A SENSORLESS MPPT TECHNIQUE FOR A GRID-CONNECTED PMSG WIND TURBINE SYSTEM

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Abstract

Maximum power point tracking (MPPT) techniques had evolved rapidly in the last decade with the evolution of power electronics. This paper presents a control technique for a variable speed, grid connected direct driven permanent magnet synchronous generator (PMSG). The PMSG is connected to the grid through three-phase diode rectifier followed by a boost converter controlled with the MPPT technique to maintain a constant DC bus voltage for different wind velocities. The paper compares between two MPPT techniques, HCS and fuzzy logic. The control depends upon sensorless rotor speed estimator through measuring the input dc voltage and current for the boost converter. The system performance is investigated using a MATLAB/ SIMULINK model for 2 MW PMSG wind turbine.

1 Introduction

Wind energy has become one of the most promising non-conventional renewable energy sources. The evolutions of power electronic devices make it available to control variable wind speeds and much more reliable to design large and small scale wind energy conversion systems (WECS) [1]. To increase the efficiency of variable-speed wind turbines, maximum power need to be extracted at different wind speeds. However, for every wind speed there is only one rotor speed which leads to extract the maximum power available, this is known as MPPT [2]. Optimal power curve for wind turbine in illustrated Figure (1).

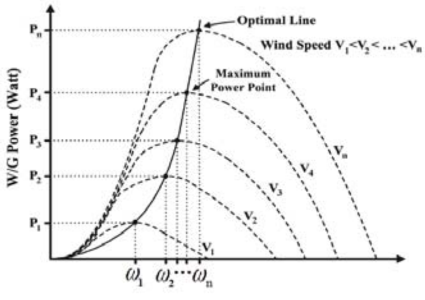


Figure (1): The power characteristic of a typical wind turbine. The trajectory labelled *(optimal Line)* represents the maximum points on the power curves

Different types of generators are used in WECS as WFIG, DFIG, SCIG and PMSG [3]. Among those PMSG was chosen for this system because it is direct driven reducing the mechanical issues and characterized with higher efficiency and energy with no need for additional power supply.

With the evolution of power electronics, using the direct driven PMSG had increased as a much reliable method for power generation. PMSG overcomes problems of noise, ride through capability, mechanical failures and maintenance issues that are very common with gearbox systems [4]. Various AC/DC converter topologies are used with PMSG, the most common among them is the back-to-back PWM power converter and the uncontrolled diode rectifier with boost converter, also there is the matrix converter and the z-source inverter. The back-to-back PWM is characterized with its low harmonics but is suffers from high switching losses and very complex control. On the other hand the diode rectifier with boost converter is characterized by its simple design and control in most cases but suffers from large harmonics and poor power factor [5]. Many MPPT techniques have been presented to extract the maximum power from the wind turbine [6-8]. MPPT techniques are classified into look up table, Hill Climbing Search (HCS), Artificial intelligent (AI), adaptive and hybrid techniques. Look up table are the most widely used techniques in WECSs where the power signal feedback (PSF) and Tip speed ratio (TSR) are the most common methods. PSF depends on the relation of optimal power versus the rotating speed while TSR depends on wind speed measurement and the optimal TSR to convert the measured wind speed into the corresponding reference for optimal generator speed. On the other hand, HCS are considered one of the simplest MPPT techniques as it does not require any mechanical sensors and the system knowledge is not needed where the system has high reliability and low complexity and cost. But HCS control suffers from extremely slow response to wind speed change and also oscillation around the optimum point is also inevitable which affects the overall efficiency of the system [9]. The AI techniques are characterized by its flexible control and suitable for non-linear systems because if it trained properly then they can extract the random data with high accuracy [10] [11]. The Neural network is a powerful technique for mapping input-output non-linear function. On the other hand fuzzy logic has the capability of transforming input into numerical values through fuzzy rules and membership functions.

