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Sensorless Control System Design of a Small Size Vertical Axis Wind Turbine

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Abstract

This paper describes control system design of a small size vertical axis wind turbine for battery charging, using permanent magnet synchronous generator (PMSG). The direct drive PMSG is connected to the battery through a switch mode rectifier where a DC-DC buck converter is used to optimize the wind power. The use of speed sensor to the control system design complicates and adds more costs to the system. To resolve this problem, a sensorless maximum power-tracking algorithm is proposed to calculate the current command that corresponds to maximum power output of the turbine. The DC-DC converter uses this current command to calculate the duty cycle which is necessary to control the pulse width modulated (PWM) active switching device. The system overview and modeling is presented, including characteristics of wind turbine, generator, batteries, power converter, control system, and supervisory system. A simulation of the system is performed using MATLAB/SIMULINK.

Keywords: *Battery charging, Permanent magnet synchronous generator (PMSG), vertical axis wind turbine, maximum power point tracking (MPPT),PWM DC-DC buck converter.*

1. Introduction

Most wind generation systems use horizontal axis turbine, they are often designed to be connected to electric grid[1]. For small size systems, vertical wind turbines have a great potential to generate electricity for applications in rural areas, such as residences far from a power grid, telecommunication towers, monitoring stations. Its main advantage is the lower connection wind speed[2].

Direct drive permanent magnet synchronous generator for vertical axis wind turbines has received much attention in wind energy application because of their property of self-excitation, which allows an operation at a high power factor and high efficiency [3].

A wind energy conversion system with PMSG can be used basically in three distinct applications: standalone systems, hybrid systems, and grid connected systems. Previous publications related to PMSG based variable speed wind turbine are mostly concentrated on grid connected system [4]. Despite the abundance of renewable energies along isolated areas, electricity supply is one of the biggest obstacles to the population because of the cost and difficulty of connecting to electrical grid.

To resolve this problem, direct-drive permanent magnet synchronous generator for battery charging, using vertical axis wind turbine is very useful for low power applications. However, for large power applications, the cost-effectiveness of such wind systems requires additional design costs[5].

The direct battery charging through a rectifier bridge represents a simple solution adopted by some manufacturers because of its simplicity and robustness [6]. Despite these advantages, several problems associated with this solution result, such as the reduction of batteries useful life and increase of power losses, and also, the wind turbine does not operate at its maximum electrical power in all operating conditions. Therefore, it is necessary to provide variable speed wind generation systems that allow the use of turbine for its maximum power coefficient in a large range of wind speed, optimizing the use of the available energy[7]. This is possible by inserting a DC-DC converter between the rectifier output and the battery to adapt the generator voltage to the battery bank voltage. Several papers have been published in this topic. For example in [8], the topology proposed uses DC-DC boost converter to regulate the battery bank current using different control strategies. The concept of the control strategy of power maximization used in paper [9] is based on the calculating of the differential power from the power-frequency curve tracking the inflexion point to reach the maximum power point.

This paper proposes a sensorless wind power topology that employs a DC-DC buck converter for battery charging using simple control algorithm; witch calculates battery current reference and introduces losses in the global behavior of the system.

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2. System Modeling

The proposed system is shown in Figure 1. It is composed of a vertical axis wind turbine connected to a permanent magnet synchronous generator (PMSG). The generator is cascaded with a battery charger composed by three-phase rectifier and DC-DC buck converter. In the aim to know the global behavior of the production system, we suppose that the batteries are composed of an ideal electric supply source Ebat in series with a resistance Rbat. The battery charger operates to obtain maximum power transferred to the batteries and can also limit voltage levels of the battery bank. The converter duty cycle is changed in accordance with control system, which receives a reference signal from the supervisory system.

2.1. Wind Turbine Performance

The proposed model is based on the steady state characteristics of the vertical axis wind turbine. The output mechanical power available from a wind turbine can be expressed as follows [10].

