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Maximum power tracking control wind turbine based on permanent magnet synchronous generator with complete converter

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Abstract

This paper discusses the problem of maximum power point tracking (MPPT) of Wind Turbine based on a permanent magnet synchronous generator (PMSG) connected to power grid trough complete static converter. To achieve this, we propose a control scheme of synchronous generator, consisting of a DC/AC device followed by a second DC/AC device. The idea behind MPPT principle is turbine speed variation depending on wind speed in case of generator indirect connection to power grid. Simulations on Matlab-Simulink can be found at the end of the paper, confirming a good consistency with study objectives of control scheme, selection of setting parameters and complete converter architecture.

Keywords: PMSG, wind turbine, complete converter, MPPT, pole placement

1. Introduction

With soaring fuel prices and predictable exhaustion of fossil fuels, alternative options are increasingly considered. The beginning of the 21st century had been marked by a spectacular rush towards renewable energy conversion systems. The ultimate objective is to get away from dependence of conventional sources of energy. Recently, this trend increased, all the more, by considerations of ecological order. Indeed, the high consumption of the traditional fossil energy sources causes serious environmental damage. Thus, all countries are now called upon to contribute international effort to combat climate change. Among all the renewable energies, three main classes emerge: mechanical (sea swell, marine currents, wind, etc), electromagnetic (solar panels, etc) and thermal (geothermal, solar thermal, etc). In particular, wind power can be converted to mechanical power by water pumping or to electrical power by using appropriate generators. The latter form has expanded rapidly throughout the world, through both household and industrial applications in connection with power grid. In financial terms, the wind turbines have a low profitability [1], given the significant cost of installation. However, they have many advantages in terms of preserving non-renewable natural resources, limiting environmental pollution and operational autonomy.

Theoretically, recovering power of wind turbine generators is limited to approximately 59% of the kinetic energy of the wind [1]. This is the Betz limit. The power coefficient C_p, takes into consideration this limit as well as frictional losses and varies with the rotational speed of the turbine. That is why, monitoring of the operating point at maximum power is recommended. Many studies have been carried out on approaches of MPPT [2]. Generally, MPPT methods can be broadly classified into those that not use sensors and those that use sensors. Sensorless methods [3] rely on the monitoring of the power

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variation. The others with sensors [3] are dedicated to researching the MPPT by control of turbine torque and specific speed, commonly known by TSR (tip speed ratio) [4], [5]. TSR control regulates directly the turbine speed or torque to maintain the TSR at an optimum value by measuring the turbine speed.

The adopted sensor method of MPPT requires real-time reading of wind speed as well as prior knowledge of wind turbine characteristics. It presents many advantages over HCS (hill climb search) method: fastness of convergence and greater stability of calculations at steady state [6]. The amount of energy recovered by conversion systems of wind energy (variable speed wind energy conversion system: VS-WECS), depends on the accuracy with which search of MPPT is done and also on the type of generator used. Energy conversion chains often use a permanent magnet synchronous generator [7]. This type of machine allows overcoming the problem of the excitation current supply, heavy to manage in a conventional synchronous machine.

To maximize the efficiency of the wind generator, various solutions were examined at different levels of conversion chain [7] according to direct or indirect grid connection. Indirect grid connection of the generator provides, in addition to the advantage of optimizing the extracted power from the wind, the opportunity to save significant starting and synchronizing time before the connection to the power grid.

The role of the power electronic interface, mounted between generator and grid, is to manage generator in order to extract the maximum of the power of the wind [8]. Ordinarily, conventional scheme of VS- WECS uses a controlled-rectifier. Indeed, Li *et al* [9] has proposed a control scheme of PMSG with PWM Controlled-rectifier. This device requires an important physical logistics (6 fully controllable switches).

