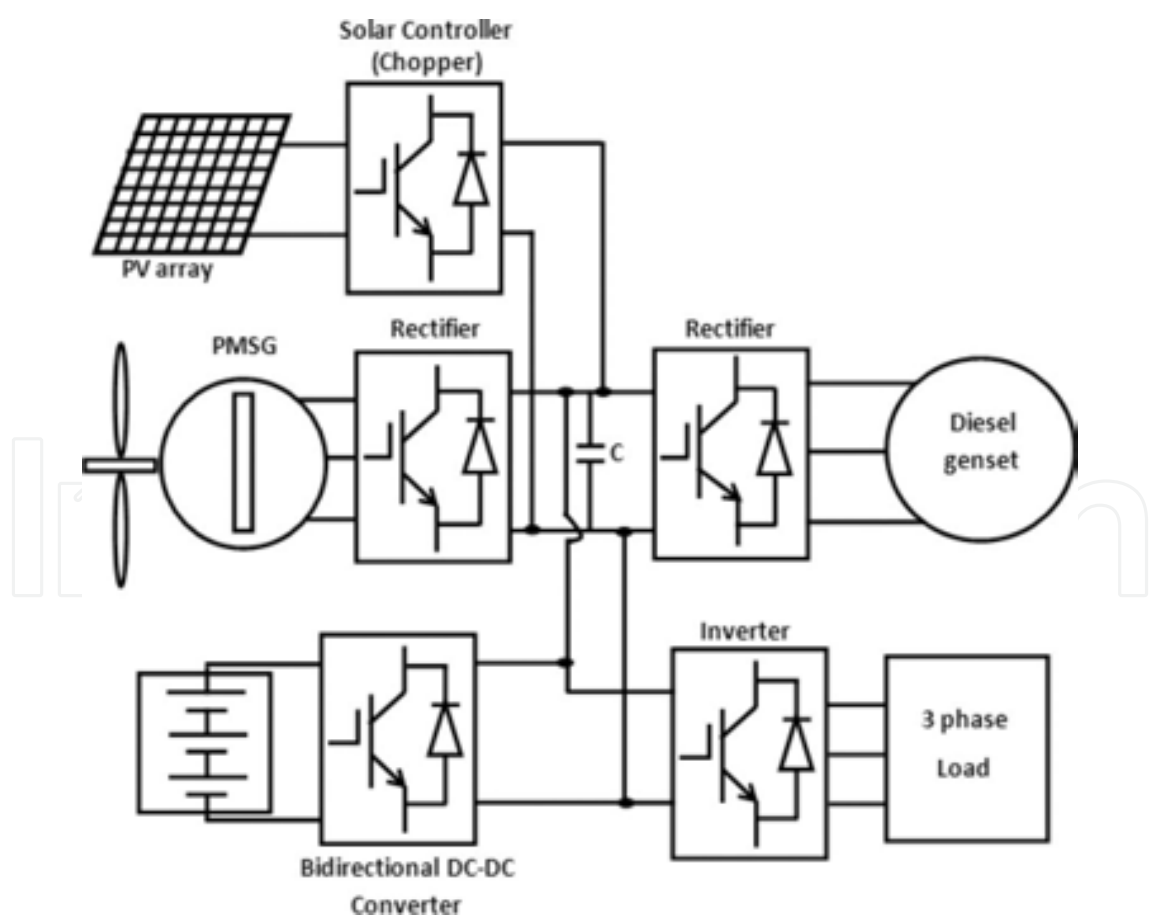


**Figure 4.** DD PMSG-based stand-alone WECS: (a) bridge diode rectifier as MSC and (b) voltage source converter as MSC.

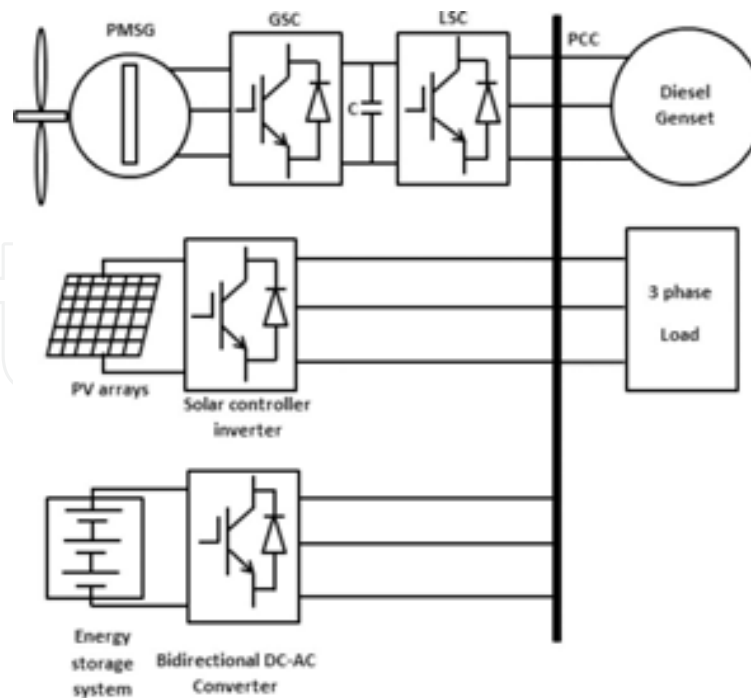


In remote area applications, due to the intermittent and randomness nature of wind, energy storage system (ESS) is required. Therefore, a bank of batteries is used as an ESS in order to ensure continuity of the power system. Indeed, in the case where production is higher than demand, the batteries are charged through the bidirectional DC-DC converter. In the other hand, when production is less than demand, the batteries provide the difference between consumption and production. Dump load is used in case of surplus power, and the batteries are fully charged. Note that for this application, hydrogen storage system (HSS) can be a good alternative to meet production and demand power. Indeed, the electrolyzer is used to store the excess power as hydrogen, which will be used to regenerate electricity via fuel cell when production is less than demand.

There are also other configurations of PMSG-based WECS for remote applications, with the integration of other sources, and using of power electronics. **Figure 5** shows the structure of the hybrid power system (HPS) with the main DC bus structure. An ESS is connected to the DC bus, which can contribute to regulate the DC voltage. A PV array and diesel genset are used to reduce the overall cost of the system and the optimization of renewable energy sources penetration rate. **Figure 6** represents the simplified block diagram of the HPS with a main AC bus structure.