$$p_m = \frac{1}{2}.\rho.S.Cp(\lambda).V_w^3 \qquad (1)$$

$$\lambda = \frac{R.\omega}{V_w} \qquad (2)$$

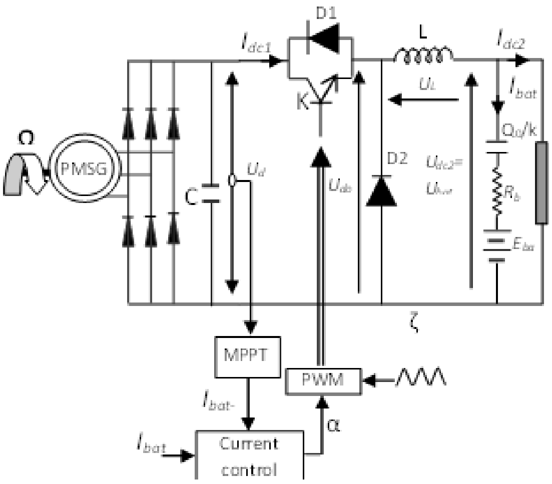

Figure1. General scheme of the proposed system

Where, ρ is the air density (typically 1.225Kg/m^3 at sea level with standard conditions, i.e. temperature of 15°C and atmospheric pressure of 101.325Kpa, S is the area swept by the rotor blades (in m^2), V_w is the wind speed (in m/s) and C_p is the so-called "power coefficient" of the wind turbine (dimensionless), with R being the radius of the turbine blades (in m) and ω being the angular speed of the turbine rotor (in rad/s).

As can be derived from Eq. 1, the power coefficient Cp is a nonlinear function of the tip-speed ratio (TSR) λ (dimensionless). Therefore, if the air density, swept area, and wind speed are constant, the output power of the turbine will be a function of power coefficient of the turbine. A generic equation is used to model the power coefficient Cp(λ), based on the modeling vertical axis turbine characteristics used in [11]:

$$C_p = -0.2121\lambda^3 + 0.0856\lambda^2 + 0.2539\lambda \qquad (3)$$

The characteristic function Cp vs. λ, is illustrated in Figure 2.As can be seen from Figure 2, at TSR-opt, Cp has its maximum value which results in the optimum efficiency, therefore, maximum power is captured from wind by the wind turbine. Figure 3 illustrates the output power of a wind turbine versus rotor speed while speed of wind changed from V1 to Vn (Vn>V1).

It can be observed that, for each wind speed, there exists a specific point in the wind generator power characteristic, this point is known maximum power point.

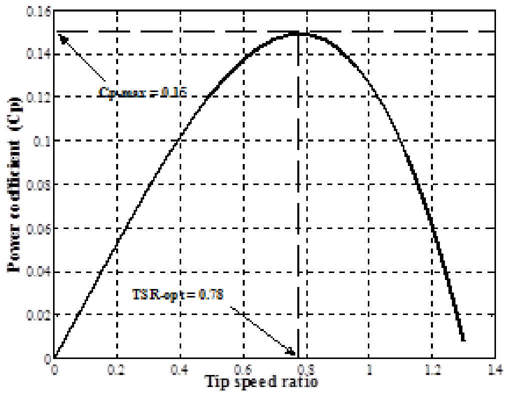

Figure2. Power coefficient versus tip-speed ratio

Thus, the control of the wind energy conversion system load results in a variable-speed operation of the turbine rotor, such that the maximum power is extracted continuously from the wind. The target optimum power from a wind turbine can be written as:

$$P_{m-opt} = \frac{1}{2}.\rho.S.C_{p-opt}.(\frac{R\Omega_{opt}}{\lambda_{opt}})^3 = K_{opt}.\Omega_{opt}^3 \qquad (4)$$

Where:

$$K_{opt} = \frac{1}{2}.\rho.S.C_{p-opt}.(\frac{R}{\lambda_{opt}})^3 \qquad (5)$$

$$\Omega_{opt} = \frac{\lambda_{opt}}{R}.V \qquad (6)$$

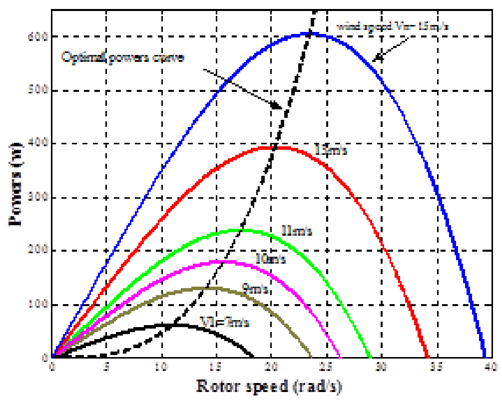

Figure 3. Power versus rotor speed at various wind speeds

2.2. Permanent Magnet synchronous Generator

The wind turbine driven PMSG can be represented in the rotor reference frame by the following model [12],[13]:

$$\begin{cases} V_d = -R_s I_d - L_d \dfrac{d}{dt} I_d + \omega L_q I_q \\ V_q = -R_s I_q - L_q \dfrac{d}{dt} I_q - \omega L_d I_d + \omega \psi_f \end{cases} \tag{7}$$