This study presents a complete scheme of wind turbine connected to power grid, using Permanent Magnet Synchronous Generator. The voltage generated by PMSG is rectified using a three-phase passive rectifier followed by a buck DC/DC converter. This device converts the AC voltage to DC voltage. The main circuit composition of grid side converter is a Boost DC/DC converter and a current Source Inverter followed by an isolation transformer.

Nomenclature

Symbols

α: Duty cycle	β: Pitch angle (°)	C_d: Scale factor (m/s)	C: Capacitance (F)
C_p: Power coefficient	δ: Internal angle (rd)	f: Friction factor (N.m.s)	η: Power efficiency
F: Cumulative distribution function		ϕ: Generator flux amplitude (Wb)	
I: Current (A)	K: Factor, ratio	L:Inductance (H)	P: Power (W)
J: Inertia of the power train (kg/m^2)		λ: Tip Speed Ratio (TSR), Eigenvalue	
p: Pole pairs	p.u.: per unit	R: Blade length (m)	r: Résistance (Ω)
R_s: Resistance of armature (Ω)		ω: Frequency alternating current (rd/s)	
s: Laplace variable	t: Time (s)	V: Voltage (V)	V_v: Wind speed (m/s)
Ω: Rotor speed (rd/s)	< >: Average rate symbol		

Indices:

0: Steady-state value; 1: Generator side, fundamental; 2: Grid side; C: Capacitor; D: Grid; d: Direct axis; f: form; G: Generator, Gearbox; l: leakage; Max: Maximum; N: Nominal; m: magnetizing; P: PWM; q: quadrature axis; R: Rectifier; RMS: Root Mean Square; s: stator.

2. Power Components

The control scheme of PMSG, which we propose (Fig. 1), is a complete convertor between PMSG and power grid with an intermediate storage capacitor. The generator side device is a cascade circuit including an uncontrolled three-phase bridge rectifier and a buck chopper [2]. Compared to MLI rectifier solution, this one gives the advantage of reliability, performance and low-cost material.

However, the grid side device is a cascade circuit including a boost chopper and a current source inverter (CSI) followed by an isolation transformer (see Fig. 2 (b)).

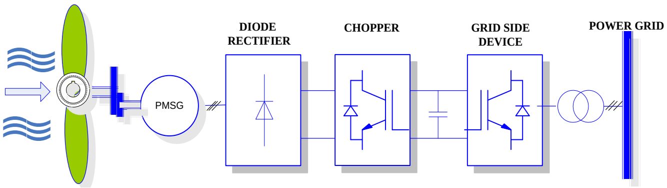
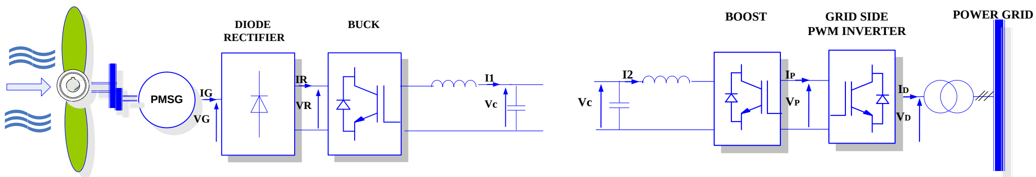


Fig.1. Proposed VS-WECS global diagram.



(a) (b)

Fig. 2. Device of VS-WECS: (a) generator side and (b) grid side.

This means an instantaneous energy recovery enabling a battery saving with all that this implies in terms of environmental impact and maintenance management.

2.1. Wind turbine model

The wind turbine power is given by the expression:

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

Maximum power extraction occurs at optimal TSR λ_{opt} which gives C_{pmax} well below Betz theoretical limit due to frictional and turbine design losses. Using a wind speed sensor, MPPT calculation module provides the generator speed reference so that we can extract maximum power. In order to assess the profitability of indirect connection equipment, it should be appropriate to perform a statistic representation of wind changes. The Weibull law provides the expression of the wind probability density distribution:

$$f(V) = K_f\,C^{-K_f}\,V^{K_f-1}\,e^{-\left(\frac{V}{C}\right)^{K_f}}$$

Rayleigh distribution is adopted by most wind turbine manufacturers, sets form factor value at 2 [10].