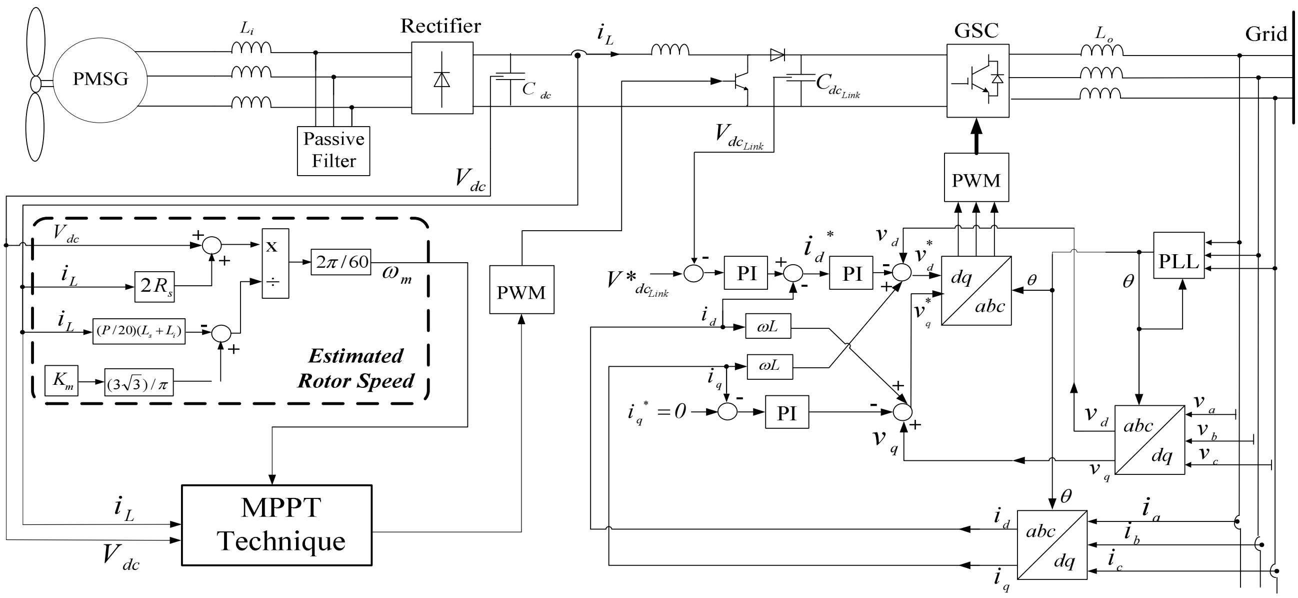


Figure (2): Block diagram of the proposed system

The AI techniques are complex and require offline training process. Finally the adaptive techniques depend on modifying basic techniques to improve the performance. MPPT techniques could be designed with wind speed sensor and rotor speed sensor or sensorless [12].

This paper compares between two MPPT techniques, conventional HCS and a fuzzy logic. Both techniques are sensorless and adapted to work with large scale wind turbine systems solving the problem of high harmonic distortion and large generator inertia

2 Wind Turbine Mathematical Model

For a variable speed wind turbine, the power captured from the wind (P_w) is given by [13].

$$P_w = \frac{1}{2}\frac{m.v_w}{t} = \frac{1}{2}\frac{\rho.A.d.v_w^2}{t} = \frac{1}{2}\rho.A.v_w^3 \tag{1}$$

where ρ is the air density, A is the Area swept by the turbine blades, d is the radius of the swept area, D is the thickness of the parcel ($D= v_w{\cdot}t$), m is the mass of air = air density × volume = $\rho{\cdot}A{\cdot}d$, and v_w is the wind speed (distance/time).

The mechanical power (P_m) generated by the wind turbine depends on the power coefficient (C_p) of the wind turbine. C_p is the ratio of the actual power delivered by the turbine and the theoretical power available in the wind. A turbine's efficiency, and thus power coefficient curve, is what differentiates one turbine from another. This is shown in Equation (2) [3].

$$P_m = P_w.C_P(\lambda,\beta) = \frac{1}{2}\rho.A.v_w^3.C_P(\lambda,\beta) \tag{2}$$

where $C_p(\lambda,\beta)$ is the power coefficient function, λ is the TSR, and β is the pitch angle.

$C_p(\lambda,\beta)$ is dependent on two factors. The first factor is the TSR, and second one is the pitch angle. TSR refers to the ratio of the turbine angular speed over the wind speed. The mathematical representation of the TSR is illustrated as:

$$\lambda = \frac{d\omega}{v_w} \tag{3}$$

where ω is the rotor speed.

