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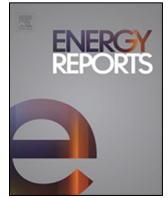
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Research paper

Non-linear and intelligent maximum power point tracking strategies for small size wind turbines: Performance analysis and comparison



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ABSTRACT

Small scale WTs (wind turbines) are known a great interest energy feeding, especially for isolated area, and water pumping application. It is very crucial to operate a WT around its maximal efficiency in order to extract a maximum energy from the wind. To achieve this goal, various MPPT (maximum power point tracking) strategies are proposed in literature. The conventional MPPT strategies, which are considered as model based methods, are unable to accomplish this objective since their designs are always based on the plant model as well as the climatic parameters. In this context, this paper presents principle and design of two modeless methods: non-linear and intelligent strategies based on HCS method. The intelligent MPPT is implemented by using FLC (fuzzy logic control) due to its ability to cope with various problems associated with conventional methods. The principle of the presented methods is based on perturbing the rotor speed and observing its results on output power. The performances of the methods are deeply analyzed and compared in terms of mechanical power extracted, electrical energy as well as load factor. Simulation under Matlab/Simulink environment of a small-scale wind turbine (6 kW) based on SCIG (Squirrel Cage Induction Generator) under various turbulent wind speed profiles, allows proving that the intelligent MPPT presents best performances compared to the conventional HCS method.

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0. Introduction

The demand of the electrical energy has increased rapidly during the current century around the world due to many reasons such as increasing economic activities and rapid population expansion. Since the fossil fuels resources will be depleted and the environmental issues will be deleterious, the renewable energy sources play a significant role as an alternative solution for energy generation. These sources exhibit many motivations such as greenhouse gases pollution freeness and infinite availability of the driving source with no harmful waste products. WTs have attracted considerable attention and enjoyed a great interest as one of the most promising and developing renewable energy sources until present due to the development of the wind turbine industry, the evolution of semiconductor technology, and the development of new methods of controlling the WTs (Mériida et al., 2014; Yaakoubi et al., 2017b,a). Under the progress development, world wind energy market share will be able to supply 12% of the electricity needed by 2020, 29.1% by 2030 and 34.2% by 2050 (EL YAAKOUBI, 2018). In term of annual installed capacity, as example, the Moroccan state aims to install an amount of 2000

MW in 2020 and 4560 MW in 2030, which represent 14% and 20% of its total electricity installed capacity, respectively. Therefore, the progress development of this source will play a significant role in increasing the rate of the installed energy and thus in achieving the Paris renewable energies agreements, by designing of reliable and efficient large scale systems. On the other hand, small scale WTs know a significant role for energy feeding of the isolated area as well as water pumping.

WT technology aims to capture a part of the kinetic energy contained in the wind and to convert it to a mechanical power available at the main shaft and then to an electrical power. Among electrical machines, SCIG is very suitable for WTs applications because it is cheap, simple in construction, easy for maintenance, and easily replaceable. The cost of the produced energy is strongly driven by the operating modes of a WT as well as the cost of the system itself. Improving the operation regime of a WT by maintaining an optimum operation in the partial load region is the main path to reduce the cost of the energy produced. In fact, in this region the system must profit freely from the wind by optimizing the aerodynamic power coefficient by means of a maximum power capture strategy (Rezaei, 2018; Yaakoubi et al., 2018b). In the full load region, the WT is controlled to smooth its output power by pitching collectively or individually the blades (Yaakoubi et al., 2018a; Yin et al., 2015a, 2016). TSR, PSF, OT

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Nomenclature

P_m	Mechanical power
$P_{m,opt}$	Mechanical power optimum value
ρ	Air density
v	Wind speed
R	Rotor radius
λ	Tip Speed Ratio
λ_{opt}	Tip Speed Ratio optimum value
β	Pitch angle
$C_p(\lambda, \beta)$	Power coefficient
$C_{p,max}$	Power coefficient maximum value
ω_m	Angular rotor speed
$\omega_{m,opt}$	Rotor speed optimum value
C_l	Load factor
P_s	Electrical power
T_g	Electromagnetic torque
ω_g	Generator speed
E	Electrical energy
E_{opt}	Electrical energy optimum value
Δ	Gradient
$\Delta\omega_{m,0}$	HCS strategy speed step
η	Generator efficiency
Z^{-1}	Time delay
v_m	Mean wind speed
MPPT	Maximum power point tracking
WT	Wind turbine
HCS	Hill Climbing Searching
FLC	Fuzzy Logic Control
SCIG	Squirrel Cage Induction Generator
DFIG	Double Feed Induction Generator
PMSG	Permanent Synchronous Induction Generator
LSS	Low Speed Shaft
TSR	Tip Speed Ratio
OT	Optimal Torque
PSF	Power Signal Feedback
P & O	Perturb and Observe
OP	Operating Point
OOP	Optimum Operating Point
MPP	Maximum Power Point
PWM	Pulse width Modulation
WRBFN	Wilcoxon radial basis function network
FPGA	Field-Programmable Gate Array

and HCS are the commonly found MPPT strategies in literature, where the major differentiation between each one resides in its attempt to use sensors for parameters measurement and WT characteristics (Abdullah et al., 2012; Eltamaly et al., 2013; Kumar and Chatterjee, 2016; Lalouni et al., 2015; Nasiri et al., 2014; Zhao et al., 2013). The TSR strategy allows regulating the generator speed to follow the wind speed changes. Its structure is simple, but its design is based on the WT characteristics and the wind speed measurement, which are difficult to obtain with enough accuracy (Yaakoubi et al., 2017a). The PSF strategy makes it possible to track the reference power versus rotational speed stored in a look-up-table. It is proved to be reliable compared to the TSR strategy, as it does not require the wind speed measurement, but its design is based on the rotational speed–power relationship which is difficult to find with accuracy. The OT control is the