The cumulative distribution function is given by expression [10]:

$$F(V) = 1 - e^{-\left(\frac{V}{C}\right)^{K_f}}$$

$F(V)$ reflects the probability to have wind speed between 0 and V.

2.2. Permanent magnet synchronous generator model

Adopting generator convention in d-q frame and the following assumptions:

- Negligible resistance of armature as well as transient time constants.
- Isotropic behavior of synchronous machine ($L = L_d = L_q$) ;

Voltage and power equations are given by:

$$v_G = \omega\sqrt{\phi_d^{\,2} - L^2\,i^2} \approx \omega\,\phi_d\,, \quad P_G \approx \frac{3}{2}\omega\,\phi_d\,\sin\delta\;\; i_G$$

Output voltage and speed of generator are quasi-proportionate. Likewise, armature current can act as an input variable to control recovered power.

2.3. Intermediate storage capacitor

Capacitor equation is given by:

$$v_C = \frac{1}{C}\int (i_1 - i_2)\, dt$$

Current i_1 is extracted from generator trough AC/DC device. Likewise, current i_2 can act as a second input variable to maintain capacitor voltage around a constant value and, for techno-economic reasons, not exceeding 200 V. Capacitor C is a smoothing one and its value is high enough to attenuate voltage peaks.

2.4. Electronic components

A. Three phase diode bridge rectifier

With an uncontrolled three-phase bridge rectifier, relation between the fundamental of generator current and rectifier output current is expressed by:

$$i_{G_{1RMS}} = \frac{\sqrt{6}}{\pi} < i_R >$$

B. Buck DC/DC converter

Step-down DC/DC converter, it enables capacitor charging with continuous-mode current. In rolling mean, we have:

$$i_1 = \frac{\alpha_1 V_R - v_C}{r_1}$$

where α_1 is the duty cycle and r_1 is the resistance associated to inductor L_1. The inductor value L_1 is set high enough to smooth ripples in current i_1.

C. Boost DC/DC converter

Step-up DC/DC converter, it enables capacitor discharging with continuous-mode current. In rolling mean, we have:

$$i_2 = \frac{v_C - (1-\alpha_2)\, V_M}{r_2}$$

where α_2 is the duty cycle and r_2 is the resistance associated to inductor L_2. The inductor value L_2 is set high enough to smooth ripples in current i_2.

D. PWM current source inverter

The inverter bridge consists of six IGBT with appropriate control law. It enables inverting current I_2 by comparing a sinusoidal current reference (modulating signal) with a high-frequency triangular wave (carrier). The current reference is in phase with voltage to eliminate reactive power exchange with power grid.

3. Dynamic Modeling

For system control (Fig. 3), we dispose of two input variables: the currents I_1 and I_2. Likewise, we dispose of two state variables: the speed rotation Ω and capacitor voltage V_c. With all quantities expressed in small variations, we define state and control vectors such as:

$$\mathbf{X} = \begin{pmatrix} \dot{\Omega} \\ \dot{V}_C \end{pmatrix} \qquad \mathbf{U} = \begin{pmatrix} \dot{I}_1 \\ \dot{I}_2 \end{pmatrix}$$

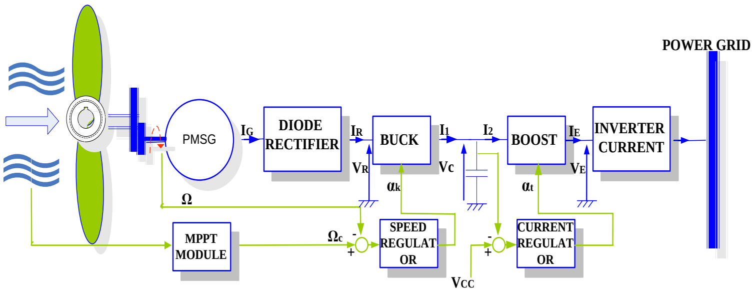


Fig. 3. Main control scheme.