A typical C_p curve (with a fixed pitch angle) is illustrated in Figure (3).

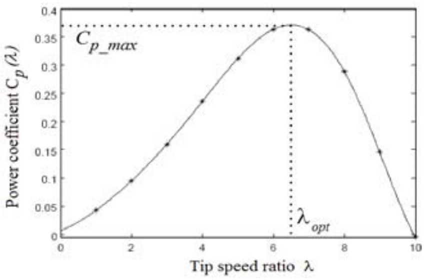


Figure (3): C_p versus tip-speed ratio λ

The turbine mechanical torque (T_m) for gearless system is given by [2].

$$T_m = P_m\frac{d}{\lambda.v_w} = \frac{1}{2}\rho.A.C_P(\lambda,\beta)\frac{R}{v_w} = \frac{\rho.A.C_P(\lambda,\beta)v_w}{2\omega} = \frac{P_m}{\omega} \tag{4}$$

A Matlab model of the wind turbine is shown in Figure (4).

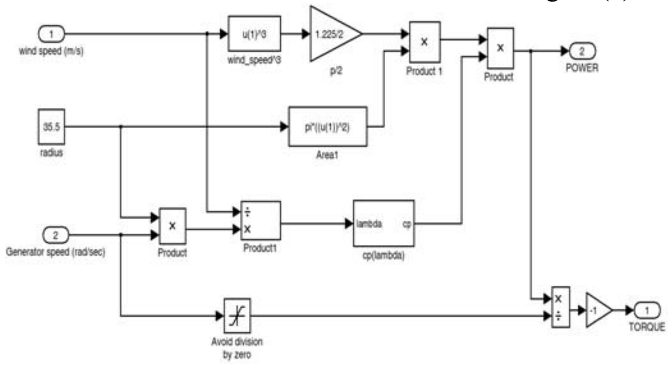


Figure (4): Matlab model of the wind turbine

A block diagram of the proposed system is illustrated in Figure (2). The proposed system is a 2 MW rated power wind turbine connected directly to 690V rated voltage PMSG, which is then connected to three phase uncontrolled diode rectifier converting the PMSG output voltage into DC voltage (V_{dc}), which is then followed by DC-DC boost converter. The boost converter help to maintain a fixed DC output voltage with maximized output power by controlling the converter's gate duty cycle (V_{dcLink}). The MPPT technique to control the converter's duty cycle can be divided into two main parts, rotor speed estimator and main control algorithm.

The diode rectifier presented in the system leads to large harmonic distortion and affecting the tracking capability of the system. A passive filter is introduced to minimize the harmonic distortion [14]. In the presented system low pass broadband filtering method is utilized as an ideal approach to block the 5^{th} and 7^{th} harmonic currents at multiple (widespread) frequencies [15]. A simple LC type low-pass broadband filter consists of a large input AC line reactor (L_i) along with the shunt filter capacitor (C_f) which is usually Δ connected ($C_f = C_{fY} = 3\ C_{f\Delta}$).The capacitor terminals are connected to the rectifier load. This simple filter can be designed to achieve satisfactory line current THD level and to minimize the input power factor [16].

3 Rotor Speed Estimation

One of the basic advantages of this system is that it is free of all kinds of mechanical sensors getting rid of all mechanical and maintenance issues that's arises from these kinds of sensors. it's very simple accurate sensorless technique depending on some known generator's parameters and only measuring the diode rectifier DC link rated voltage (V_{dc}) and the inductance current (I_L) [17]. The mathematical representation of the rotor speed estimation is given by [16].

$$\omega_m = \frac{V_{dc} + 2R_S i_L}{\frac{3\sqrt{3}}{\pi} K_m - \frac{P}{20}(L_i + L_S) i_L} \tag{5}$$

Where ω_m is the estimated rotor speed, K_m is the peak line to neutral back emf constant in V/rpm, R_s is the stator winding resistance in Ohm, L_s is the stator Leakage Inductance in mH, L_i is the In-Line inductance mH, and P is the number of poles. A block diagram for the rotor speed estimation system is illustrated in Figure (2).

