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An Independent Maximum Power Extraction Strategy for Wind Energy Conversion Systems

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Abstract

A new Hysteresis Maximum Power Tracking scheme, which is independent of wind turbine or turbine generator characteristics, is proposed and investigated in this paper. As a comparison, two other wind energy conversion control schemes, namely DC-link Voltage Based Linear Control and Hill-Climb Maximum Power Tracking, are studied. A simplified wind turbine model using MATLAB/SIMULINK is given in this paper as well. Simulations for these schemes have been conducted. Some field test waveforms are also presented.

1 Introduction

Traditional wind energy generation theory reveals that a maximum turbine energy conversion efficiency occurs when the tip-speed ratio (defined in Equation (5)) is kept at its optimal value [1]. However, due to the difficulties in tip-speed ratio measurement, a control strategy based on the tip-speed ratio is practically difficult to implement. Several control schemes are then proposed to improve the performance of maximum wind power extraction strategies without measuring the tip-speed ratio [3][4]. Basically these schemes depend on the characteristics of a wind turbine, which means the turbine characteristics have to be obtained either before or during the execution of these control schemes.

Control schemes independent of wind turbine or turbine generator characteristics are therefore appreciated in wind energy conversion systems. An independent maximum power extraction strategy is more flexible since it can be applied in different wind energy conversion systems, is more accurate since it eliminates the turbine characteristic measurements, and is easier to implement. Three control strategies are proposed and evaluated in the paper. Their suitability for wind energy conversion systems is compared. An improved maximum power extraction strategy has been identified for wind energy conversion systems.

1.1 Hardware Environment

Maximum power tracking schemes introduced in this paper are general purpose control algorithms which are not hardware specific. They have two basic constraints. One is these schemes need an inverter dc-link voltage or a generator output voltage as the input signal. The other one is that the system output power can be controlled.

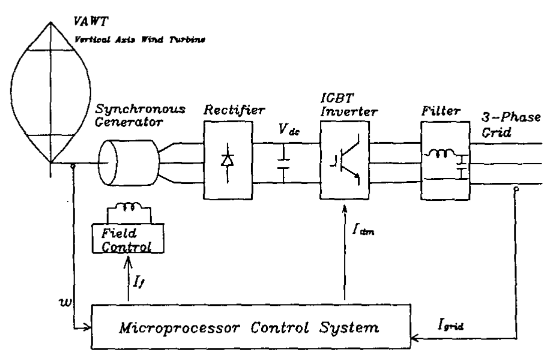

Figure 1 Hardware structure of a wind energy conversion system.

Figure 1 is the system hardware structure used as the environment of investigation in this paper. In this system, the dc-link voltage V_{dc}, can be measured directly. Since the voltage of a utility grid is stable, the system output power is directly controlled by adjusting the output current of the inverter. The magnitude of line current, I_{dm} is the demand current to control the system output power [5].

1.2 Basic Characteristics of Wind Turbines [1]

In order to describe the following control schemes, a brief review of wind turbine characteristics is presented here. Wind turbines are governed by Equations (1) to (5),

$$T_m - T_{Load} = J\frac{dw}{dt} \quad (1)$$

$$P_m - P_{Load} = w*J\frac{dw}{dt} \quad (2)$$

$$P_m = C_p(\lambda)*P_w = C_p(\lambda)*0.647*A*u^3 \quad (3)$$

$$C_p(\lambda)*0.647*A*u^3 - \eta*P_{out} = w*J\frac{dw}{dt} \quad (4)$$

$$\lambda = \frac{r_m*w}{u} \quad (5)$$

where the following terms are defined as: T_m - wind turbine mechanical torque; T_{load} - load torque ; J - turbine moment of inertia; w - turbine angular speed; P_m - turbine mechanical power; P_w - wind power; P_{out} - system output power; P_{load} - turbine load power; u - wind speed; A - sweeping area of the turbine rotor; C_p - turbine performance coefficient; λ - tip-speed ratio; r_m - maximum radius of the turbine rotor; η - efficiency of the generator -inverter set.

Equation (3) reveals that the most important parameter of a wind turbine in energy conversion is C_p. C_p is a function of tip-speed ratio λ, which is defined by Equation (5). Their relationship is graphically shown in Figure 2, C_p curve of a VAWT (vertical axis wind turbine). The goal of maximum wind power extraction control schemes is to keep wind turbines operating at their optimal tip-speed ratios, where the maximum energy conversion efficiency of wind turbines can be reached. In order to simplify the following discussions, η is assumed as unity. Therefore, P_{load} is equal to P_{out} in our discussions.