The state-space representation is written in the following form:

$$\mathbf{X}' = \mathbf{AX} + \mathbf{BU}$$

where

$$\mathbf{A} = \begin{pmatrix} A_{11} & -A_{12} \\ 0 & 0 \end{pmatrix} \qquad \mathbf{B} = \begin{pmatrix} -B_{11} & 0 \\ B_{21} & -B_{22} \end{pmatrix}$$

Our system verifies controllability and observability conditions but not stability condition (two eigenvalues equal to or greater than 0). We look to establish a control law by full-state feedback in order to stabilize the system. The problem consists of determining **K** such as:

$$\mathbf{U} = \mathbf{KX}$$

where

$$\mathbf{K} = \begin{pmatrix} K_1 & 0 \\ 0 & K_2 \end{pmatrix}$$

The state matrix of closed-loop system **H** is then:

$$\mathbf{H} = \mathbf{A} + \mathbf{BK}$$

where

$$\mathbf{H} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}$$

The characteristic polynomial of **H** is given by:

$$F(s) = |s\mathbf{I} - \mathbf{H}| = s^2 + a\,s + b$$

On the other hand, we look to identify the system with the one stable and defined by $\mathbf{H}_0$ such as:

$$\mathbf{H}_0 = \begin{pmatrix} -\lambda_0 & 0 \\ 0 & -\lambda_0 \end{pmatrix}$$

This system admits a characteristic polynomial given by:

$$F_0(s) = s^2 + 2\lambda_0 s + \lambda_0^2$$

Comparing the two polynomials, we establish that K_1 is a solution of a quadratic equation such as:

$$MK_1^2 + NK_1 + P = 0$$

With M, N and P are functions of V_{C0}, I_{10}, Ω_0, J and C. This quadratic equation enables determining gain values K_1 and K_2 of the feedback matrix.

4. Algorithm

The conversion circuit includes two devices disposed in cascade:

- AC/DC device: Automatic adjustment of continuous-mode capacitor charging current I_1 is performed by the buck converter.
- DC/AC device: Automatic adjustment of continuous-mode capacitor discharging current I_2 is performed by the boost converter.

The generator control current is performed in full state feedback by pole placement. The results are illustrated by simulations at the end of the paper.

5. Results and Discussions

We consider a PMSG with the following characteristics: 16000 W, 400 V, 50 Hz, R_s= 0.645, L_l = 0.002228 H, L_{md} = 0.05297, L_{mq} = 0.02518, J = 0.1278, f = 0.013, p = 2, and the series inductance of isolation transformer is 10^{-4}. Likewise, we consider a three-bladed wind turbine with the following characteristics: the nominal power P_N = 8100 W, the blade radius R = 2,245 m, the gearbox ratio K_G = 5, Wind turbine power occurred for λ_{opt} = 8.1 and giving C_{pmax} = 0.48.

Fig. 4 depicts power curves as functions of generator speed for three significant values of wind speed:

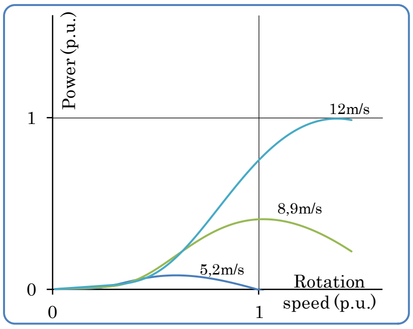


Fig. 4. Power curves as functions of rotation speed.