3 MPPT Technique

In this section, two types of MPPT techniques are discussed. The first is conventional fixed step HCS technique and the second is a variable step fuzzy technique.

A- Conventional HCS Technique

Hill climbing search (HCS) technique is one of the simplest MPPT techniques as it requires measurement of the power only [19]. It is based on perturbing the turbine shaft speed in small steps ($\Delta\omega$) and observing the resulting changes in turbine mechanical power increase or decrease as illustrated by Figure (5) [20, 21].

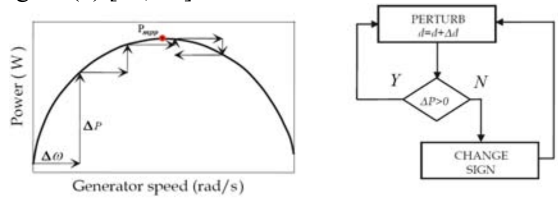


Figure (5): Principle of HCS MPPT.

The presented technique depends on taking an initial estimated rotor speed (ω_m) and measuring the generator's power (P), then start increasing or decreasing the rotor speed by a step (ω_{step}) and measuring the power with each step, then calculating signs for both ΔP and $\Delta\omega$. The output ω_{ref} is calculated using Equation (6). Figure (6) and (7) gives simple illustration of the HCS technique.

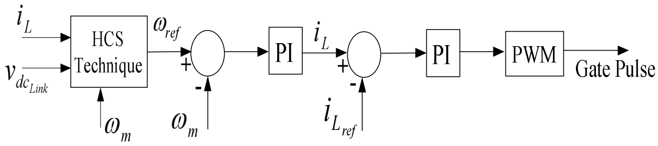


Figure (6): Block diagram of conventional HCS technique

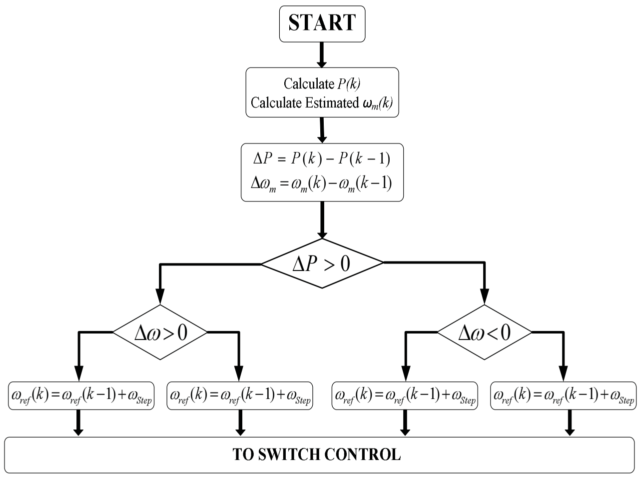


Figure (7): Flow chart for presented HCS technique

$$\omega_{ref}(n) = \omega_{ref}(n-1) + Sign(\Delta P) Sign(\Delta\omega)\omega_{step} \tag{6}$$

The converter controller contains two control loops in cascade. The first loop controls the boost inductor current by means of controlling ω_m with a speed PI regulator. This output is considered the reference for the next cascaded loop with controls the boost PWM signal by controlling i_L with a current PI regulator [22].

Ziegler-Nichols' Ultimate Gain Method was considered for the PI tuning [23]. This method is based on experiments executed on an established control loop for the system model [24].

B- Fuzzy Logic Technique

Fuzzy logic MPPT technique is considered as an extension for the HCS technique. It is governed by a set of rules which choose different control actions according to the state of the system at that instant while in HCS the control decision is taken based on only one if-else statement. The main advantage over HCS is that is moves with a variable step size unlike HCS with uses a fixed step size. This help to minimize oscillations in the output. Like HCS, fuzzy control does not require to know system parameters or equations [25] [26]. But it needs to define an optimal set of rules and corresponding control actions; calculating lots of boundaries and gains which differs from one system to another so the fuzzy controller has to be build dedicated to each system [27] [28]. The inputs for the proposed fuzzy are the error and the change of error as shown in Equations (7) and (8).

$$error = \frac{\Delta P}{\Delta \omega_m} = \frac{P(k) - P(k-1)}{\omega_m(k) - \omega_m(k-1)} \quad (7)$$

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

A block diagram for the proposed fuzzy controller is illustrated in Figure (8). Also set of membership functions is shown in Figures (9) and (10) while the set of rules is illustrated in Table 1.