Where:

L_d : Stator inductance in direct axis(H).
L_q: Stator inductance in quadrature axis (H).
R_s : Stator phase winding resistance (Ω).
Ψ_f: Amplitude of the flux linkages (v.s/rad).
I_d : direct axis current (A)
I_q : quadrature axis current (A)

The electromagnetic torque is expressed by[12], [13]:

$$C_{em} = \frac{3}{2} P[(L_q - L_d) i_d i_q + i_q \psi_f] \tag{8}$$

Where, P is PMSG number of pairs of poles.

The dynamics of the machine is given by the following mechanical equation:

$$C_m - C_{em} - f\Omega = J \frac{d\Omega}{dt} \tag{9}$$

Where:

C_m : Motor torque developed by the turbine shaft (Nm)
C_{em} : Electromagnetic torque developed by the generator (Nm)
$f\Omega$: Friction torque
J: Moment of inertia referred to generator shaft (Kgm^2)
f: Friction coefficient.
Ω: mechanical angular velocity of the turbine (rad/s).

The relation between the rotor angular velocity of the generator ω and the mechanical angular velocity of the wind turbine rotor Ω is expressed as[12], [13]:

$$\omega = P.\Omega \tag{10}$$

2.3. *Three phases diode bridge rectifier*

The diode rectifier is the most commonly used topology in power electronic applications. For a three phase system, it is consisting of six diodes. The diode rectifier can only be used in one quadrant, it is simple and it is not possible to control it. The DC voltage and current output depend on the generator voltage and current as following[14]:

$$U_{dc} = \frac{3}{\pi} E_{ab}^{\max} = \frac{3*\sqrt{6}}{\pi} E_a^{eff} \tag{11}$$

$$I_{dc} = \frac{\pi}{\sqrt{6}} I_a \tag{12}$$

Where:

U_{dc} and I_{dc}: Medium output voltage and current of rectifier.
E_a and I_a: Output voltage and current of generator (phase a).

2.4. *Battery Model and State of Charge*

The battery model is inspired from Ford batteries model. It is formed by an ideal voltage supply E_{bat} in series with resistance $R_{bat}$and capacity Q(Ah) as illustrated in Figure 1. The electrical model is given by the following expression [15]:

$$V_{dc2} = E_{bat} - K \frac{\int I_{bat} dt}{Q_0} - R_{bat}.I_{bat} \tag{13}$$

Where:

K is a constant depends on the battery.

$-\dfrac{\int I_{bat} dt}{Q_0}$ Is a term that indicates the state of discharge.

2.5. *DC-DC Buck Converter Model*

The standard unidirectional topology of the DC-DC buck converter of the Figure. 1, consists of a switching-mode power device containing basically two semiconductor switches (a rectifier diode D2 and a power transistor K with its corresponding anti-parallel diode D1) and an inductor L. The output DC voltage is produced at a level lower than its input DC voltage. This converter acts as an interface between the full-wave rectifier bridge and the battery bank, by employing pulse-width modulation (PWM) control techniques. Operation of the DC-DC converter in the continuous (current) conduction mode (CCM), i.e. the current which is flowing continuously in the inductor during the entire switching cycle, facilitates the development of the state-space model because only two switch states are possible during a switching cycle, namely, (i) the power switch K is on and the diode D2 is off; or (ii) K is off and D2 is on.

Electric equations that describe the dynamics of the DC-DC buck converter over a commutation period are given by:

$$U_{do} = \alpha U_{dc1} \tag{14}$$

$$U_{do} = U_{bat} + U_L \tag{15}$$

$$U_{do} = E_{bat} + R_{bat} I_{bat} + L \frac{dI_{bat}}{dt} \tag{16}$$

Where, I_{bat} is the converter output current (battery current charging), U_{bat} is the output voltage, U_{dc1} is the buck converter input voltage, U_L and U_{d0} are respectively, inductor (L) and diode rectifier (D2) voltages.