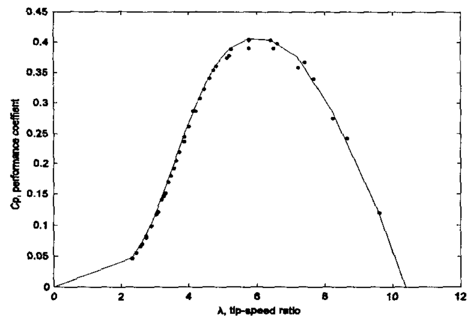

Figure 2 A VAWT coefficient Cp(λ) curve.

1.3 DC-link Voltage Based Linear Control

DC-link voltage based linear control scheme uses Equation (6) to decide the system output power P_{load}. For permanent magnet synchronous generators and wound field synchronous generators with a fixed field current, the generator output voltage is proportional to its rotor speed, which is proportional to the turbine rotor speed. Thus V_{dc} should be roughly proportional to the turbine speed. As shown in Figure 3, when the wind speed increases, the turbine angular speed and the DC-link voltage should also increase to keep C_p at its maximum value. The maximum power should change as the dash line in Figure 3.

$$P_{load} = K * (V_{dc}-V_{dc0}) \quad (6)$$

In Equation (6), constant K is the slope of the output power curve and V_{dc0} is the minimum value to maintain the normal operation of an IGBT inverter. Constant K has to be decided through field experiments or

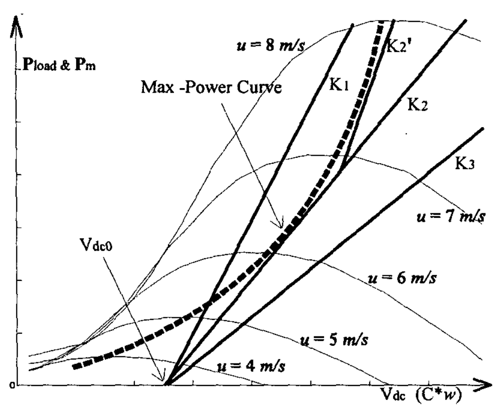

Figure 3 The principle of Linear Control.

simulation studies. For three control slopes shown in Figure 3 as K1, K2 and K3, K3 is far from the dash curve, so that its performance is not good. K2 has relatively good performance when wind speed is between 5.5 to 7 m/s, while K1 has its relatively good performance when wind speed is between 5 to 5.5 m/s and 8 to 9 m/s. As an improvement, the output power can be controlled by a piece wise linear curve K2 and K2' as seen in Figure 3.

The linear control scheme is simple and stable. But it is neither a max-power tracking algorithm, nor an independent control algorithm. The proper control coefficient K is turbine specific and is difficult to select.

1.4 Hill-Climb Maximum Power Tracking Scheme

Hill-Climb max-power tracking scheme has been applied successfully in photovoltaic systems [2]. In order to transfer its principles to wind energy conversion systems, modifications, field tests and simulations have been done.

As shown in Figure 4, when I_{dm} decreases in Region (2), P_{load} decreases, resulting in increased turbine speed w and tip-speed ratio λ. The max-power point can be reached at a certain I_{dm} value. The P_m characteristics include two regions, the up-hill region and down-hill region as shown in Figure 4. The fundamental principle of Hill-Climb tracking is to detect derivatives of P_m, i.e. to identify whether P_m is in the down-hill region or in the up-hill region. In the up-hill region, P_m should be increased. Otherwise, P_m should be reduced. In this way, P_m should be kept at the maximum value.

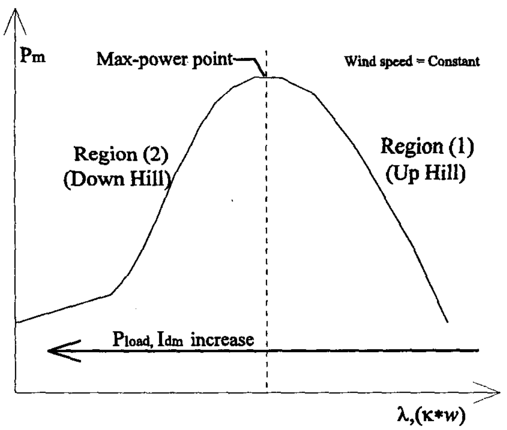

Figure 4 Relationship of variables in a wind conversion system with a constant wind speed.