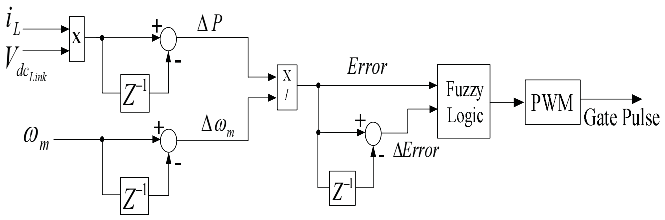
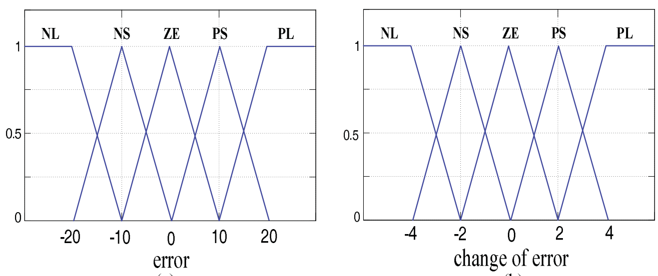


Figure (8): Block diagram of proposed Fuzzy technique



(a) (b)

Figure (9): Membership functions of input variables (a) Error $\Delta P(k)$ /$\Delta\omega(k)$ (b) Change of Error

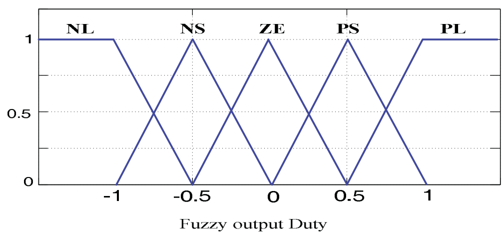


Figure (10): Membership function of output variable; Duty

Error / Δ Error	NL	NS	ZE	PS	PL
NL	NL	NL	NS	NS	ZE
NS	NL	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PL
PL	ZE	PS	PS	PL	PL

Table 1: Fuzzy logic rules

4 Simulation Results

The performance of the proposed system is investigated using a MATLAB/SIMULINK model of a 2 MW, 690V, grid connected, PMSG wind turbine system. The system parameters are illustrated in Table 2 [29] [30].

Wind Turbine parameters	*Value*
Rated Power (MW)	2.3
Blade diameter (m)	71
Rated wind speed (m/s)	14
Number of blades	3
Turbine Inertia J_T (Kg.m^2)	670
PMSG parameters	
Rated Power (MW)	2
Rated Voltage (V)	690
Rated Stator Frequency (Hz)	11.25
Number of Poles P	30
Stator Winding resistance R_s (mΩ)	0.73051
d-axis Synchronous Inductance L_d (mH)	1.21
q-axis Synchronous Inductance L_q (mH)	2.31
Flux Leakage (V.s)	4.696
Stator Leakage Inductance L_s (mH)	1.2
Rated Rotor Speed (rad/sec)	2.356
Generator Inertia J_G (Kg.m^2)	8000
Peak line to neutral back emf constant K_m (V/rpm)	14.15

Table 2: Wind Turbine and PMSG parameters.

The wind turbine optimal power characteristic is shown in Figure (11).

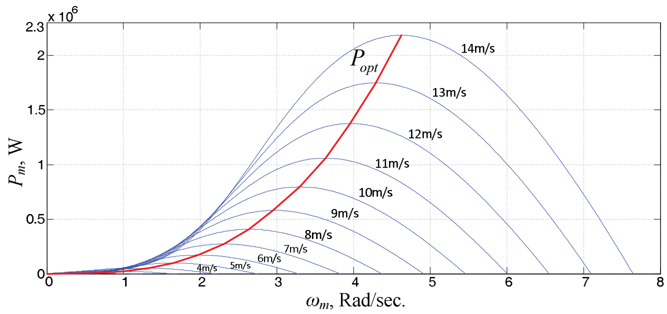


Figure (11): Wind turbine optimal power characteristics

The system results are tested and compared for both HCS and Fuzzy control techniques. Results are taken at three wind speeds; 14m/s for 1 sec. duration then speed go down to 9m/s for another 1 sec. then it speeds up again to 12m/s for 1 sec. as shown in Figure (12). Figure (13) illustrates the turbine output torque at different speeds.