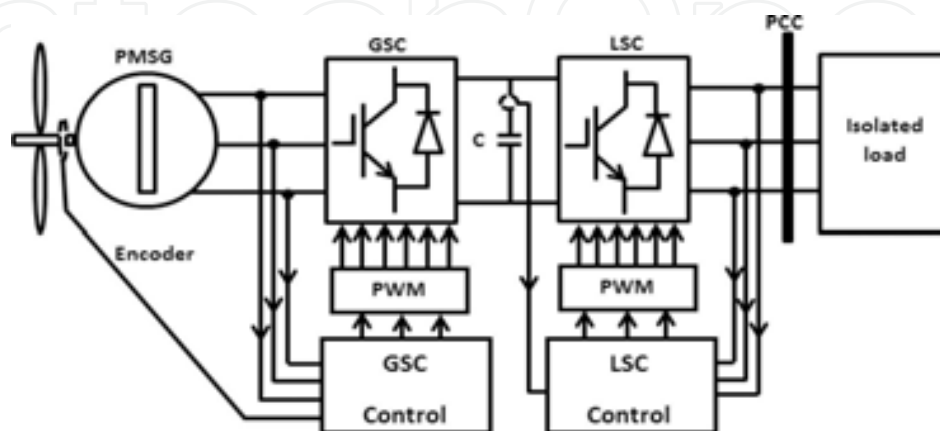
**Figure 5.** PMSG-based WECS with the DC main structure.



**Figure 6.** PMSG-based WECS with the AC main structure.

## 2.4. Control of PMSG

A global scheme of DD PMSG control scheme is illustrated in **Figure 7**, where two controlled PWM VSI, GSC and LSC, are used. These back-to-back converters are controlled in the aim to improve the captured wind power and increase the system performance by adjusting the power factor [44, 65]. The GSC is controlled to maximize the extraction of wind power. Indeed, vector control law associates space vector modulation (SVM) and maximum power point tracking (MPPT) algorithm is used to maximize the provided power under varying wind speed condition.



**Figure 7.** DD PMSG control scheme.



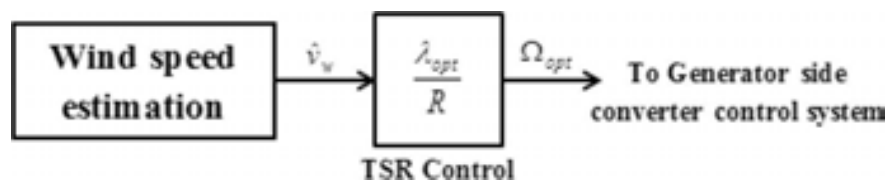


Figure 9. Detailed scheme of FOC applied to the GSC.

#### b) Hill Climbing Searching (or Perturb & Observe) technique

The P&O algorithm, which is the sensorless mathematical optimization approach to seek the optimum local point for a given function, is widely used in the literature in order to extract the maximum energy [2, 76-81]. Nevertheless, this technique has many drawbacks such as mechanical stress due to the constant perturbations [82] and permanent fluctuation around the optimal point [66, 83], especially with medium and large inertia wind turbine. In [84, 85], additional control strategies have been added to a basic P&O algorithm in order to resolve the problems listed above. However, some disadvantages such as the response to fast variations of the wind speed are still persisting. In the other hand, it is not easy to choose step size: A large step size means a fast response but generates more oscillations around the optimum point, and then, efficiency is reduced, where the small step size increases stability and efficiency but makes lower convergence of the control [78, 86]. Accordingly, the performance of these algorithms is particularly low in case of strong changes in wind speed, which is the case of most wind turbines. Then, the development of new algorithms including these issues is required. The P&O control principle is depicted in **Figure 10**. In [78], it has been reported the absence of difference of the wind power resulting from the variation of the wind speed and those resulting from the change in the previous perturbation.

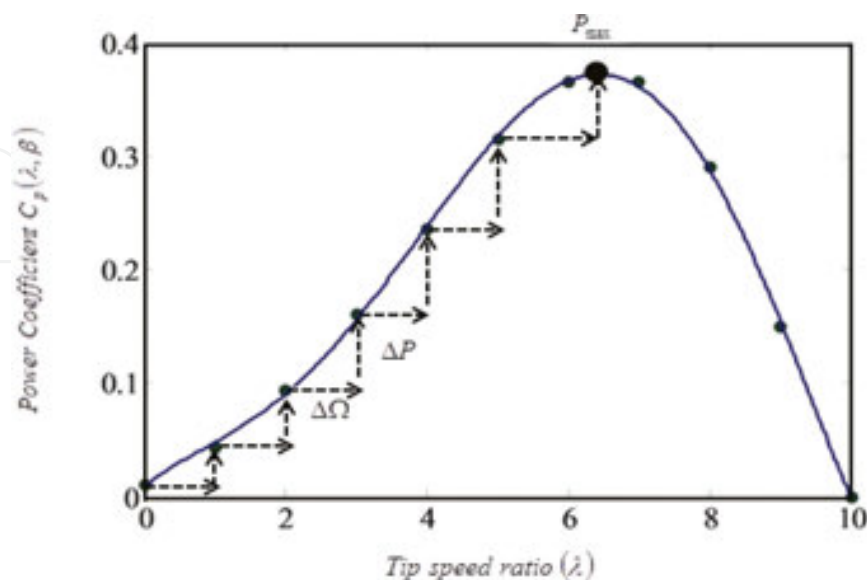
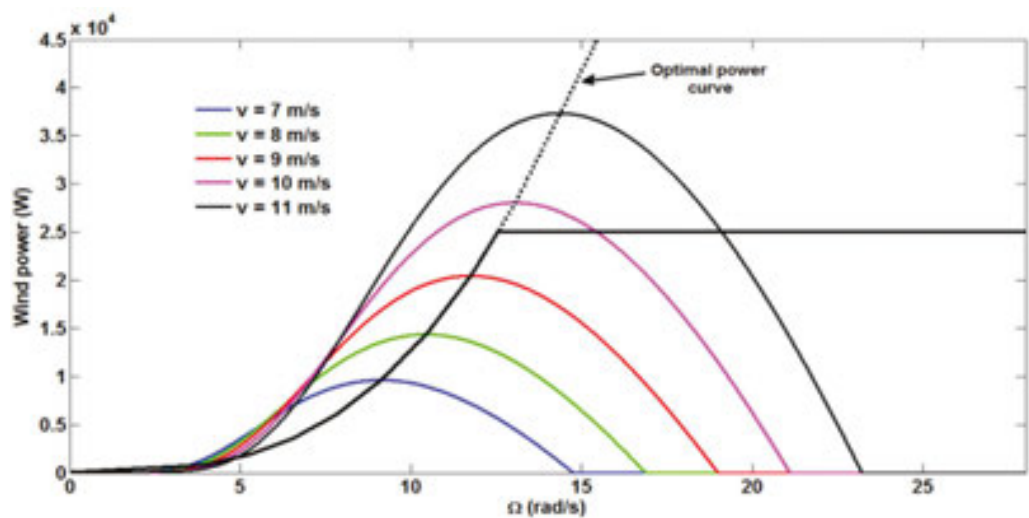