3. Control of DC-DC buck converter with maximum power extraction

The battery current charging can be controlled by controlling the duty cycle of the switch (K) at any wind speed to extract maximum power from the wind turbine. Figure 4shows the control block diagram of DC-DC buck converter. Since the battery current charging I_{bat} depends on the power of the battery P_{bat}, we can consider this power as reference stat variable according to following relation:

$$I_{bat}^{ref} = \frac{P_{bat}^{ref}}{U_{bat}} \tag{17}$$

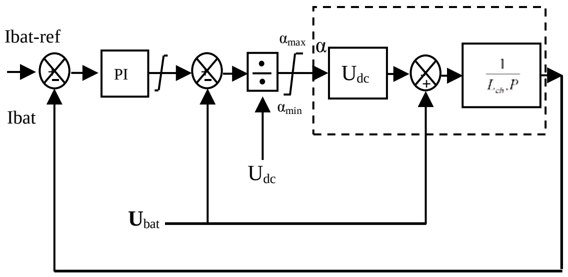

Figure 4. Control block diagram off dc-dc buck converter

3.1. *MPPT*

The senseless control strategy proposed in this work is based on the indirect piloting of the battery current charging. This can simplify wind power conversion system and minimize its cost, without reducing the energizing efficiency. We consider that the rotor speed picture is given by the PMSG electromotive force; both parameters are then bound to output rectifier voltage. The mechanical speed sensor can be suppressed and replaced by a simple voltage measure which can be assimilated to the rotation speed according to followingequation:

$$U_{dc}(\Omega)=\frac{3}{\pi}.E_{ab}^{max}=\frac{3.\sqrt{6}}{\pi}.\psi_{f-eff}.P.\Omega=\mu.\Omega \quad (18)$$

Where, μ is a constant given by:

$$\mu=\frac{3.\sqrt{6}}{\pi}.\psi_{f-eff}.P \quad (19)$$

Therefore, the target optimum battery current charging can be given by:

$$I_{bat}^{ref}=\frac{K_{opt}}{U_{bat}}.\Omega^3=\frac{K_{opt}}{U_{bat}}.(\frac{U_{dc}}{\mu})^3=\frac{\sigma.(U_{dc})^3}{U_{bat}} \quad (20)$$

$$\sigma=\eta.K_{opt}.(\frac{\pi}{3.\sqrt{6}.\psi_{f-eff}.P})^3 \quad (21)$$

The maximal power of the battery is given therefore by:

$$P_{bat}^{max}=f(U_{dc})=\sigma.(U_{dc})^3 \quad (22)$$

The MPPT device gotten is illustrated therefore on Figure5.

$$U_{dc}[K]\longrightarrow\frac{P_{bat}^{max}=f(U_{dc})}{U_{bat}}[K]\longrightarrow I_{bat}^{ref}[K+1]$$

Figure 5. Control algorithm of the battery current

The control algorithm includes then, the following steps:

- Measure output diode rectifier voltage.
- Determine the reference current charging of the battery.

3.2. *Compatibility of the Proposed Structure opposite the Battery Voltage*

For an optimal working régime, the output rectifier voltage value can be determined according to the wind speed by the following expression:

$$U_{dc1}=\frac{3.\sqrt{3}}{\pi}.p.\psi_{f-max}.\frac{\lambda_{opt}}{R}.V_v \quad (23)$$

While neglecting losses, the output rectifier voltage can be written according to the battery voltage Ubat and duty cycle α by:

$$U_{dc1}=\frac{U_{bat}}{\alpha} \quad (24)$$

According to the wind system application conditions, the simple DC-DC buck converter imposes some limitations. The converter input voltage possesses minimal and maximal stops, determined by the battery voltage U_{bat} and duty cycle stops α_{min} and α_{max},

The minimum input voltage of DC-DCbuck converter is defined by:

$$U_{dc1}^{min}=\frac{U_{bat}}{\alpha_{max}} \quad (25)$$

Therefore, the minimal wind speed can be calculated according to the battery voltage:

$$V_v^{min}=\frac{\sqrt{3}.\pi.R}{9.p.\psi_{f-max}\lambda_{opt}\alpha_{max}}.U_{bat} \quad (26)$$

Admitting that the duty cycle maximal value equal to 0.99, it is possible to find the minimal speed of wind assuring the good functioning of the wind power conversion system for different battery voltages. For the duty cycle lower limit that is supposed equal to 0.1, there is no problem posed, because the wind values gotten are very big.