A comparison between rotor speeds in case of measured and estimated shown in Figure (14). The percentage of error between both measured and estimated error is illustrated in Figure (15) at both HCS and fuzzy technique which shows that while using fuzzy control the oscillations are minimized. The error in worse case is less than 4% which proves that the rotor estimation system is accurate and close to the real measured rotor speed.

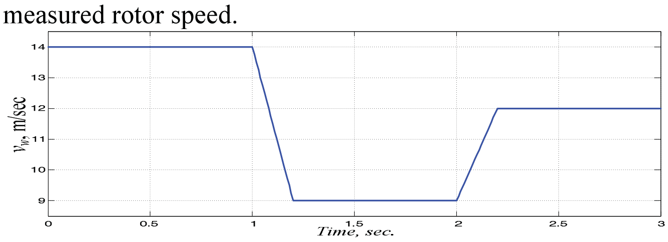


Figure (12): Wind speed

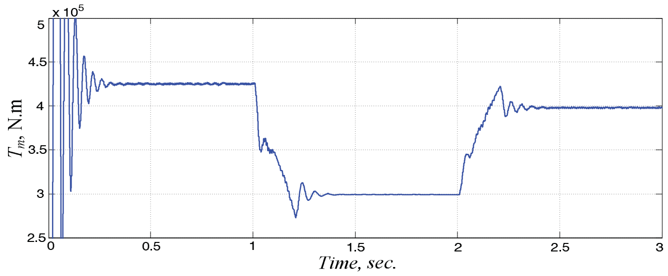


Figure (13): Wind Turbine output torque

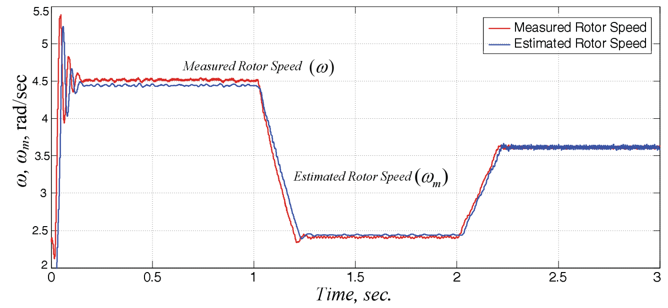


Figure (14): Estimated and measured rotor speed

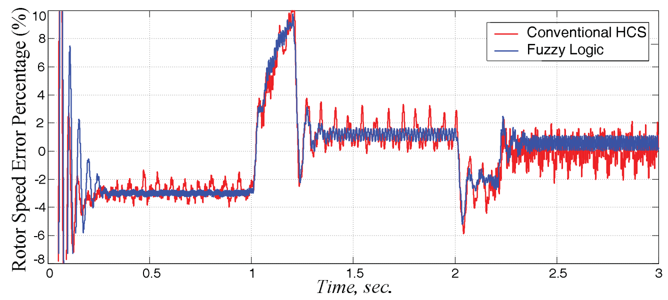


Figure (15): Percentage of error between measured and estimated rotor speed

Figure (16) shows that the controlled boost converter that the MPPT technique maintains constant output voltage (V_{dcLink}) with the change in wind speed changing the output current and power according to the wind speed as illustrated in Figure (17). Figures (18) and (19) illustrated the output grid voltage (v_g) and current (i_g) where figure (19) verifies the system achieves unity power factor at the grid side. Comparing optimal power curve in Figure (11) with figure (20), this verifies that the system was capable to extract maximum power. Also as comparing the output power in Figure (20) it is clear that using HCS technique lead to oscillations of about 1% while in case of fuzzy control the oscillations are negligible as in fuzzy the variable step size help reaching the optimum power without oscillating around it.