Figure 10. P&O control principle.

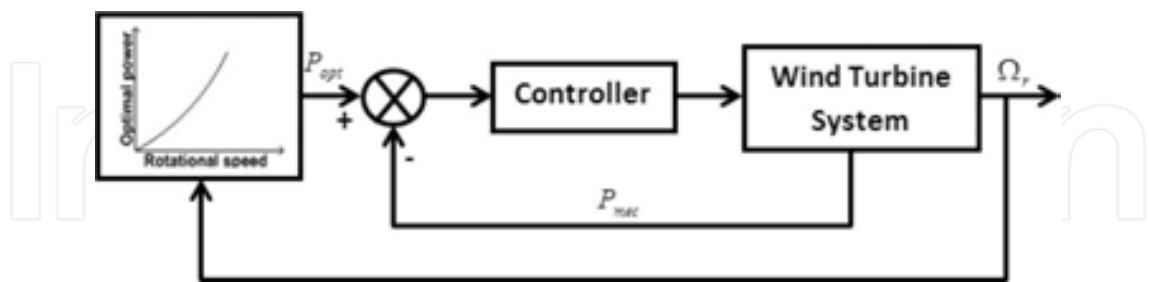
Some studies [76-78] have proposed a modified step-size algorithms in order to improve efficiency and the precision of the conventional P&O algorithms.

c) *Power Signal Feedback (PSF) Control technique*

The PSF control technique requires the knowledge of the optimum power curve of wind turbine (see **Figure 11**) as function of the rotor speed, which is obtained from experimental tests. Then, the recorded data for maximum output power and the corresponding rotor speed must be implemented in a lookup table [86-88]. The measured rotor speed is used to provide the optimal power to extract as shown in **Figure 12**. In [88], the optimum power depends on the rotor speed and the output DC voltage is used to calculate the optimum power [79].



**Figure 11.** Wind power curve as function of the rotor speed for different wind speed.



**Figure 12.** Block diagram of PSF control algorithm to track the optimum power point.

d) *Optimal Torque Control (OTC)*

The principle of the OTC strategy consists of the adjusting of the generator’s speed according to a maximum power reference torque for a given wind speed (see **Figure 13**) [89]. Indeed, to ensure the maximum capture of the available wind power, the TSR must be kept at its optimal value ( $\lambda_{opt}$ ). The characteristic torque as function of rotor speed is shown in **Figure 14**.

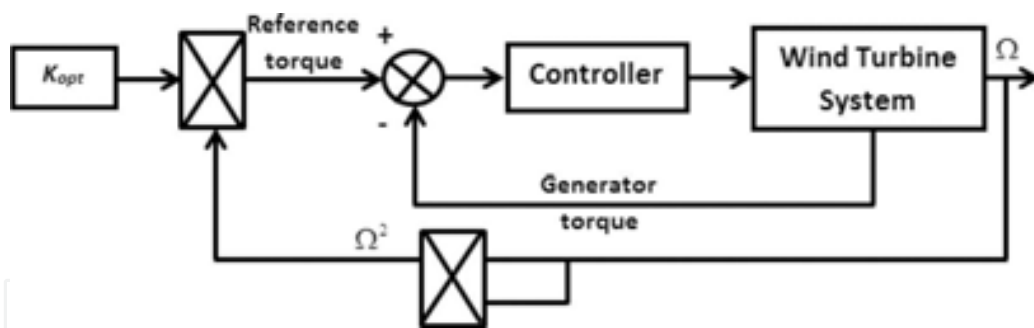


Figure 13. Block diagram of OTC control algorithm to track the optimum point.

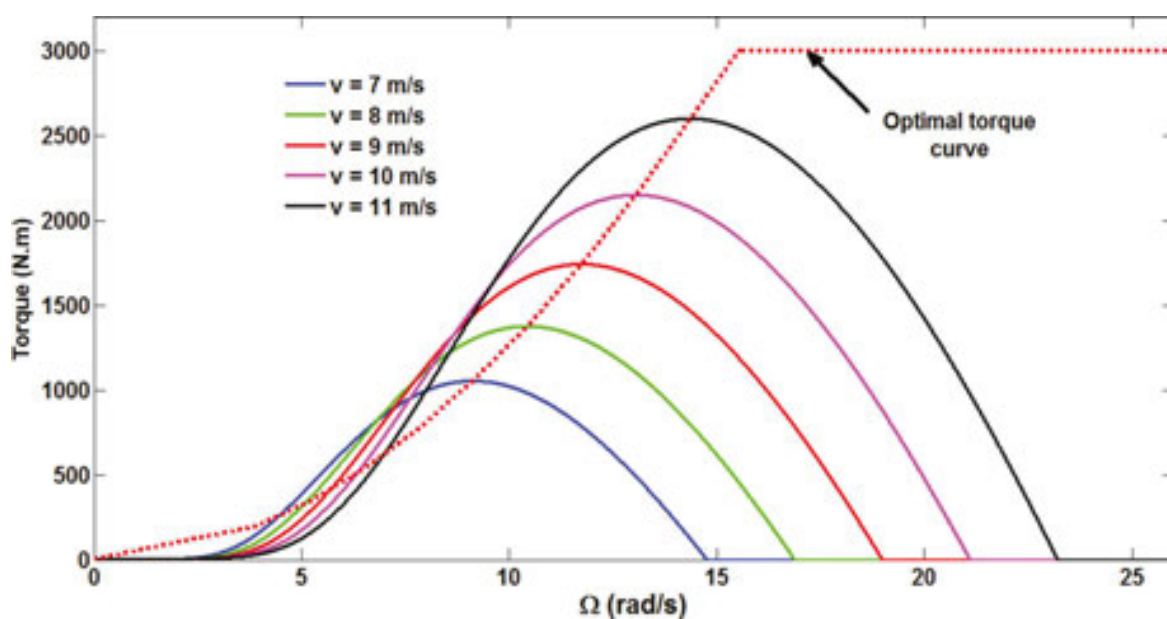


Figure 14. The characteristic torque as function of rotor speed for different wind speed.