In solar energy conversion systems, since the photovoltaic power and the system output power are approximately the same, P_{load} is used in max-power searching by controlling the output current. In wind energy conversion systems, demand current I_{dm} or output power P_{load} is directly controlled. However the relationship between P_{load} and wind turbine power P_m is governed by Equation (2). An increase in P_{load} in the down-hill region will yield a negative turbine rotor acceleration, reduce rotor speed and tip-speed ratio, which, in turn, may result in a reduced turbine power P_m. Thus a simple Hill-Climb algorithm may cause unstable operation of a wind energy conversion system. In order to apply Hill-Climb strategy to wind energy conversion systems, a sophisticated Hill-Climb control algorithm is requested.

When Hill-Climb tracking scheme was applied in a 10 kW system with a permanent magnet synchronous generator, P_{load} was selected as a control variable. It was observed in the field tests that the I_{dm} kept increasing until V_{dc} reached its minimum value. This indicates that a simple Hill-Climb control, while works well for photovoltaic systems, results in a high demand current, low dc-link voltage and high total harmonic distortion (THD) in the output current. Therefore, it is inadequate for complex wind energy conversion systems.

2 Hysteresis Maximum Power Tracking Scheme

In order to improve the power output of wind energy conversion systems at variable wind speed, the authors have proposed a Hysteresis Maximum Power Tracking scheme. The scheme has two control modes. Mode 1 uses Equation (7) to calculate the output power increment ΔP_{load}, while Mode 2 uses Equation (8) to decide the output power decrement, where constant K_d is the dynamic tracking slope, constant **C** is the max-point searching step size, and constant **D** is the max-point searching range. As shown in Figure 5, there is a hysteresis loop when dV_{dc}/dt is between -D and +D .

$$\underline{Mode\ 1:}\quad \Delta P_{load} = K_d * \frac{dV_{dc}}{dt} + C\ ;\quad (\frac{dV_{dc}}{dt} \geq 0)$$
$$= 0\ ;\quad (-D \leq \frac{dV_{dc}}{dt} < 0) \qquad (7)$$
$$\underline{Mode\ 2:}\quad \Delta P_{load} = K_d * \frac{dV_{dc}}{dt} - C\ ;\quad (\frac{dV_{dc}}{dt} \leq 0)$$
$$= 0\ ;\quad (0 < \frac{dV_{dc}}{dt} \leq D) \qquad (8)$$

To switch from Mode 1 to Mode 2, the system needs to satisfy one of the following conditions: (1) dVdc/dt ≤ -D; (2) V_{dc} -V_{dc0} < -K, where V_{dc0} is the previous DC voltage when dVdc/dt equals to zero, **K** is the total DC voltage variation from V_{dc0} to present. To switch from Mode 2 to Mode 1, the system needs to satisfy one of the other two conditions: (1) dVdc/dt ≥ D; (2) dVdc/dc > 0 consecutively in Mode 2.

Dynamic wind power tracking performance. In these two modes, a differential controller (K_d*dVdc/dt) is used to improve the system dynamic tracking ability. Considering that $\mathbf{V_{dc}}$ is roughly proportional to the turbine speed ***w***, when a wind gust occurs, the system will enter Mode 1 due to dVdc/dt ≥ D. From Equation (7), the larger the dVdc/dt, the larger the $\mathbf{\Delta P_{load}}$, so that the system output power shall track the gust power rapidly. Mode 2 control has a similar fast tracking ability when the wind speed decreases. Constant $\mathbf{K_d}$ governs the dynamic tracking performance of the system.

Max-power searching performance. Constant **C** governs the max-power searching speed. When the wind

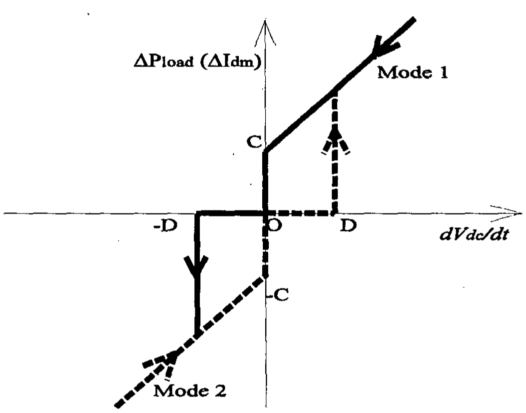

Figure 5 Hysteresis Max-power Tracking Scheme.

speed is fixed, as in Figure 4, the system is operating at a balance point in Region (1), where dVdc/dt equals to zero. According to Equation (7) of Mode 1 control, $\mathbf{\Delta P_{load}}$ here is equal to **C**. Then the system will increase its output power. The turbine speed will drop a little before the system reaches a new balance point. A small negative dVdc/dt occurs because of the drop in the turbine speed. Since wind speed is unchanged, -D ≤ dVdc/dt < 0, $\mathbf{\Delta P_{load}}$ is then set to zero, which means the system will wait for dVdc/dt coming back to zero. The system will increase $\mathbf{P_{load}}$ once more after dVdc/dt back to zero. If dVdc/dt is always less than zero, the system has passed the max-power point.