most used by modern WTs, where the desired electric torque is proportional to the square of the generator speed (EL YAAKOUBI, 2018). Since the turbine parameters vary over time and the climatic parameters change from site to other, this technique performs wrong. Extremum optimum seeking is another method for implementing the MPPT strategy (Ghaffari et al., 2014; Iyasere et al., 2012). HCS strategy is a modelless and a sensor-less wind speed method. It allows climbing the OP of the WT to the optimal value based on the mechanical power versus rotational speed characteristic, without requiring the WT model and the climatic parameters. It enables to adapt the rotor speed to the wind speed changes by employing a pre-defined speed step perturbation, according to the signs of the rotor speed and the mechanical power changes. This technique is found to be simple, it needs less information from the WT and is applicable to any kind of system as it is independent from the plant model. However, it suffers from many drawbacks especially those related to the choice of the rotor speed size step. In fact, a large speed step leads to rapid WT response, but it results to exceeding the OOP and thus to large oscillations. By contrast, a small speed step allows tracking the OPP without oscillations but the tracking process might take a long time (EL YAAKOUBI, 2018). Moreover, this method does not differentiate between the power changes resulted from the wind speed and the speed perturbation, which may lead to wrong decisions (Munteanu et al., 2009). In presence of these problems, the conventional HCS is not able of tracking the MPP.

FLC is an alternative solution to implement the MPPT method of the WT. It allows tracking the response and thus to overcome the undesirable oscillations around the OOP. Usually, controllers based on fuzzy logic have been chosen for their advantages such as simplicity of design, without knowing the exact mathematical model of the process to be controlled (Viveiros et al., 2015). In conventional automatic, generally the process is modeled through a number of differential equations, or at least with analytical relations. In some situations, the modeling approach is difficult, though impossible to realize, so the conventional control design becomes more complex. Moreover, the control design complexities increase substantially with the nonlinearities of the plant. FLC makes it possible to overcome the difficulties and complexities met in the systems modeling, and the various uncertainties inherent in their operation. It incorporates an intelligent thinking, which permits the complex systems to be modeled using higher level of expertise based on an accumulated knowledge and experience. It allows expressing knowledge with subjective concepts as very large, too small, moderate ...etc., which are mapped under well-defined rules. Fuzzy logic approach can be applied to the development of intelligent algorithms for control and optimization purposes. The usual way to implement a fuzzy controller is to realize it as a computer program on specialized processor like FPGA and Raspberry Pi. Various works are interested to FLC implementation (Lee et al., 2008; Patyra and Grantner, 1999; Ramadan et al., 2014a,b).

In this paper we design and analysis the performances of the conventional HCS strategy and an intelligent MPPT strategy based on FLC for control of a small scale WT driving a SCIG. The performances of the two strategies are analyzed and compared by simulation in terms of relevant parameters such as mechanical power extracted, electrical energy and load factor. The rest of the paper is organized as follows: In the first section significant literature researches will be reviewed. In the second section we introduce the WT model. In the third section, we present the wind turbine control including the conventional and the intelligent HCS based on FLC. In the fourth section simulation results will be presented and discussed. The paper finishes by conclusion and future researches.

1. Literature review

Various improvements are conducted in literature to improve the tracking process of the MPPT strategy based on the HCS method. Among these methods, the adaptive and the intelligent are of great interest. Thereafter, the relevant contributions are highlighted.

In Ref. [Abdeddaim and Betka \(2013\)](#), a control for maximum power extraction from a connected grid WT based on DFIG is proposed. The control algorithm tracks the MPP for wind speeds below the rated speed and ensures the power will not go over the rated power for wind speeds above the rated value. In Ref. [Eltamaly et al. \(2013\)](#), a technique for maximum power extraction from a connected grid direct drive WT is proposed. The MPPT algorithm is based on fuzzy logic theory to permanently extract the optimal aerodynamic power from the wind. In Ref. [Belmokhtar et al. \(2014\)](#), an improved method based on fuzzy logic that estimates wind speed from the mechanical power for a WT that drives a DFIG, is proposed. The proposed method reduces the speed variation range of the wind generator, which leads to the downsizing of the PWM and takes into account the system losses. In Ref. [Uddin and Patel \(2016\)](#), a MPPT control for a WT based on an interior PMSG, that incorporates an algorithm to minimize the losses, is proposed. The proposed algorithm uses the estimated active power output of the generator as input and generates the command speed so that the power produced is maximized. In Ref. [Simoes et al. \(1997\)](#), a control approach for tracking the MPP for a WT based on SCIG is proposed. The control approach searches the optimum rotor speed that maximizes the production of the WT. In Ref. [Elnaggar et al. \(2014\)](#), a method based on a novel numerical optimization algorithm to search for the maximum power that the turbine can capture from the available wind power is proposed. In Ref. [Dahbi et al. \(2016\)](#), a novel combined MPPT-pitch angle robust control system of a variable-speed wind turbine using Neural Network (ANN) to extracting a maximum power as well as to limiting the extra power. In Ref. [Yin et al. \(2018\)](#), a new multi-point aerodynamic method is proposed for maximum energy capture based an objective function for multi-point aerodynamic. In Ref. [Mokhtari and Rekioua \(2018\)](#), maximum power point tracking using Ant Colony algorithm in wind turbine is developed. In [Huang et al. \(2015\)](#), a new control strategy for large scales wind energy conversion systems to achieve power output maximization and operating cost minimization. The control method includes an intelligent MPPT and box uncertainties. In [Yaakoubi et al. \(2017a, 2016\)](#), an intelligent MPPT strategy based on fuzzy logic for a wind turbine driving a squirrel cage induction generator. In [Lin and Hong \(2010\)](#), an intelligent control based on a WRBFN in combination with HCS MPPT strategy for a PMSG. The proposed technique makes it possible to cope with various problems associated with the aforementioned methods, such wrong operation under rapid changes of the wind speed and changes in the turbine characteristics and the climatic conditions.