By replacing the wind speed expression from eq. (1) in eq. (2), we can get the following expression:

$$p_{mec} = \frac{1}{2} \rho \pi R^5 C_p(\lambda, \beta) \frac{\Omega^3}{\lambda^3} \quad (11)$$

If TSR is maintained at its optimal value ( $\lambda_{opt}$ ), the previous relation is expressed as follows:

$$p_{mec}^{opt} = \frac{1}{2} \rho \pi R^5 C_p^{opt}(\lambda, \beta) \frac{\Omega^3}{\lambda_{opt}^3} \quad (12)$$

If we consider that the wind power is equal of the product of torque and speed, the optimal torque can be written as follows:

$$T_{\text{mec}}^{\text{opt}} = \frac{1}{2} \rho \pi R^5 C_p^{\text{opt}}(\lambda, \beta) \frac{\Omega^2}{\lambda_{\text{opt}}^3} = K_{\text{opt}} \Omega^2 \quad (13)$$

where

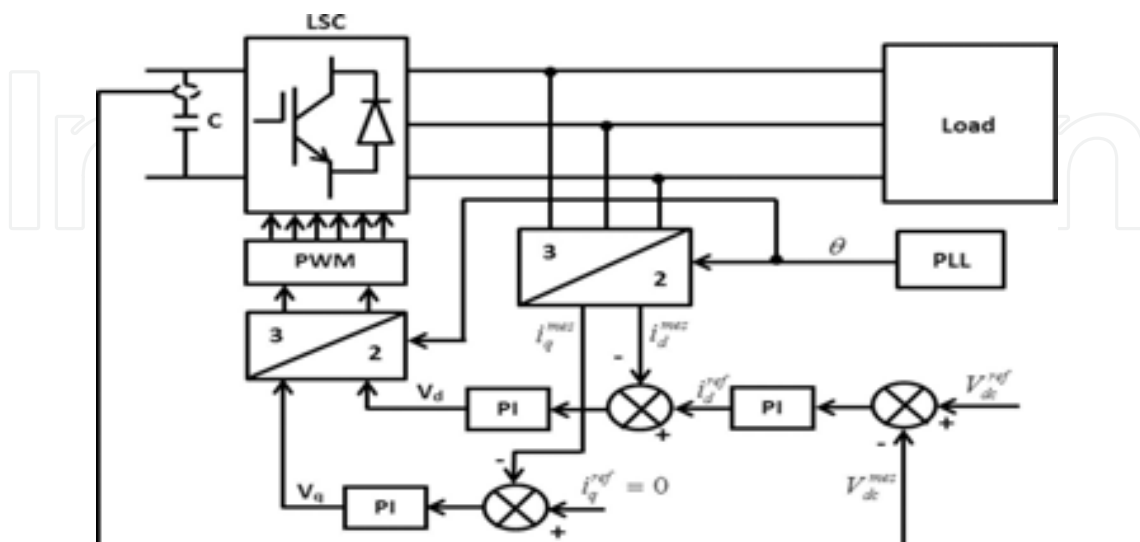
$$K_{opt} = \frac{1}{2} \rho \pi R^5 \frac{C_p^{opt}(\lambda, \beta)}{\lambda_{opt}^3} \quad (14)$$

The OTC method is simple to analyze, easy to implement, and efficient since the measured wind speed is not required achieving the maximum power generation. Nevertheless, in case of strong and fast change of wind speed, the response is low. Indeed, no direct measurement of wind speed allows not reflect the rapid change in the value of the reference torque.

### 2.4.2. Load Side Converter Control

The main objective of load side converter (LSC) control is to maintain the DC-link voltage,  $V_{dc}$ , constant regardless the amount and direction of the active power, and the power factor by adjusting the amount of the reactive power. Then, the requirements of unit power factor can also be reached. In order to achieve the control, voltage and current on load side and the DC-link voltage are measured. Since the load voltage-phase angle is needed to accomplish the vector oriented control (VOC) of LSC, phase-locked loop (PLL) is used to track the load voltage vector [90].

In this study, a DC-link voltage and a unit power factor control are applied. Since we focus our work essentially on the analysis of MPPT's performances, the scheme used in this work was given in several papers [91–95].



**Figure 15.** Block diagram of vector control of LSC.



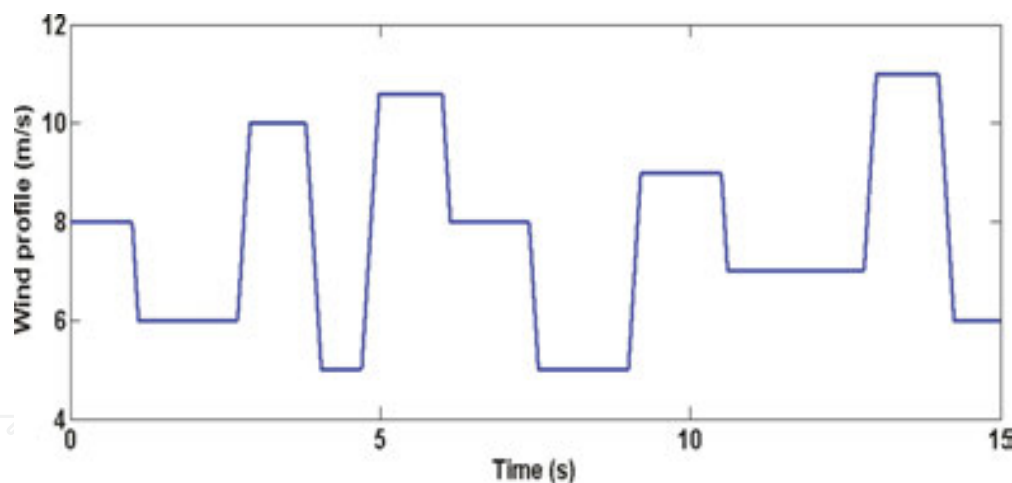
**Figure 15** illustrates the overall control scheme of the LSC. The control of the DC-link voltage and the power quality is also reached by current regulation on a synchronously rotating reference frame.