When dVdc/dt equals to zero under Mode 1 control, Vdc0 = Vdc is recorded. If dVdc/dt is negative for a sustained period, when Vdc-Vdc0 > -K, the system switches to Mode 2 control. In Region (2), if $\mathbf{P_{load}}$ increases, the turbine speed will drop. Therefore the system may also switch to Mode 2 control due to dVdc/dt ≤ -D. In Region (2), when $\mathbf{P_m}$ > $\mathbf{P_{load}}$ due to a decreased $\mathbf{P_{load}}$ in Mode 2, the turbine speed begins increasing with a positive dVdc/dt, until passing max-power point and entering Region (1). (Here a proper value of D is important to keep 0< dVdc/dt <D, otherwise the system will switches to Mode 1 before passing the max-power point.) In Region (1) when Mode 2 control decreases $\mathbf{P_{load}}$ again, dVdc/dt will be positive for the second time, satisfying Condition (2) for Mode 2-to-Mode 1 switching. Thus, the system will switch to Mode 1 control.

Overall, in Region (1) Mode 1 increases $\mathbf{P_{load}}$ step by step until the system passes the maximum power point and goes into Region (2). In Region (2) Mode 2 decreases $\mathbf{P_{load}}$ step by step forcing the system back to Region(1). These two control modes interact with each other to keep the system working around the max-power point. Future work should be done on how to select K_d, C, D and K properly and intelligently.

3 Simulations

System simulation using Matlab / Simulink has been conducted for these three control algorithms. A

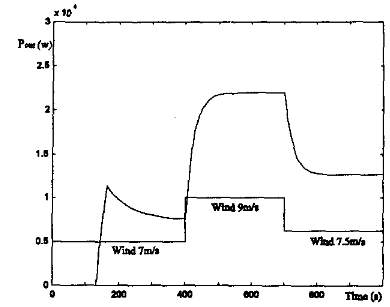

Figure 6 Wind speed and output power under Linear Control.

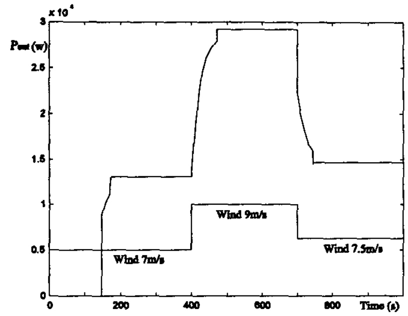

Figure 7 Wind speed and output power under Hysteresis Control.

simplified wind turbine model is used in the simulation. As shown in Figure 12, the turbine model is the Simulink description of Equations (1)-(5), given in Section 1. Cp(λ) in Equation (4) should be obtained by turbine experiments and may be expressed as a lookup table in the model. The model takes ***u*** and $\mathbf{P_{load}}$ as inputs, and ***w*** as an output.

The energy conversion efficiency of the turbine can be observed directly through Simulink Scopes in the model. As shown in Figure 6 and 7, the wind speed is set as 7 m/s at the beginning of simulation. As a step input, the wind speed jumps to 9 m/s at the moment of 400 seconds, and then drops to 7.5 m/s at the time of 700 seconds. The load is added to the turbine when turbine speed reaches 80 rpm. The system output power is also shown in these two figures, which indicate that the Hysteresis Max-power Tracking scheme has better dynamic tracking speed and higher power output than the Linear Control. The corresponding turbine efficiencies under these two

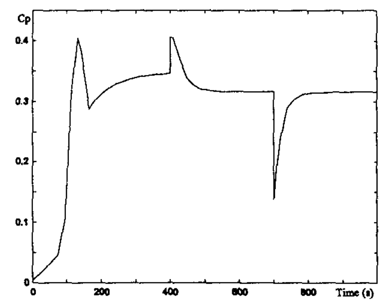

Figure 8 Turbine efficiency under Linear Control.