These mentioned methods allow finding the optimum rotor speed that maximizes the production of the wind speed based on the electrical power and the rotor speed through the MSC. Alternative control techniques are proposed in literature to avoid using mechanical sensors by using diode rectifier, since its voltage is proportional to the rotor speed. In Ref. [Daili et al. \(2015\)](#), a modified MPPT based on two modes, normal mode where the classical HCS is used to track the OPP under steady state wind speed and a predictive mode is used to track the new MPP under rapid changes of the wind speed, is proposed. In Ref. [Hong et al. \(2013\)](#), an intelligent approach for maximum power capture from a grid connected direct drive WT is proposed. The method is based on the HCS method and the WRBFN using a back-propagation learning algorithm with modified particle swarm

optimization. In Ref. [Hussain and Mishra \(2016\)](#), an adaptive control for maximum power capture is proposed. The MPPT proposed combines the computational behavior of the HSC, TSR, and PSF control strategies in order to take advantages of all methods. In Ref. [Zeng et al. \(2008\)](#), a MPPT strategy based on fuzzy control for a direct drive WT is proposed. The proposed MPPT makes it possible to locate the system OPs along the maximum power curves based on the inverter DC-link voltage and current. In [Yin et al. \(2015b\)](#), an intelligent method is developed for WT control. The control method includes a MPPT strategy based on fuzzy logic to derive the peak power points, and an integral sliding mode current controller to track these points. In [Yin et al. \(2015\)](#), a fuzzy logic sliding-mode control strategy is elaborated to control a direct-driven WT for maximum energy extraction and machine side converter current harmonics reduction. The proposed strategy consists of a controller based on fuzzy logic to generate the optimum dc-side current, and a current controller based on sliding mode approach to track the optimum dc-side current. The current harmonics are eliminated by employing a resonant filter integrated into the fuzzy logic controller. In [Dalala et al. \(2013\)](#), a MPPT strategy is proposed to control a small scale WT by using the dc current as the perturbing variable. The proposed method is based on two modes a P&O mode with adaptive step size under slow wind speed fluctuation conditions, and a prediction mode employed under fast wind speed change conditions. In [Lalouni et al. \(2015\)](#), a hybrid HCS control method, which is a combination of the OT control and the conventional HCS methods, is proposed.

2. WT modeling

Wind energy conversion system includes various multidisciplinary subsystems which can be classified as aerodynamic, structural and electrical. The aerodynamic subsystem represents the aerodynamic model of the WT. The structural subsystems include blades, tower and drive train models. The electrical subsystems include the generator, the back-to-back converter and the system control models. In order to model the dynamic behavior of the overall system, models of the different components need to be derived and coupled consecutively. The model used in this paper is presented in [EL YAAKOUBI \(2018\)](#).

The aerodynamic power extracted from a WT is given by the following expression ([Darvish Falehi and Rafiee, 2018](#)):

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

The power coefficient is modeled by the following expression

$$C_p(\lambda, \beta) = \left[0.5 \left(\frac{116}{\lambda'} \right) - 0.4\beta - 5 \right] \exp \left(-\frac{21}{\lambda'} \right) \quad (2)$$

With $\lambda' = [1/(1 + 0.008\beta) - 0.035/(\beta^3 + 1)]^{-1}$

The tip speed ratio is defined as the ratio of the ratio tip speed and wind speed:

$$\lambda = \frac{\omega_m R}{v} \quad (3)$$

The load factor of the WT is the fraction of the extracted aerodynamic power and the available power:

$$C_l = \frac{P_m}{P_{m,opt}} \quad (4)$$

The electrical power generated is expressed as the product of the electromagnetic torque yield and the generator speed:

$$P_s = T_g \cdot \omega_g \quad (5)$$

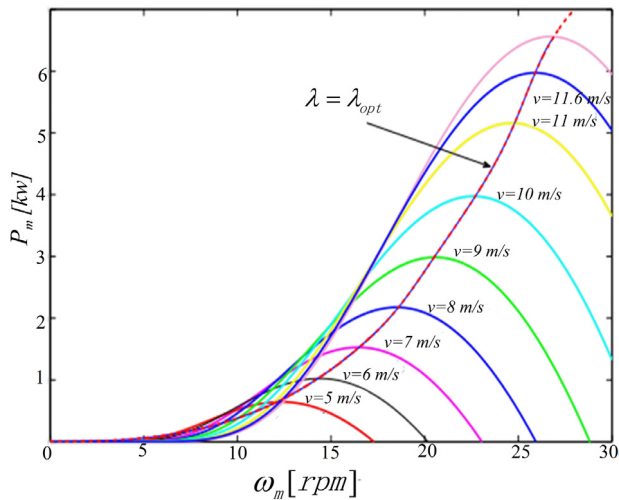


Fig. 1. Mechanical power function of the rotor speed.

The electrical energy extracted from the system, is the integral of the real active power over a time:

$$E = \int P_s dt \quad (6)$$

The structural model is lumped in one mass as its dynamic is large compared to the electrical dynamic. The system electrical is based on the model presented in Yaakoubi et al. (2017a).