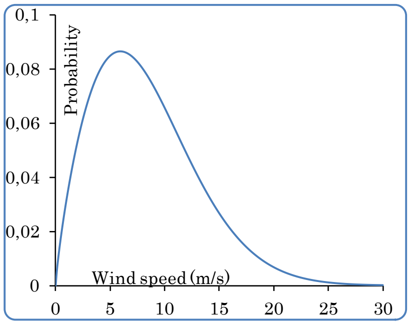


Fig. 5.Weibull distribution of the wind.

Theses curves show that:

- Maximum power is equal to nominal power and occurs at a wind speed of 12 m/s when rotation speed is 1.38 p.u.
- Maximum power is equal to 0.40 p.u. at a wind speed of 8.9 m/s when rotation speed is 1 p.u.
- At a wind speed of 5.2 m/s, wind turbine stops working when rotation speed is equal to 1 p.u. (for instance, direct connection case) and maximum power occurs at a rotation speed of 0.6p.u.

On the other hand, we consider the following parameter values for Weibull distribution (Fig. 5): C = 9, 3 m/s, K = 1, 8, we obtain the following characteristics:

<V>: 8, 3 m/s, $F(5, 2)$ = 0, 30

In the case of direct connection, our wind turbine will stop working for perhaps 30% of time. For illustrative purposes, we consider a wind speed profile as given:

$$V(t) = \begin{cases} 12 \text{ m/s for } 0 \le t \le 6 \text{ s} \\ 8{,}9 \text{ m/s for } 6 \le t \le 9 \text{ s} \\ 5{,}2 \text{ m/s for } 9 \le t \le 12 \text{ s} \end{cases}$$

The Fig. 6 depicts the simulation results of wind turbine simultaneously in start-up phase and production region.

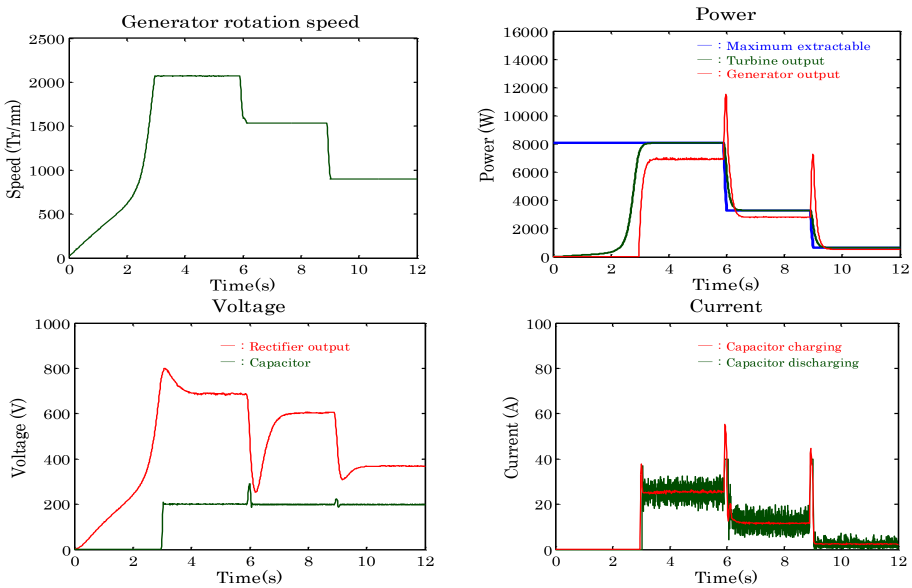


Fig. 6. Simulation results of wind turbine generation for variable wind profile

6. Conclusion

Our MPPT approach is proving satisfactory in terms of fastness of convergence, stability and requirements of wind turbine starting. The proposed method ensures a non-stop production. In start-up phase, there is no need to perform a heavy synchronizing and coupling procedure such as in direct connection. Furthermore, the use of a non-controlled rectifier and a buck converter confers reliable and slow-cost characters to our conversion device. Nonetheless, adoption of standard electric characteristics, both for generator and electronic components, may be damaging in term of dispersion of energy.

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