The output voltage signals, which are generated from the current controllers, are used by the space vector pulse width modulation SVPWM module to produce the IGBT gate control signals to drive the LSC. Moreover, to increase the transient performance of the inner current loops, the  $d$ - $q$  decoupled current control through vector control is applied.

The proportional-integral (PI) controllers are used in both outer and inner control loops, and their gains are determined by trial and error method.

### 3. Simulation results and discussions

In order to achieve a comparative analysis of different MPPT algorithms, we consider an isolated application of direct-drive wind turbine driving a PMSG as shown in **Fig. 7** and **8**. The WTG represents a 14 kW variable-speed wind turbine equipped with a 12.5 kW PMSG. An isolated and balanced three-phase resistive load is connected to the LSC and draws a variable active power from the wind power system. The parameters of the WTG are given in Appendix.



**Figure 16.** Wind speed profile

To validate the effectiveness and the dynamic of the PMSG control via GSC, some simulations are carried out using Matlab/Simulink software program. **Figure 16** illustrates the wind speed profile that incident on the wind turbine, while **Figure 17** shows the performance of the generator speed control. As we can see, the measured rotor speed tracks with a good accuracy the reference optimal value, since the tracking error is kept less than  $\pm 1.5\%$  all the time. Wind power and electrical power provided by the PMSG are depicted in **Figure 18**. The instantaneous generator currents are indicated in **Figure 19**. The variation of the power coefficient ( $C_p$ ) with the wind speed is kept at its optimum value as shown in **Figure 20**.

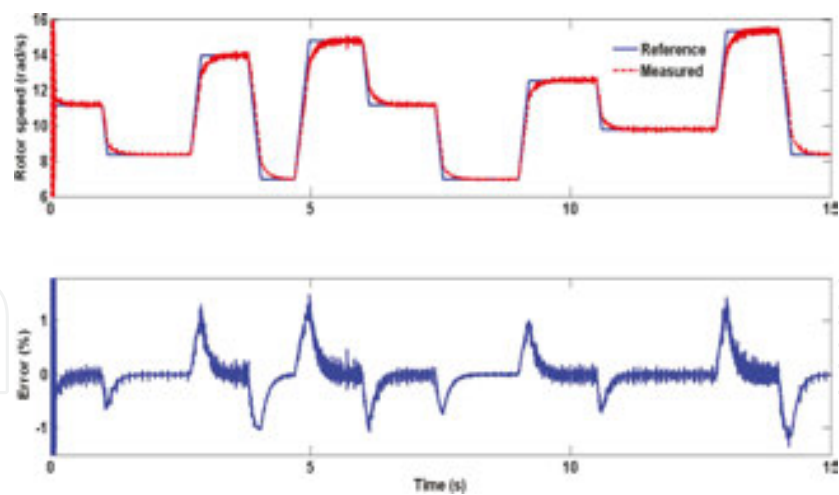


Figure 17. Generator speed control performance.

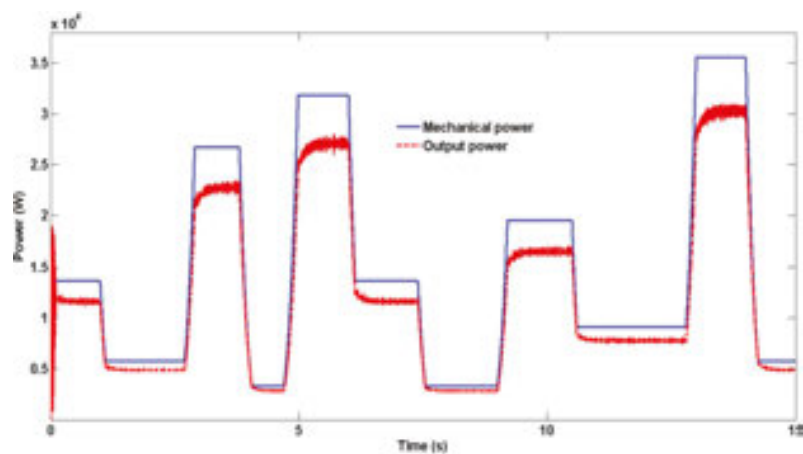


Figure 18. Wind power and output electrical power.