3. WT control for MPPT

The WT control for MPPT strategy aims at operating the turbine around its optimum operation whatever the wind speed increases or decreases. The optimum operation is achieved by running the turbine at the maximum aerodynamic power coefficient.

The mechanical power versus the rotational speed of the 6 kW WT for different wind speeds is plotted, in Fig. 1. As can be seen, the mechanical power extracted for each wind speed is maximum at a specific value of the rotational speed, which corresponds to an optimal rotational speed ($\omega_{m,opt}$). Thus, for each wind speed the WT has an optimum rotational speed in which the extracted power is maximized. All these rotational speed values constituting the OOR, which corresponds to the optimal TSR (λ_{opt}). Therefore, it is necessary to maintain λ at its optimal value, regardless the wind speed changes, by integrating an appropriate MPPT for a maximum power capture from the WT.

3.1. HCS strategy

3.1.1. HCS principle

HCS or P&O is a non-linear, dynamical and a model-less searching method. Its principle is based on perturbing the rotor speed and observing its results on output power. Its advantages principal is that it makes possible to track dynamically the MPP without returning to the turbine characteristics, the mathematical model of the plant and the wind speed measurement (Belmokhtar et al., 2014). According to its location on the curve P_m function of ω_m of a typical WT, moving the OP to its OOP can be achieved by perturbing the rotor speed until its optimal value ($\omega_{m,opt}$) as illustrated in Fig. 2. Supposing that the WT operates at point P_1 , if the output power increases with the latest rotor speed increment, the HCS searching process continues in the same direction of the increment (Case 1), elsewhere if the output power

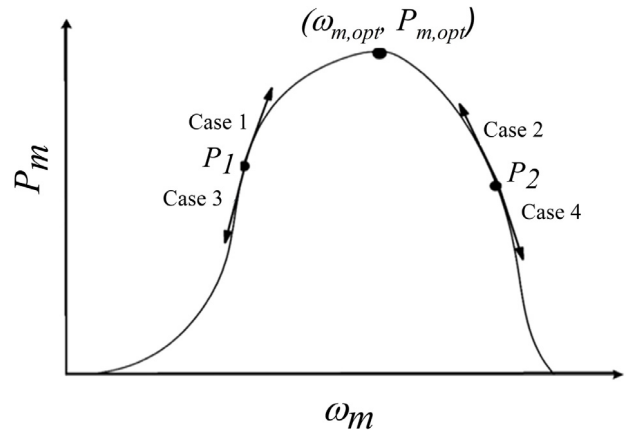


Fig. 2. HCS principle.

decreases the searching process is reversed (Case 3). Assuming now that the turbine operates at point P_2 , if the output power decreases with the latest speed decrement the searching process of the strategy continues in the same direction of the decrement (Case 2), elsewhere the searching process is reversed (Case 4). Therefore, the ratio $\frac{\Delta P_m}{\Delta \omega_m}$ can give useful information about the OOP location. This means that if the latest rotor speed step results to a positive value of the ratio, the HCS algorithm continues of increasing the rotor speed until zeroing the ratio; elsewhere if the latest rotor speed step leads to a negative value, the algorithm decreases the rotor speed until achieving the OOP.

3.1.2. HCS flowchart

The HCS flowchart is illustrated by Fig. 3. The algorithm starts its process by measuring the electrical power generated and the mechanical rotor speed. Thus, calculating the mechanical power, and the mechanical power and the rotor speed gradients. The electrical power is measured based on the stator currents and voltages measurements, while the rotor speed is obtained from a mechanical sensor placed on the LSS (Yaakoubi et al., 2017a). The mechanical power harvested from the wind is estimated from the electrical power, based on Eq. (7):

$$P_m = \eta P_s \quad (7)$$

The mechanical power and the rotor speed gradients, at a step (k), are given as the difference between two successive measurements by Eqs. (8) and (9), respectively:

$$\Delta P_m(k) = P_m(k) - P_m(k-1) \quad (8)$$

$$\Delta \omega_m(k) = \omega_m(k) - \omega_m(k-1) \quad (9)$$

The principle of the method, as depicted in the flowchart, is summarized as follow: If both the power and the rotor speed changes are positive and negative at the same time, the algorithm will increase the reference rotor speed by a fixed predefined speed step $\Delta \omega_{m,0}$ according to Eq. (10). If the power gradient is positive and the rotor speed change is negative, and vice versa, i.e., the power gradient is negative and the rotor speed gradient is positive; the HCS will decrease the reference rotor speed by the same predefined step whatever the size of the speed and power gradients. Elsewhere, if the power gradient is zero whatever the rotor speed gradient sign, no action to do, i.e., the WT OP is at its optimal value. Finally, the algorithm returns to the next step if the wind speed changes and the process will be repeated iteratively.

The estimated optimal rotor speed at the step k is given by the following equation, which the sum of the speed at $k-1$ iteration and the predefined fixed step:

$$\omega_{m,opt}(k) = \omega_m(k-1) + \Delta \omega_{m,0} \quad (10)$$

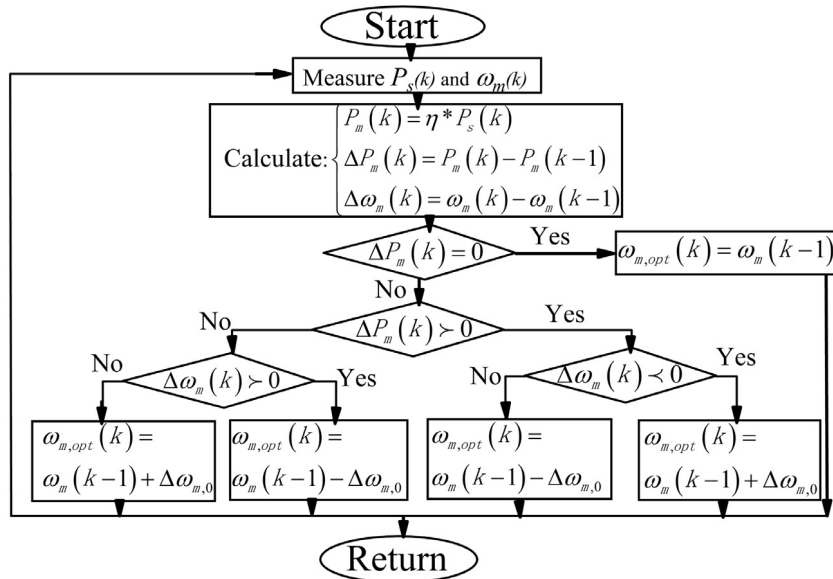


Fig. 3. HCS flowchart.

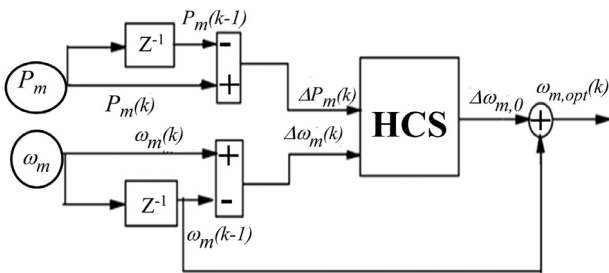


Fig. 4. HCS structure.

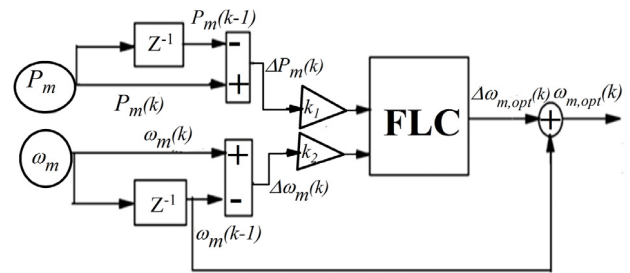


Fig. 5. MPPT based on FLC structure.

3.1.3. HCS structure

The structure of the strategy is given by Fig. 4. The control strategy has two inputs, which are the mechanical power and rotor speed. The output from the HCS is the reference rotor speed that will be inputted to the rotor speed controller. Since the wind speed changes rapidly over time, the reference step size remains fixed although the size of these steps changes. Therefore, the HCS strategy is not able to drive the OP of the WT to the OOP.

3.2. MPPT based on FLC

3.2.1. MPPT based on FLC structure

The goal of the MPPT based on FLC is to adjust permanently the WT rotor speed to the wind speed changes, in such a way to operate the WT around its higher level of aerodynamic efficiency (i.e., $C_p = C_{p,max}$). In fact, by monitoring of the produced mechanical power versus rotational speed, at any wind speed, the MPPT based on FLC strategy makes it possible to maintain the rotor speed at its optimal value, without high amplitude oscillations. This is done by increasing or decreasing the rotor speed according to the rate sign of the characteristic, as depicted in Fig. 2. If $\frac{\Delta P_m}{\Delta \omega_m} > 0$, the MPPT-FLC increases ω_m by a variable step $\Delta \omega_{m,opt}$ given at its output according to Eq. (11). In contrary, if $\frac{\Delta P_m}{\Delta \omega_m} < 0$, the MPPT-FLC strategy decreases the speed by an adaptive step. Elsewhere, if $\frac{\Delta P_m}{\Delta \omega_m} = 0$, no action to do.

The structure of the MPPT strategy is given in Fig. 5. The inputs to the MPPT-FLC are $\Delta \omega_m$ and ΔP_m , while the output is

$\Delta \omega_{m,opt}$. Finally, the reference rotational speed that maximizes the extracted power from the wind at the step k , is given by:

$$\omega_{m,opt}(k) = \omega_m(k-1) + \Delta \omega_{m,opt}(k) \quad (11)$$

3.2.2. MPPT design

FLC design is based on four steps: fuzzification of the control inputs, making the appropriate decisions according to fuzzy inference and inference rules, and finally defuzzification of the control output.

3.2.3. Fuzzification

The fuzzification step consists of defining the membership function to each linguistic variable. This allows determining with good precision the degree of membership function of the input as function of its real value with respect to each fuzzy set (Yaakoubi et al., 2017a). The choice of the membership function type, the fuzzy sets as well as the repartition of the universe of discourse of each variable is not an evident task (Belmokhtar, 2015). This choice is usually based on the process to be controlled as well as the performances desired. In fact, choosing membership functions with small number of sets might simplify the design, while a large number might augment complexity of the design by increasing the computing time. The universe of discourse of the MPPT inputs and output are devised into seven fuzzy sets within the interval $[-1, 1]$, in order to cover the whole operating regime of the WT. The linguistic notations used are Negative High (NH), Negative Medium (NM), Negative Low (NL), Negative (N), Zero (Z), Positive

Table 1
Fuzzy rules.

$\Delta\omega_m$	ΔP_m						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	Z	NM	NB	NB
NM	PB	PM	PS	Z	NS	NM	NB
NS	PM	PS	PS	Z	NS	NS	NM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	NS	Z	PS	PS	PM
PM	NB	NM	NS	Z	PS	PM	PB
PB	NB	NB	NM	Z	PM	PB	PB

(P), Positive Low (PL), Positive Medium (PM), and Positive High (PH). The membership functions used are Gaussian symmetric and distributed equally for positive and negative regions, of all the variables. Moreover, the variables are normalized in the interval $[-1, 1]$ by their respective scaling factors k_1 , k_2 and k_3 (see Fig. 6).

