A Fast Maximum Power Point Tracking Strategy Based On Variable Structure Control for Wind Energy Application

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Abstract— **Nowadays, the wind energy due to its substantial advantages over fossil fuel based energy sources and other renewable energy sources, is growing significantly. In order to have a profitable and efficient wind energy harvesting system, wind turbines should continuously operate at maximum power point under wind velocity variations. This paper proposes a very fast and high-efficient Maximum Power Point Tracking (MPPT) control method for variable speed wind turbines. This control strategy possess a variable structure based on sliding mode control and could be simply implemented on a Wind Energy Generation System (WEGS). The main components of a WEGS are introduced and detailed theoretical analyses are presented. The verification of the theoretic analysis is done through simulating a 2.7 MW variable-speed PMSG based WEGS being controlled by the proposed controller.**

Keywords- Maximum Power Point Tracking (MPPT), Variable structure control, Permanent Magnet Synchronous Generator (PMSG), Wind Energy Generation System (WEGS).

I. Introduction

The growing global concern about the environmental problems caused by fossil fuel based energy resources in recent decades has given rise to the development of renewable energy sources as wind, solar and geothermal. Among these environmental friendly energy sources, wind energy has attracted more attention. Since, the generated power involves lower generation costs [1].

To have a high-efficient Wind Energy Generation System (WEGS) the employed wind turbine should always operate at its optimal operation point in its power-rotor speed characteristic kwon as Maximum Power Point (MPP). The most important challenge with wind turbines is that their MPP varies with the wind speed variations. Accordingly, a Maximum Power Point Tracking (MPPT) control strategy should be applied to a WEGS.

Diverse MPPT approaches are introduced in literature. Some propose linear control methods [2] and [3]. Although these methods have simple structure and high eligibility around the system operating point, they are incapable to track the wind speed alterations suitably. Some others propose intelligent control strategies as Neural Network and Genetic Algorithm [4] and [5]. These approaches benefit virtually appropriate dynamic response and high efficiency. However, they are complicated and their implementation is costly. Some papers implement Hill Climbing MPPT method [6]. This methodology suffers from slow dynamic response. In [7] a modified Hill Climbing MPPT method is introduced and dynamic response is ameliorated at the expense of a more complicated control structure. In [15] a MPPT method is proposed using a fuzzy logic controller. This controller has also a complicated structure.

In this paper an innovative MPPT control strategy is introduced. This strategy benefits a variable structure control based on Sliding Mode Control which is a robust nonlinear control approach. The sliding surface is selected such that the controller has very fast dynamic response. Furthermore, this method has a simple structure and its implementation involves relatively low costs.

The remainder of paper is organized as follows: A WEGS and its main components are described in section II. Section III introduces the proposed MPPT control strategy. To verify the performance of the proposed controller, some simulations have been done. Section IV is assigned to simulation results and discussion. Finally, section V concludes the paper.

II. SYSTEM CONFIGURATION

Figure 1 depicts the configuration of a WEGS. As illustrated, the harvested wind power is fed to a Permanent Magnet Synchronous Generator (PMSG) through wind turbine. The PMSG is controlled by an active rectifier with the MPPT controller such that it is able to capture the maximum available power from the wind turbine. The output voltage of PMSG is rectified and charges the DC link capacitor. Finally, the harvested power is fed to the power system through a PWM inverter. Following gives a brief description of the wind turbine and PMSG. The proposed MPPT controller will be discussed in the following section.

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A. *Wind Turbine*

A wind turbine converts the kinetic energy of wind into mechanical form. Indeed, as air flows to its blades a pressure difference is developed across its high and low sides and cause it to rotate. Hence the kinetic energy is transformed to mechanical form.

There are two main types of wind turbines: fix speed and variable speed types. Recently, the variable speed types are attracting great attention, since they have numerous advantages over fixed speed types such as high efficiency and performance, low mechanical stress and high power quality [8] and [6] and [9]. Furthermore, they can operate at maximum power point at a wide range of wind speeds [10].

The maximum power produced by a variable speed wind turbine is expressed as [1]:

$$P_m = \frac{1}{2}\Pi \rho C_p(\beta,\lambda)R^2 v_w^3 \qquad (1)$$

Where, v_w is the wind speed, ρ and R are air density and blade radius respectively. C_p is the power coefficient, a function of pitch angle (β) and tip speed ratio (λ) and λ is obtained as [11]:

$$\lambda = \frac{R\,\omega_m}{v_w} \qquad (2)$$

Where, ω_m is the angular speed of rotor. Wind turbine mechanical power vs. its rotor speed characteristic for various wind velocity is depicted in figure 2.