4. Results and discussions

The model of the PMSG based variable speed wind turbine system of Figure 1 is built using Matlab/Simpower dynamic system simulation software. The parameters of the Turbine and PMSG used are given in Table 1. The power converter and the control algorithm are also implemented and included in the model. The wind profile input data used during this study are shown in Figure6. In the aim to know the load voltage effect on the system behavior, three different batteries are used during this 120-s simulation period as shown in Figure7. As shown in Figure8, the peak power follows the wind speed profile, and it is close to the actual maximum power for each variation of wind speed. Figure 9 represented the power coefficient which is kept almost constant and very close to the maximum value Cp-max=0.15. And since global losses are proportional to the current, measured power illustrated in Figure 8 is less important for low voltages as shown after 80seconds, and follows closely the power reference for high voltages. As the wind speed decreased or increased, the controller tracks maximum power by varying the duty cycle over the whole range of input wind conditions as shown in Figure 9. It seems that with increase in battery voltage, the sensorless controller increases the duty cycle which directly controls the modulation index of the PWM DC-DC converter. In that case, the charging current decreases and the output power increases. Figure11 shows optimum power versus wind speed, where connection wind speed V_{cut-in} is very low (about 2.7m/s), and battery voltage variation effect is observed in the form of peaks. The integrated value of the maximum power at the end of the simulation is the maximum energy available from the wind with this wind energy conversion system. Simulation results show that the overall energy captured is optimized by the control strategy throughout the range of wind speed as can be seen in Figure12