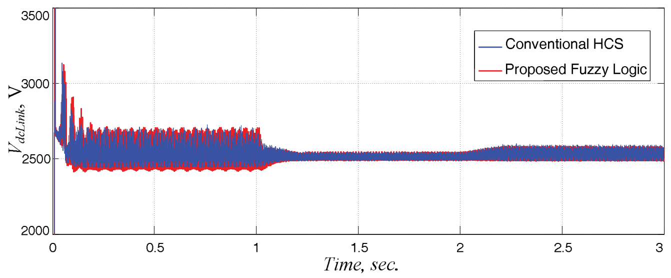


Figure (16): Boost output voltage

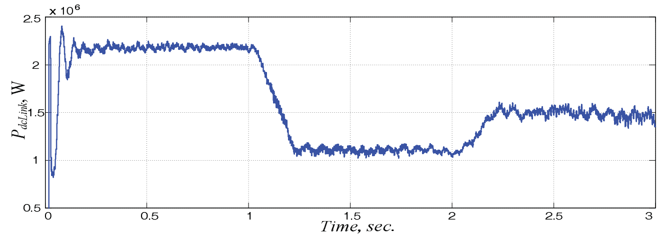


Figure (17): Boost output power

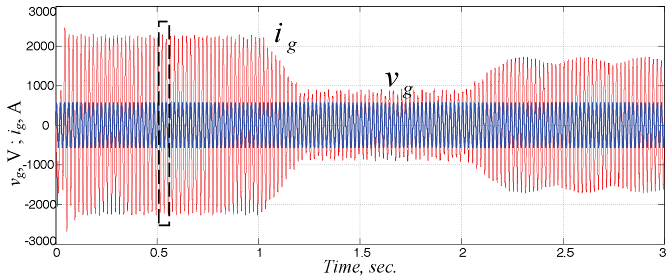


Figure (18): Grid voltage (v_g) and current (i_g)

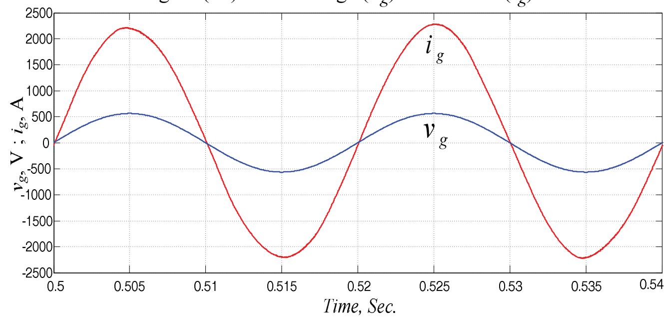


Figure (19): Zoom in of Grid voltage (v_g) and current (i_g) (at 14m/s)

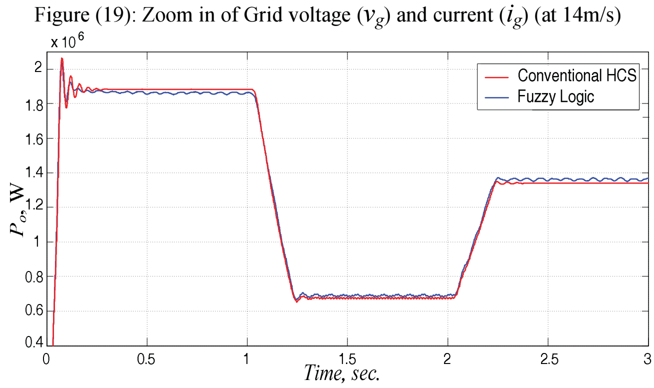


Figure (20): Grid output power

4 Conclusion

This paper presents a WECS PMSG wind turbine system that is characterized by its simple design, and sensorless MPPT control technique. Two MPPT techniques are introduced and compared, conventional HCS based with fixed step size and fuzzy logic with variable step. Both techniques are adapted to work with large scale wind turbine system. Although both HCS and fuzzy were capable to extract maximum power but fuzzy logic help to enhance the output power oscillations removing all the oscillations that appears in HCS. The control algorithm depends on a rotor speed estimation system. The results for both techniques were investigated and verified using MATLAB/SIMULINK.

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