3.2.4. Fuzzy inference

Fuzzy inference allows determining the output of the controller function of the inputs, based on the linguistics rules base. Fuzzy inference engine is a relation defined between fuzzy subsets to make decisions, by aggregating the rules base. The inference method used in this paper is that of Mamdani and Sugeno. In this method, the operator *AND* is represented by the *Minimum* function, the operator *OR* is represented by the sum or medium and the operator *THEN* is represented by the *Minimum* function (EL YAAKOUBI, 2018). The fuzzy output of the variable is the aggregation of the 49 rules of the inference matrix.

3.2.5. Fuzzy rules

Fuzzy logic aims to formalize and implement the way of a human reasoning by means of fuzzy rules base, consisting of IF...THEN rules (Yaakoubi et al., 2017a). Its action consists of expressing the rules base, which are established based on a deep knowledge of the human expert, by a qualitative analysis of the plant behavior. Based on the exact and accurate knowledge of the WT behavior, the heuristic rules (IF...THEN) are expressed in the fuzzy domain. These linguistics rules are summarized in Table 1, and are called inference matrix.

As illustrated by the table, if power and speed increments are PH (vs. NH), a NH (vs. PH) speed increment is required to drive the OP to the OOP. If power and speed increments are PM (vs. NM), a NM (vs. PM) rotor speed increment is necessary to drive the OP at its optimum value. If power and speed increments are PL (vs. NL), a NL (vs. PL) rotor speed increment suffices to maintain the OP to the OOP. If the power increment is zero whatever the rotor speed increment sign, no action to do. This means that the OP is already at its optimum value.

3.2.6. Defuzzification

Defuzzification consists of transforming the output linguistic variable to crisp values based on the total area of its membership functions, to obtain the real value of the reference rotational speed. The gravity center method is the commonly used method and will be used in this paper to estimate the real output from the fuzzy controller. The real output from the controller d_{cn} corresponds to the position of the gravity center of resulted membership, is thus expressed as (EL YAAKOUBI, 2018):

$$d_{cn} = x_{Gr} = \frac{\sum_{i=1}^{49} \mu_{ci}(x) \mu_{Gi}(x) S_i}{\sum_{i=1}^{49} \mu_{ci}(x) S_i} \quad (12)$$

where S_i is the area of the fuzzy set of the command increment d_{cn} corresponding to the i th rule, x_{Gr} is the abscissa of its gravity center, $\mu_{ci}(x)$ is the membership degree of the output and $\mu_{Gi}(x)$ is the membership degree of the gravity center.

Table 2
Controllers parameters.

Parameters	Value
k_1	0.004
k_2	0.005
k_3	47
$\Delta\omega_{m,0}$	0.5

Table 3
WT parameters.

Parameters	Value
Rated power	6 kW
Rotor inertia	3 kg m ⁻²
Generator inertia	0.01 kg m ⁻²
Rotor radius	2.5 m
Gearbox ratio	6.25
Generator efficiency (η)	0.95

4. Simulation results

In this section we evaluate the performances of the control strategies by simulating the 6 kW WT driving the SCIG under the turbulent wind speed profile of Fig. 8. The parameters of the 6 kW WT model and the controllers are given by Tables 2 and 3 respectively. Detailed parameters are can be found in EL YAAKOUBI (2018). Figs. 7–11 illustrate the wind speed, the rotor speed, the power coefficient and the mechanical power, respectively. The results of Figs. 7 to 10 are estimated according to a chosen time scale of 1 min, which is sufficient to demonstrate the effectiveness of the proposed method. Fig. 11 represents the accumulated energy produced, so as we increase the time the extracted energy increases accordingly, and thus to illustrate the effectiveness of the proposed in terms of produced energy.

It can be observed from Fig. 8, that the estimated WT rotor speed follows closely the wind speed changes over time. From Fig. 9, it can shown that WT operation is kept around its optimum operation with fewer oscillations, when using the intelligent MPPT compared to the HCS strategy.

The mechanical power harvested from the wind is maximized because it tracks well the available mechanical power, as shown in Fig. 10. It can be observed also that the extracted power by the proposed control is larger than that produced by the HCS strategy.

It can be stated from the obtained results, that the proposed control strategy is able to maintain the WT around its optimum operation despite of high fluctuations of the wind speed.

The oscillations in the transient response of Figs. 8, 9 and 10 are due to the fact that the initial WT OP is not initialized. This leads the turbine to oscillate before achieving its OP. However, about 3 s, the WT achieves its steady regime with fewer oscillations. The oscillations exhibited in the permanent regime are caused specifically by the rapid fluctuations of the wind speed. Generally, such improvement in the performances is associated with fluctuations of output power. For the HCS the situation is even worse, if the OP is not fixed at the beginning the WT may never reach its permanent regime. For this reason, the WT OP of when using the MPPT based on HCS strategy has been fixed until $t = 10$ s ($\omega_{m,opt} = 19$ rpm).