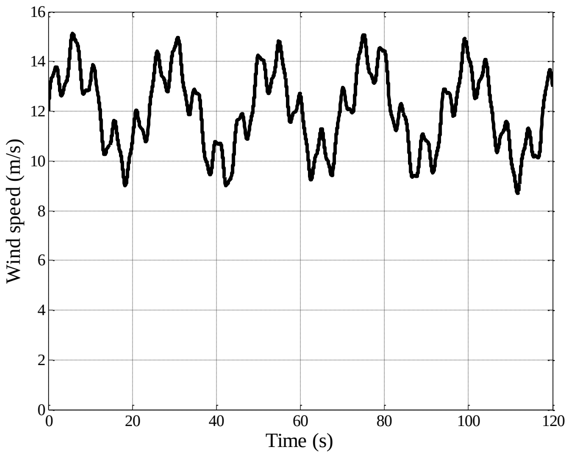

Figure 6. Wind speed profile

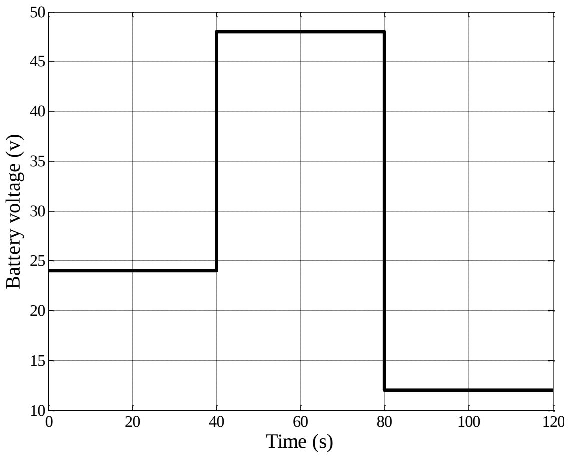

Figure 7. Battery voltages

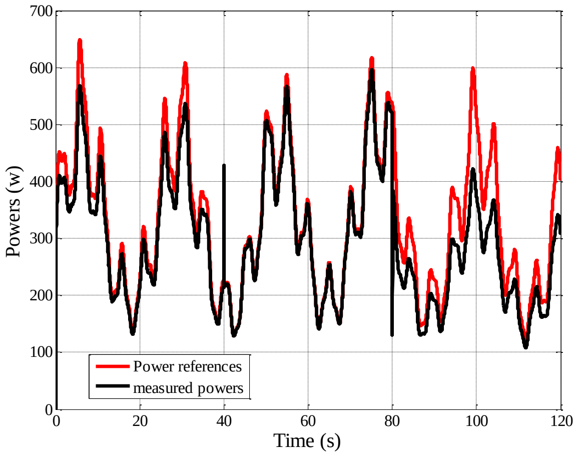

Figure 8. Optimal and maximized powers

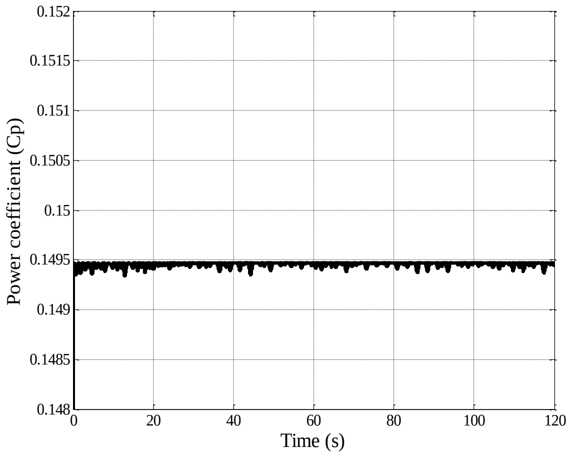

Figure 9. Power coefficient

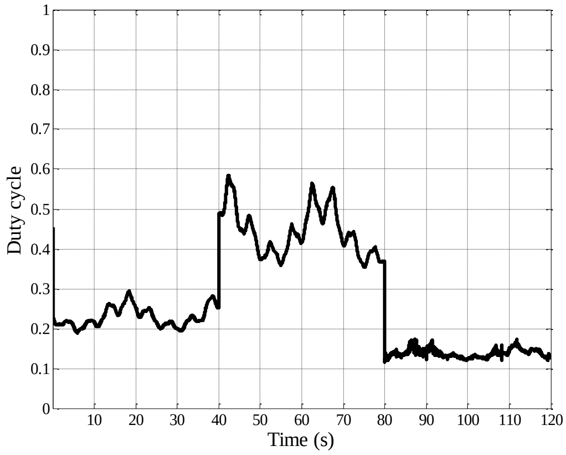

Figure 10. Duty cycle

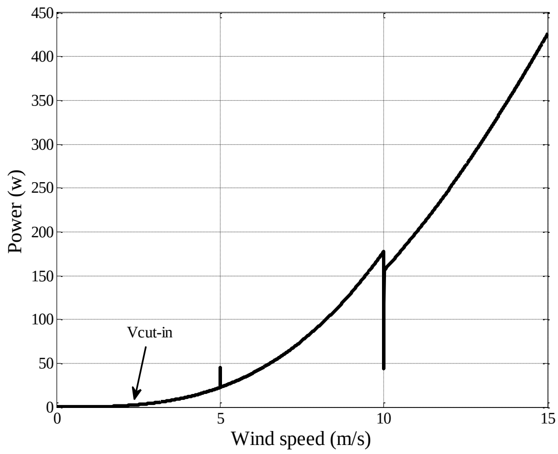

Figure 11. Power versus wind speed

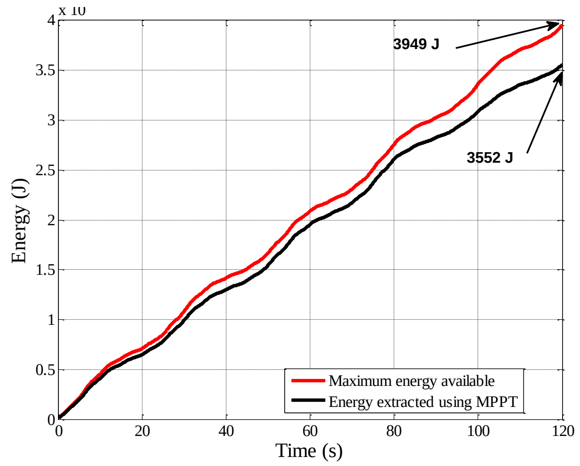

Figure 12. Optimal and maximized energies

Conclusion

A simple sensorless control strategy applied in small size wind generator systems for charging batteries has been proposed. A complete modeling and simulation of turbine, generator, converter, and battery was developed. The MPPT system was designed and studied via simulated results. The main target of the proposed system is the exploitation of the available wind energy at low speeds in an optimum operating point without compromising the efficiency at higher wind speeds. The algorithm control of DC-DC buck converter is designed with reduced overall cost which improves its use in domestic life with a large safety margin because it is designed to be connected with low voltage batteries.

Table 1. Wind energy system parameters

Wind turbine	
Density of air	1.225 Kg/m^3
Area swept by blades, S	2 m^2
Optimum coefficient, K_{opt}	0.0474 Nm/(rd/s)^2
PMSG	
No, of poles	34
Rated current	4.8 A
Rated voltage	90 V
Armature resistance, R_S	1.137 Ω
Magnet flux linkage	0.15 Wb
Stator inductance, L_S	2.7 mH
Rated power	600 W
Inertia	0.1 Kgm2
DC-DC buck converter	
filtering voltage capacity	3.3 mF
Smoothing inductance	2.5 mH
Cutting frequency	5 kHz
Diode threshold voltage	0.65 V
Transistor threshold voltage	0 V
Diode conduction resistance	20.7e-3 Ω
Transistor conduction resistance	85e-3 Ω

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