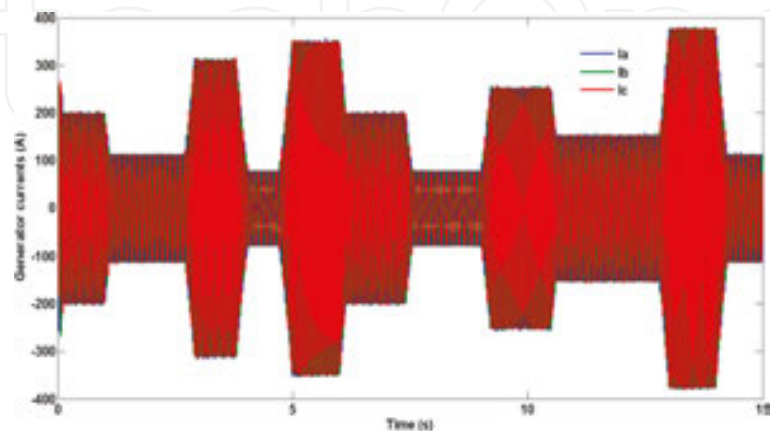
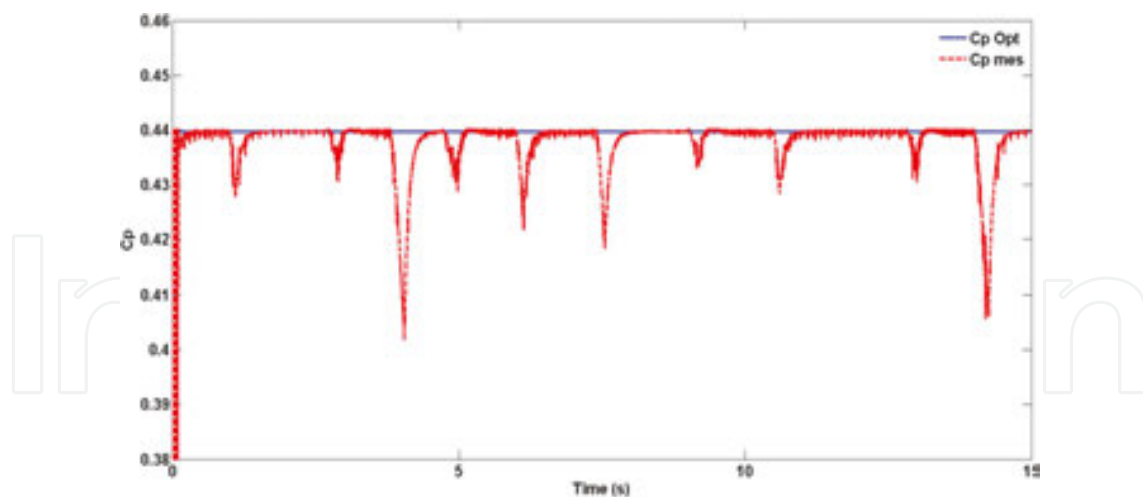


Figure 19. Three-phase currents of the PMSG.



**Figure 20.** Power coefficient.

Subsequently, a comparative analysis of the performance of a new MPPT P&O strategy based on fuzzy logic techniques, which is known to be an excellent tool for modeling and management of nonlinear systems and the conventional P&O MPPT, is presented. The control strategy of the fuzzy logic is based on an expert human operator to interpret a situation and initiate its appropriate command action. Generally, a controller based on fuzzy logic has two inputs and provides a control action. For FLC P&O, inputs are quantized into 5 levels represented by a set of linguistic variables: negative big (NB), negative (NS), zero (Z), positive (PS), and positive big (PB). The fuzzy rules base formulation of FLCP&O is shown in **Table 1**. These rules are chosen to perform the optimization of wind generation capture as follows: (i) When the input signals are far from the optimal point, the output of the FLCP&O provides a big step size; (ii) when the inputs are close to the optimum point, the output is set to a small value of step size; and (iii) once the inputs are close to the optimum point, then the step size is set to zero. In this article, we use the min and max operators as t-norm and t-conorm, respectively. Triangular membership functions are used, principally due to their efficiency and high-performance computing. The membership adopted for both inputs and output variables is illustrated in **Figures 21** and **22**, respectively.

Step size		$\Delta Power$					
		NB	N	Z	P	PB	
$\Delta Speed$			NB	NB	N	Z	P PB
N	NB	N	Z	P	PB		
Z	NB	N	Z	P	PB		
P	NB	N	Z	P	PB		
PB	NB	N	Z	P			

**Table 1.** Fuzzy rules base formulation of FLCP&O.

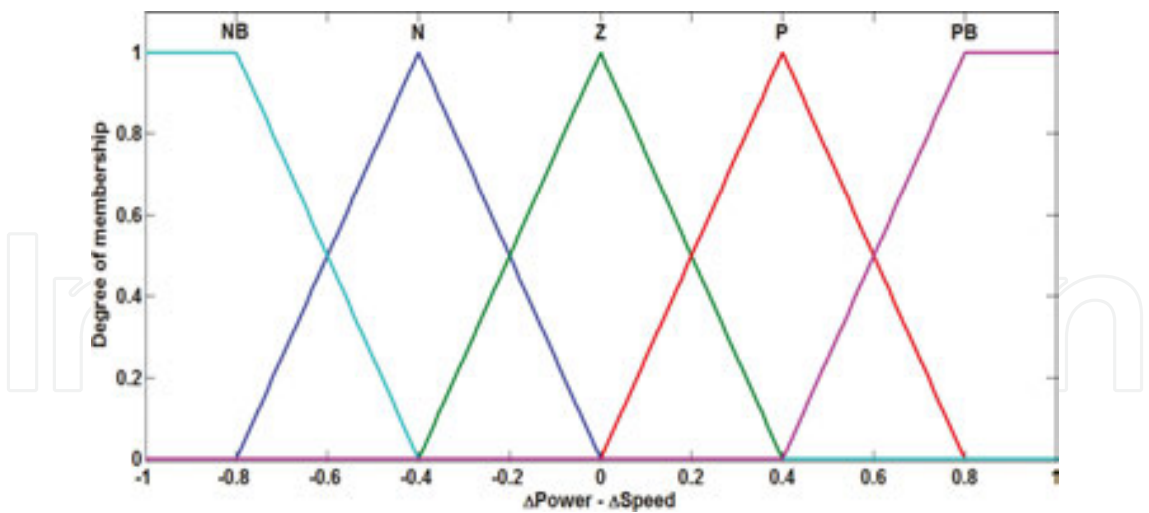


Figure 21. Membership functions of the inputs variables.

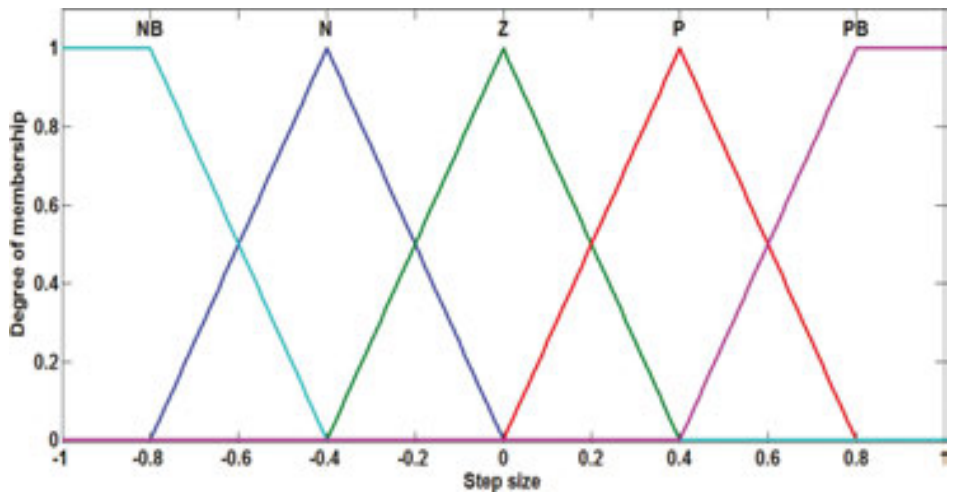


Figure 22. Membership functions of the output variables.