In terms of generated energy, Fig. 11 compares the electrical energy generated by the two control strategies to the optimum available energy. As can be seen, the energy generated by the MPPT based on fuzzy logic is slightly lower than the WT optimal energy. Up to 20 s, the energy produced by MPPT based on FLC is lower than that obtained by the HCS. This is due to the fact that the WT OP when employing the MPPT based on HCS is fixed. From 20 s to 40 s, the energy produced by the MPPT-FLC increases gradually and becomes slightly higher to that generated

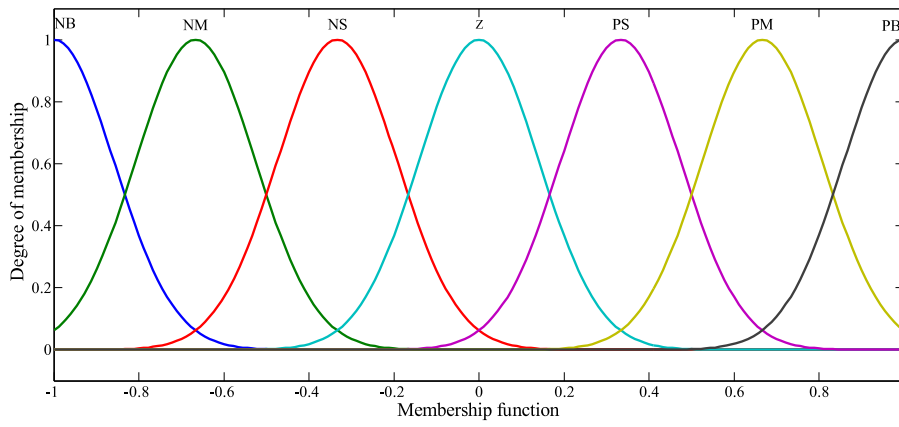


Fig. 6. Membership functions of the inputs and output.

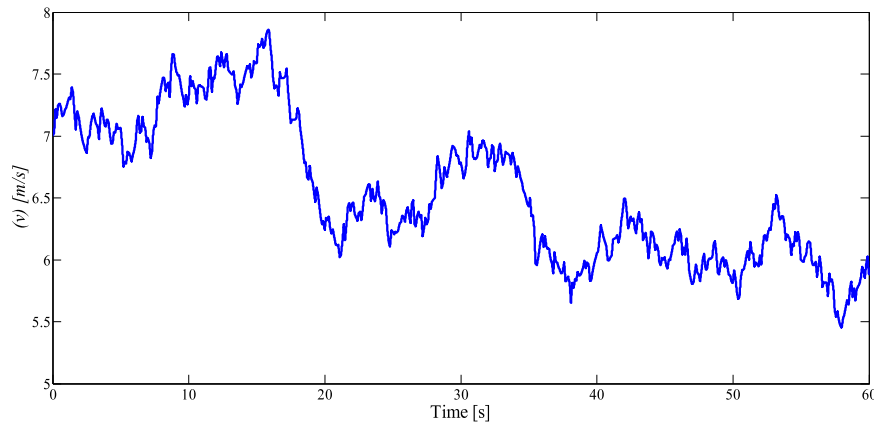


Fig. 7. Wind speed profile.

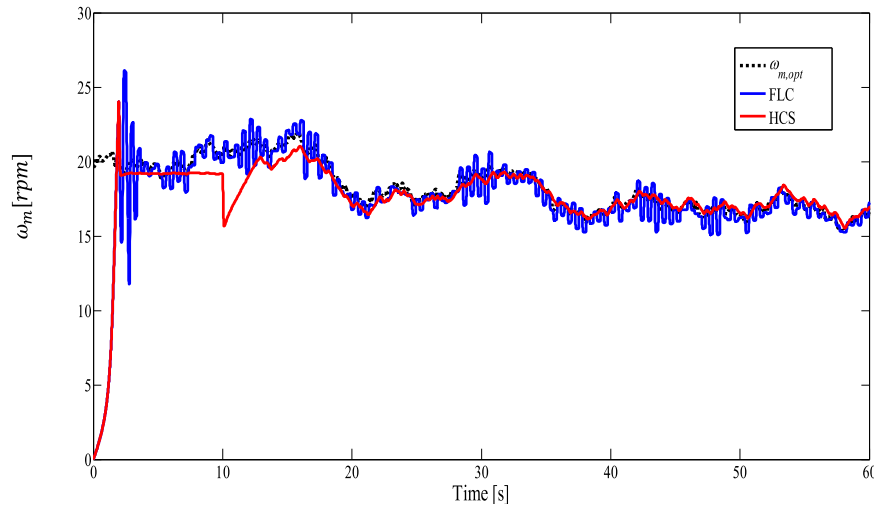


Fig. 8. Rotational speed.

by the MPPT based on HCS. It can be concluded that the MPPT based on FLC extracts more energy compared to the MPPT based on the HCS method. So, during this period the MPPT based on FLC extracts 2.38% more accumulated energy compared to the conventional HCS. This benefit may not be shown clearly due to the considered short time scale (100 s), the small size of the system as well as the limited computational capacity of the calculator. However, this amount is significant because it is given by Ws. Normally, the usual electrical energy unit is kWh. On the other

hand, the extracted energy follows well the optimum energy that could be extracted from the system. However, the delay from the energy produced to the optimum energy is caused by the long-time constant of the WT rotor. In fact, at every change of wind speed, this time constant induces a delay to the WT to follow the wind speed changes. Table 4 gives the load factors obtained by the two MPPT strategies for various wind speed profiles. The produced power from the turbine is averaged around the simulated period to derive the load factor. As shown, the