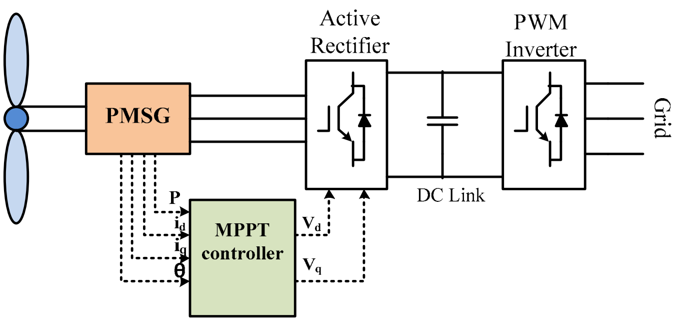

Figure 1. the configuration of the wind energy generation system

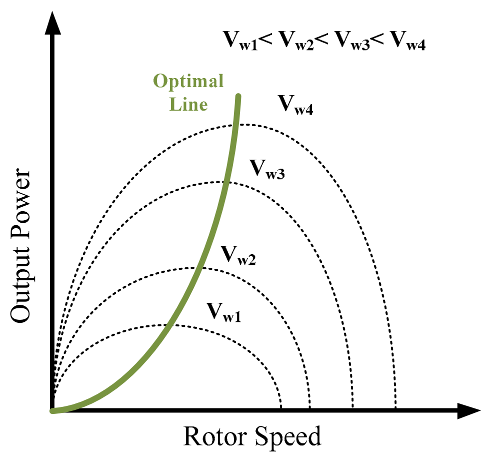

Figure 2. Wind turbine mechanical power vs. its rotor speed characteristics for various wind velocity

B. *PMSG*

In order to convert mechanical energy produced by the wind turbine into electric form various types of electric generators are proposed. Some utilize a DC generator with separate excitation [11]. However, they involve high maintenance costs due to their brushes. Some other papers propose a Doubly Fed Induction Generator (DFIG) or simple three-phase Induction generators [12] and [13]. These generators have a gearbox in their structure which increases the generator weight and impose additional maintenance cost and reduces reliability [14]. Besides, they are high speed electric machines which results in a noisy wind generation system. The drawbacks of DC generators and DFIGs can be avoided by employing a PMSG in the WEGS. PMSGs have simple structure and they are self-excited, brushless and gearless electric machines. Accordingly, the WEGS employing PMSG is light weight, low noise, high reliable and high efficient.

The output voltages of a PMSG on the d and q reference frame are obtained as follows:

$$V_d = -R_s I_d - L_s \frac{dI_d}{dt} + \omega_r L_q I_q \qquad (3)$$

$$V_q = -R_s I_q - L_q \frac{dI_q}{dt} - \omega_r L_d I_d + \omega_r \psi_f \qquad (4)$$

Where, R_s is the stator resistance per phase, I_d and I_q are the stator currents on the d and q axis respectively. L_d and L_q are stator inductances on the d and q axis respectively, ω_r is the angular rotor speed and ψ_f is the rotor magnetic flux.

The generated electric power is:

$$P = \frac{3}{2}\left(V_d I_d + V_q I_q\right) \qquad (5)$$

III. THE PROPOSED MPPT STRATEGY

The proposed MPPT strategy is a variable structure control (VSC) based on sliding mode control. The sliding surface is shown as the optimal line in figure 2 which is selected as:

$$S^* = P - K_{opt}\,\omega_r^3 = 0 \qquad (6)$$

Where K_{opt} is:

$$K_{opt} = \frac{1}{2}\rho C_p \frac{R^5}{\lambda^3} \qquad (7)$$

It should be noted that the K_{opt} varies due to the aging phenomenon. Accordingly, to specify the K_{opt}, the MPPs are determined by a search algorithm and the best curve satisfying $K_{opt}\,\omega_r^3$ is fitted to MPPs. Thus, K_{opt} is determined. This procedure is repeated annually and new K_{opt} is specified.

According to (1) in order to capture the maximum available wind power, if S>0, ω_r should augment and if S<0, ω_r should diminish. In other words:

$$S\,\dot{\omega}_r > 0$$

The block-diagram of the proposed MPPT controller is shown in figure 3.

As demonstrated, the controller produces the reference rotor speed as:

$$\omega_{ref}^{*} = \left(K_p + \frac{K_I}{S}\right)\left(e_s + K\,\mathrm{sgn}(e_s)\right) \tag{8}$$

Where K_I and K_p are PI controller gains, which are selected based on the desired dynamic response. sgn represents the sign function and e_s is the error signal which is equal to:

$$e_s = S - S^{*} \tag{9}$$

In (8) K is the adaptive VSC gain. Namely, in order to have a fast response this gain adapts with the error amplitude and is as follows:

$$K = K_1 |e_s| \tag{10}$$

Where K_1 is a constant value selected according to desired response.