The main drawback of this conventional P&O MPPT is the calculation of step size. Indeed, a major step modification allows a faster convergence of the system, but increases the oscillation around the optimal point. On the other hand, a small step size reduces the oscillations, but it makes the system slower to reach the optimal point, especially in case of rapid changes of wind speed. Fuzzy logic provides an adaptive step size, and its value depends on the distance between the current point and the optimal point. Indeed, if the actual point is very near to the optimum point, the variation is not very larger, thereby increasing the speed of convergence, and while the actual point is nearby the optimum point, step size decreases avoiding oscillation around the optimal point. **Figure 23** shows the profile wind speed. **Figure 24** depicts the performance of new FLCP&O and the conventional P&O MPPT listed in [70]. As we can see, the new FLCP&O strategy (black dashed curve) is almost confused with the optimal value (red curve). The variation of the step size for both P&O MPPT is illustrated in **Figure 25**.

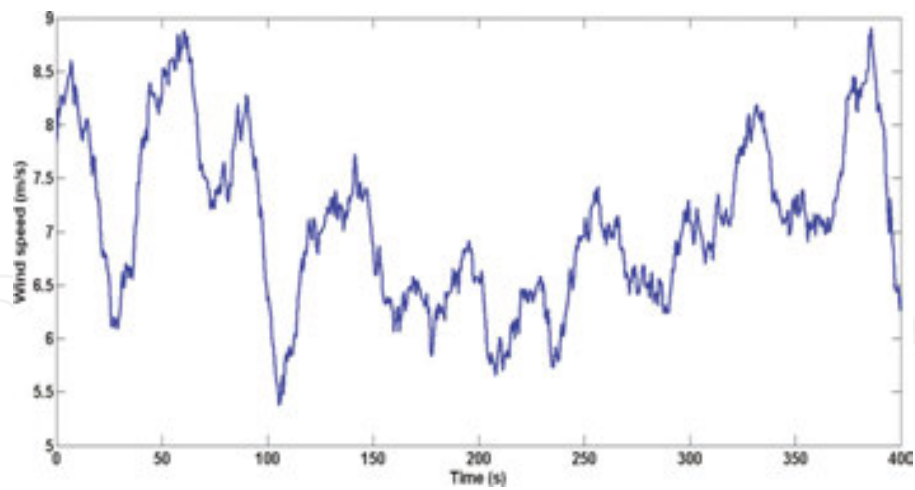


Figure 23. Profile of wind speed.

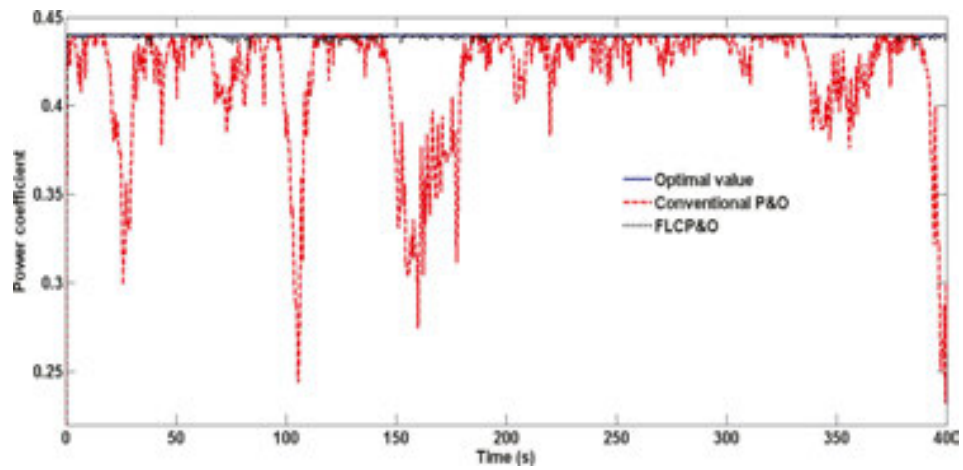


Figure 24. Comparison of the performances of a new FLP&O and the conventional P&O MPPT.