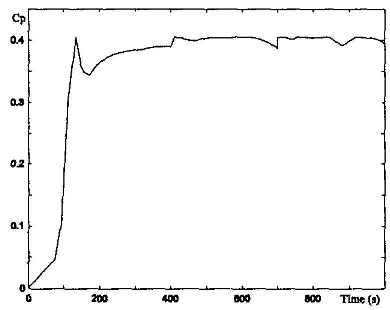

Figure 9 Turbine efficiency under Hysteresis Control.

different control schemes are shown in Figure 8 and 9. Obviously, the average turbine efficiency under the Hysteresis Max-power Tracking scheme is higher than that under the Linear Control.

4 Field Test Data

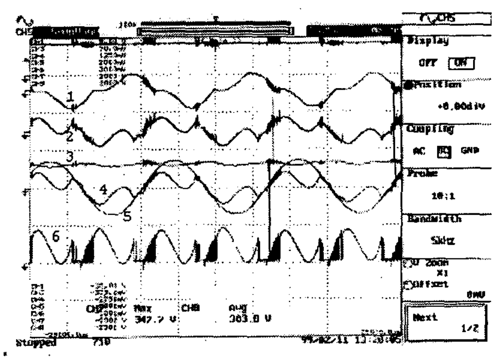

Figure 10 Field test waveforms of Hill-Climb scheme.
(1) Rectifier line current; (2) Inverter output current before a filter; (3) DC-link voltage; (4) Grid current after a filter; (5) Grid voltage; (6) DC-link current.

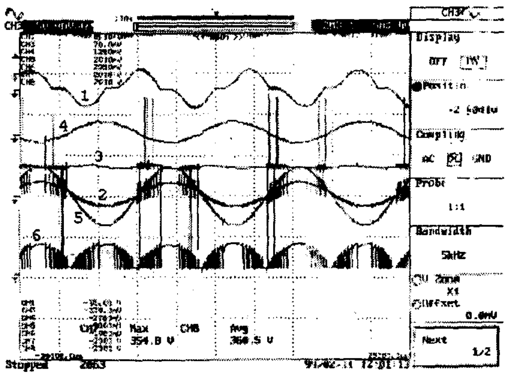

Figure 11 Field test waveforms of Linear Control scheme.
(1) Rectifier line current; (2) Inverter output current before a filter;
(3) DC-link voltage; (4) Grid current after a filter;
(5) Grid voltage; (6) DC-link current.

A 10 kW single phase wind energy system was used as a test platform. DC-link voltage based linear control scheme and Hill-Climb Max-power tracking scheme have been tested. The system output waveforms presented here were recorded by a digital scope.

As shown in Figure 10, since Hill-Climb scheme sent a high current demand $\mathbf{I_{dm}}$ to the inverter, while $\mathbf{V_{dc}}$ was insufficient, a high harmonic content was observed in the output current. Figure 11 was recorded when the Linear Control scheme was operating. The output current is sinusoidal at high wind speeds. The wind speed recorded for Figure 11 s is higher than that for Figure 10.

5 Summary and Conclusion

The principle of a new Hysteresis Maximum Wind Energy Extraction strategy, which is independent of turbine-generator characteristics is proposed and simulated in this paper. Other two control schemes, namely DC-link Voltage based Linear Control and Hill-Climb Max-power Tracking, and a simplified wind turbine model are also introduced. Some field test waveforms are provided. Simulation and field test results indicate that Hill-Climb scheme is inadequate for a wind energy conversion system. Although Hysteresis Max-power Tracking Scheme has a better performance in simulations, it still needs to be improved and field tested for further confirmation.

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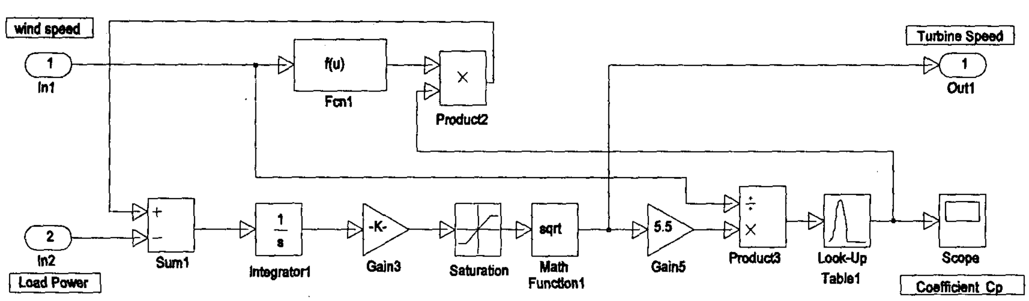

Figure 12 Simplified Wind Turbine Model.