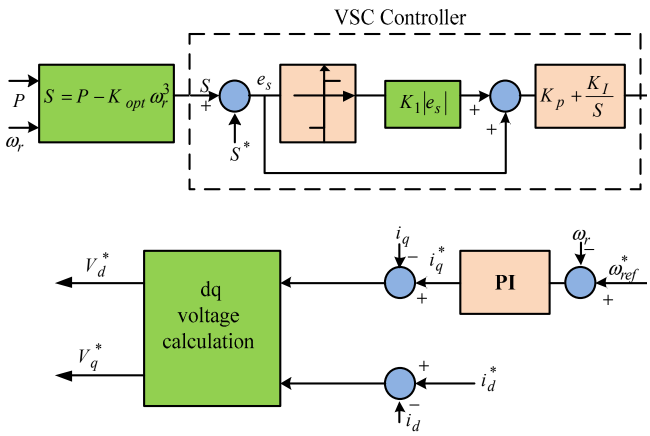

Figure 3. The proposed MPPT controller

IV. SIMULATION RESULTS

In order to validate the performance of the proposed MPPT strategy the controller is tested on the WEGS discussed in II with the MPPT control strategy described in III. The simulations are done with MATLAB/Simulink. The main parameters of the system are tabulated in Table I. In order to simplify the problem formulation, the simulations done with per-unit values.

The profile of the wind speed in a 5 second period based on the National Renewable Energy Laboratory (NREL) website data is shown in figure 4.

Table I. System parameter values

Wind turbine specifications	Mechanical output power	2.7 MW
	Rated wind speed	18 m/s
	Pith angle	0
	Maximum power at base wind speed	0.73
	Base rotational speed	1 p.u.
	K_{opt}	1 p.u.
PMSG specifications	Flux linkage	116.9
	Inertia	1000 kg/m^2
	Number of pole pairs	11
	Winding resistance	0.5 mΩ
	Rated rotor speed	13.2 rad/s
	Stator inductance L_d	0.00375 H
	Stator inductance L_q	0.0055 H

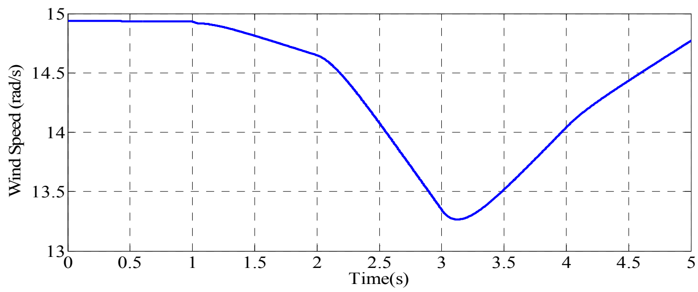

Figure4. Wind speed variations for a 5 second period

According to (1) the maximum available wind power varies with the wind speed variations. In figure 5 the maximum available wind turbine power under wind speed variations based on figure 4 is shown by the red dashed graph and the generator output power is illustrated by the blue solid graph. Figure 5 verifies that with the proposed controller the WEGS tracks the MPP properly. It should be noted that the 1% steady-state error is due to PMSG active losses.

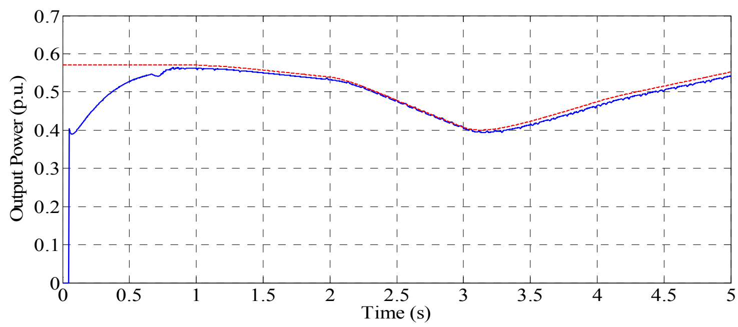

Figure5. The maximum available power (dashed graph) with the PMSG output power

To analyze the dynamic performance of the controller a step change is applied to the wind velocity. Figure 6 shows the captured power from turbine and maximum available power under a step change in wind speed from 12 m/s to 18 m/s. As illustrated, the output power reaches its optimal value in lower than 0.5 second and the controller has a very fast dynamic response.

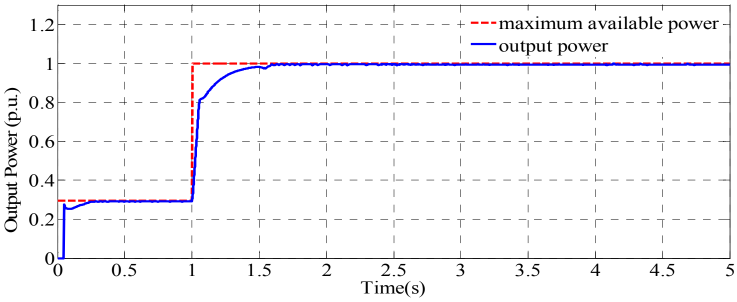

Figure 6. The output power under a step change in wind velocity

V. CONCLUSION

A novel control strategy for MPPT of WEGS has been introduced. The control method was a variable structure control based on sliding mode control. An innovative switching surface has been selected based on power vs. rotor speed characteristics of the wind turbine. The proposed fast control strategy was tested on a 2.7 MW WEGS employing a PMSG and it has been simulated utilizing MATLAB/Simulink. The simulation results verified that the proposed controller, in spite of its simple structure and low cost implementation, had a fast dynamic response and it is capable to track wind speed variations properly.

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