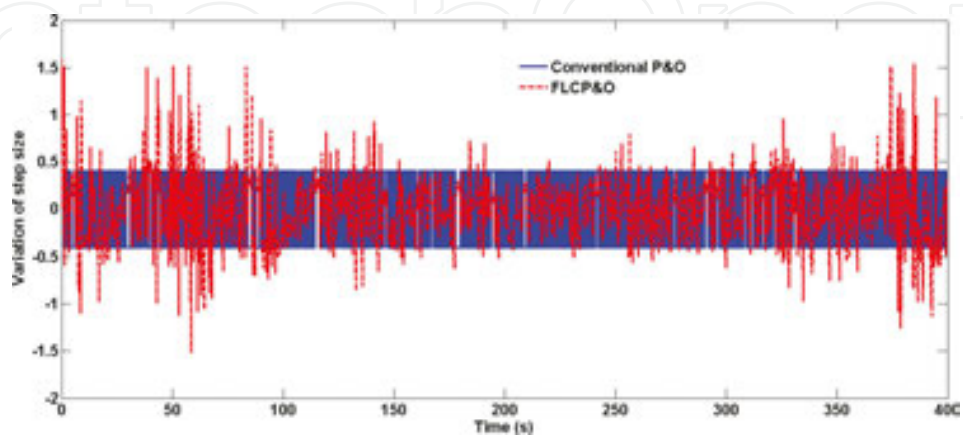
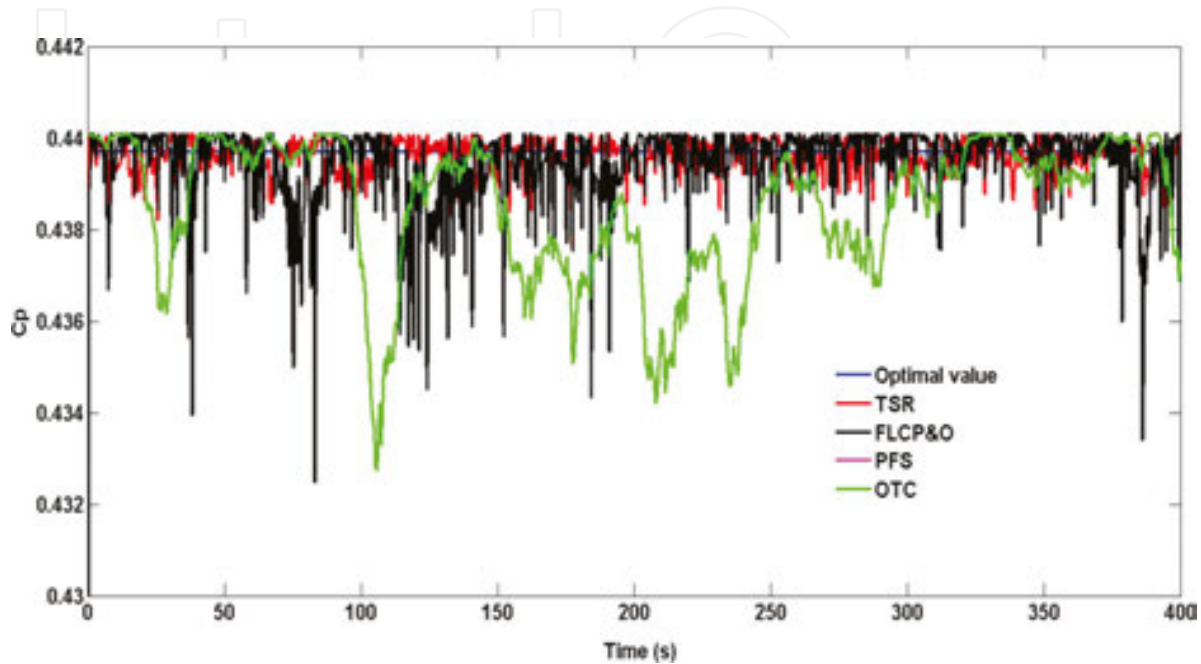


Figure 25. Variation of the step size for both P&O MPPT algorithms.



After showing the effectiveness and the dynamics of the proposed control strategy system, the assessment of the performance of the different MPPT algorithms is achieved. The comparison of the values of the power coefficient for different MPPT algorithms is depicted in **Figure 26**. As we can see, the FLCP&O provides the best performances versus OTC MPPT and PFS MPPT methods.



**Figure 26.** Comparison of the power coefficient for different MPPT methods.

## 4. Conclusion

In this work, a comparative study of different MPPT algorithms is presented. Firstly, the effectiveness and dynamics of the strategy control to extract maximum power, which is implemented using Matlab/Simulink/SimPower dynamic simulation system, are performed. The simulation results demonstrate that the proposed control strategy provides best performances in both transient and steady states. Thereafter, a new P&O MPPT algorithm based on fuzzy logic techniques, which provides a variable step size, was presented. The performances of this novel algorithm were compared to those of the algorithm presented in conventional literature. This new approach allows obtaining a power coefficient, where its value is very close to the maximum value.

After that, a comparative study between a MPPT algorithms applied to the DD-PMSG has been accomplished. The comparison of their performances is presented and analyzed. It is seen that the new sensorless FLCP&O gives a best performance with comparison to the OTC and PFS MPPT methods. Moreover, this approach is independent to the aerodynamic characteristics of the turbine unlike the OTC and PFS MPPT methods.

## Nomenclature

Acronyms	Signification	Acronyms	Signification
AF	Axial flux	PMSG	Permanent Magnet Synchronous Generator
DD	Direct-Drive	PLL	Phase-Locked Loop
DTC	Direct Torque Control	P&O	Perturb and Observe
ESS	Energy Storage System	PSF	Power Signal Feedback
FLC	Fuzzy Logic Controller	PWM	Pulse Width Modulation
FOC	Field Orientation Control	SVM	Space Vector Modulation
GSC	Grid Side Converter	TSPM	Transverse Flux Permanent Magnet
HBCC	Hysteresis Band Current Control	THD	Total Harmonic Distortion
HPS	Hybrid Power System	VSI	Voltage Source Inverter
IGBT	Insulate Gate Bipolar Transistor	VOC	Voltage-Oriented Control
LSC	Load Side Converter	WECS	Wind-energy Conversion System
MPPT	Maximum Power Point Tracking	WTG	Wind Turbine Generator
OTC	Optimal Torque Control		
Greek letters		Signification	
$\lambda$		Tip Speed Ratio (TSR)	
$\rho$		Air Density [ $\text{kg/m}^3$ ]	
$\beta$		Blade Pitch Angle	
$\Phi$		The Magnet Flux [Wb]	

## Appendices

### Wind turbine parameters

Rated power [kW]	14
Cut-in wind speed [m/s]	5
Cut-off wind speed [m/s]	25
Rated wind speed [m/s]	12
Rotor radius (R) [m]	2.5
$\lambda_{\text{opt}}$	8.1

### PMSG parameters

Rated power [kW]	12.5
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Number of pairs poles	8
$R_s$ [ $\Omega$ ]	0.5
$L_s$ [mH]	0.5
Moment of inertia (J) [ $\text{kg/m}^2$ ]	10
Rated rotor speed [rad/sec]	314

## Author details

Karim Belmokhtar<sup>1\*</sup>, Hussein Ibrahim<sup>1</sup> and Mamadou Lamine Doumbia<sup>2</sup>

\*Address all correspondence to: [kbelmokhtar@eolien.qc.ca](mailto:kbelmokhtar@eolien.qc.ca)

1 TechnoCentre éolien, Gaspé, Québec, Canada

2 University of Quebec at Trois-Rivieres, 3351, Rue des Forges, Trois-Rivières, Québec, Canada

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