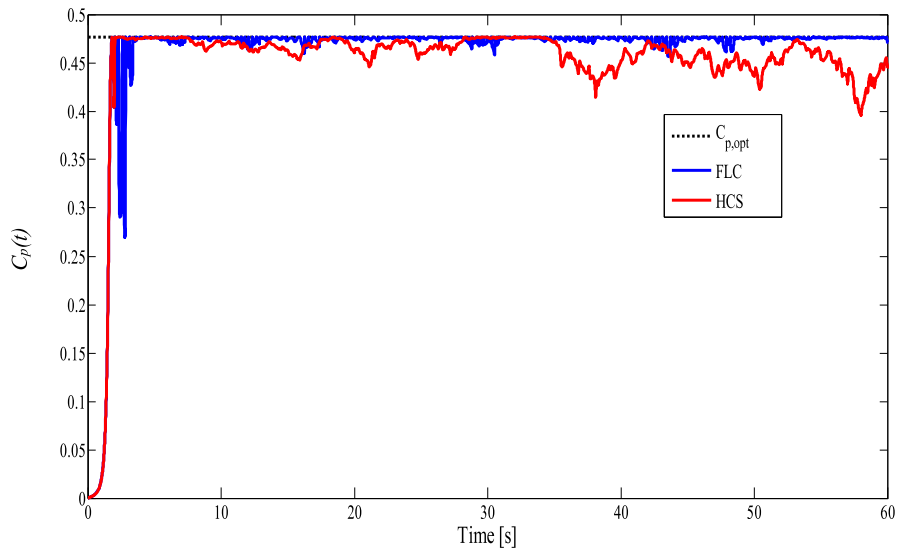


Fig. 9. Power coefficient.

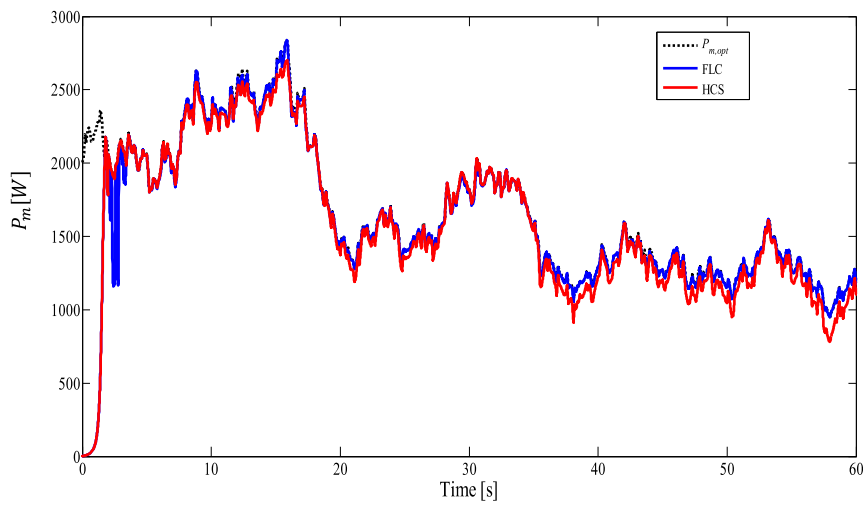


Fig. 10. Mechanical power.

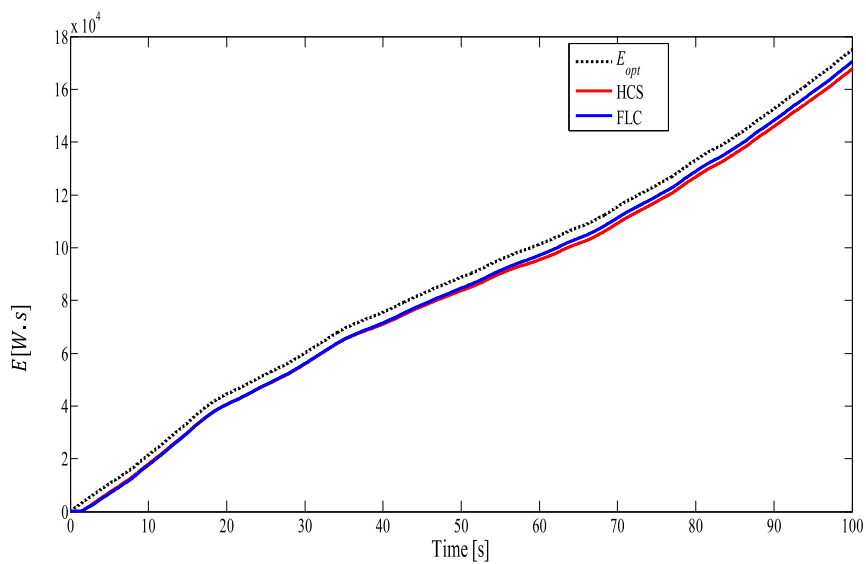


Fig. 11. Electrical energy.

Table 4
Load factor.

v_m [m/s]	C_l (%)	
	HCS	FLC
7	76	85
9	78	87
11	74	91

load factor of the WT associated to the implemented strategy is higher when compared to the MPPT based on HCS. This allows concluding that the proposed control scheme has good potential to extract a maximum power from the wind as compared to the MPPT based on HCS.

Conclusion

Small scale WTs are gained recently a great interest for isolated area energy feeding, water pumping as well research and development. Improving the efficiency of a small sized WT by integrating of non-linear and intelligent MPPT strategies is the major contribution of this paper. A survey of non-linear and intelligent MPPT strategies proposed in various literature has been provided. A description principle and design of hill climbing method and fuzzy logic control approach is deeply highlighted. Simulation of a small scale WT (6 kW) driving a Squirrel cage induction generator is conducted in Matlab/Simulink under various operating conditions to investigate the performances of the two methods. The mechanical power estimated by the developed method follows well the trends of the wind speed, and the power coefficient is maintained at its optimal value during the wind turbine operation despite the fluctuations rapid of the wind speed. The load factor is significant for all wind speeds, and the electrical energy generated is important. These findings allow proving that the maximum power point tracking strategy based on fuzzy logic has the ability to extract more energy from the wind turbine as compared to the conventional control based on HCS method. Extensions of this work may cover taking the wind turbine response in order to improve the effectiveness of this method for the large systems, and the power smoothing in order to mitigate the fluctuations of output power. Moreover, it is important to implement experimentally the control method.

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