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Sliding mode voltage control strategy for capturing maximum wind energy based on fuzzy logic control

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A B S T R A C T

A sliding mode voltage control strategy is proposed in this paper to capture the maximum electrical energy from wind. This control strategy mainly includes a fuzzy logic controller and a sliding mode voltage controller. The fuzzy logic controller is designed to derive the optimum DC-side voltage, while the sliding mode voltage controller is employed to track the derived optimum voltage with minimum steady-state error and hence to capture the maximum wind energy. This paper illustrates how major issues in the design and implementation of the two controllers can be handled effectively. Comparative experimental results demonstrate that significant performance improvements in maximum wind energy capture can be achieved by using the proposed control strategy.

Introduction

Wind energy systems have recently attracted considerable attention and enjoyed an improved interest as one of the most promising and important renewable energy sources due to the technological enhancement and significant power cost reduction [1]. As such systems continue to grow in size and power, more and more effective and innovative control strategies are expected to improve the wind energy generation capabilities such as higher reliability, cost-efficiency and quality of power conversion. In particular, maximum power point tracking (MPPT) control algorithms can be employed to capture the maximum electrical energy from wind by maintaining the optimum tip-speed ratio in the partial load region [2].

Recently, a considerable amount of MPPT techniques have been presented in the literature. Such techniques can be basically categorized into four groups based on the specified performance and measurement requirements: Tip speed ratio (TSR) control, Optimal torque (OT) control, Power signal feedback (PSF) control as well as Perturbation and observation (P&O) control [3].

The TSR control method seeks to regulate the generator speed to track the maximum power points that can be determined theoretically or experimentally as a reference. In [4], an on-line training recurrent fuzzy neural network (RFNN) controller with a high-performance model reference adaptive system (MRAS) observer was presented for the sensor-less TSR control of a wind energy system. That proposed output power maximization control could be achieved without mechanical sensors for stand-alone wind power applications. In [5], a robust nonlinear control strategy that regulated the tip-speed ratio was proposed for a variable speed wind power system. In [6], a sensor-less TSR control algorithm was designed based on support-vector regression.

For the optimal torque control method, generator torque can be regulated to a reference value corresponding to the maximum power conversion coefficient. In [7], a neural network had been trained offline to learn the turbine optimal torque characteristics which were then employed to achieve the MPPT control. In [8], a torque controller was added to the power control loop to effectively reduce the moment of inertia of wind turbines. The torque controller was less sensitive to the turbine parameters and could improve the MPPT control performance.

The PSF control method uses a form of lookup table that records the data points of the maximum output power and its corresponding rotational speed to implement the MPPT control without measuring wind speed. In [9], a MPPT algorithm was proposed to adjust the induction generator frequency and reactive power. In [10], a small-signal analysis on the performance of wind turbine under the MPPT control was presented. In [11], an aerodynamic power observer was proposed to fasten the MPPT control speed. In [12], an improved MPPT control method was designed to broaden the MPPT control bandwidth based on conventional optimum power method.

The P&O control method or hill-climb searching (HCS) method continuously changes the wind turbine operating points by perturbing a design variable in a small step-size and observing

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the resulting changes in the measured output power without requiring prior knowledge of the wind turbine characteristics. This method is advantageous in independence, simplicity and flexibility but cannot be implemented in large or medium scale wind turbines due to power oscillations. Additionally, it is difficult to select an appropriate step-size. In [13], the optimum relationship between the rectified DC voltage and current was rapidly obtained by advanced P&O control. In [14], a new and much quicker MPPT algorithm was proposed. In that algorithm, large iterative steps were used to move within a close range of MPP. In [15], a simple MPPT step and search algorithm was presented for an optimal extraction of output power by sensing only DC link power. In [16], an adaptive compensation MPPT controller was proposed for a micro-scale wind power generation system without mechanical sensors. A single-stage AC-to-DC converter was then proposed to replace the traditional two-stage converter and incorporate the MPPT control for achieving high efficiency. In [17], an online training Wilcoxon radial basis function network with hill-climb searching MPPT strategy was proposed for a variable-speed wind turbine. In [18], a hill climb searching MPPT algorithm was proposed by intelligently changing the variable step size to keep up with the rapid changes in wind speed.

This paper proposes an innovative maximum power tracking control approach for a direct drive wind energy system. The developed control strategy mainly consists of a fuzzy logic MPPT controller and a sliding mode voltage controller. The proposed control strategy possesses the improved capability of capturing the maximum energy from wind. This paper illustrates how major issues in the design and implementation of the two controllers can be handled effectively. Comparative experimental results are presented to illustrate the achievable significant performance improvements in maximum power extraction by using the control strategy. From a practical perspective, the two controllers are simple and easy to be implemented in actual wind energy systems.

System design and characteristics

Fig. 1 shows a representative topology of the investigated wind energy system. As illustrated in this figure, a two-bladed, fixed-pitch wind turbine directly transmits the aerodynamic torque and power to a multi-pole three-phase permanent magnet synchronous generator (PMSG). The generator power is then fed to the utility grid through a 3-phase bridge rectifier, a boost converter and a grid-connected inverter. The generator voltage can be rectified by the diode rectifier-bridge, boosted by the boost converter, and consequently fed to the utility grid via the voltage source inverter. The boost converter can be properly controlled to guarantee the maximum power capture, high conversion efficiency and high system reliability.

The mechanical kinetic energy captured by the wind turbine is proportional to the cube of wind speed and can be calculated as

$$P = \frac{1}{2}\pi\rho R^2 v^3 C_P(\lambda,\beta) \tag{1}$$

where P is the mechanical power (W), v denotes the wind speed at the center of the turbine rotor (m/s), R is the radius of the wind rotor (m), ρ is the air density (kg/m^3), λ is the tip speed ratio (TSR), β is pitch angle, C_P denotes the power coefficient which is a nonlinear function of TSR and the pitch angle.

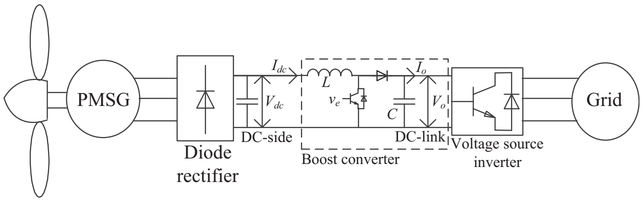

Fig. 1. Wind energy system configuration.

$$C_P(\lambda,\beta) = c_1\cdot\left(\frac{c_2}{\lambda_i} - c_3\cdot\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\cdot\lambda \tag{2}$$

where c_1, c_2, c_3, c_4, c_5 and c_6 denote the constant aerodynamic coefficients of the wind turbine, respectively.

The coefficient λ_i can be described as

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

The tip speed ratio λ (TSR) can be described as

$$\lambda = \frac{\omega R}{v} \tag{4}$$

where ω is the wind rotor angular velocity (rad/s).

Eq. (4) indicates that the TSR is the ratio between the tip rotor speed and the upstream wind speed of the wind turbine. For this fixed-pitch wind turbine, there is a maximum power point at which the power coefficient has the maximum value and an optimum TSR λ_{opt} [19].

Thus, the maximum mechanical energy can be expressed as

$$P_{max} = k_P\cdot\omega_{opt}^3 \tag{5}$$

where P_{max} is the maximum mechanical power, k_P is the power coefficient, ω_{opt} is the optimum wind rotor angular velocity.

For the diode rectifier-bridge connected PMSG with constant flux, the phase back electromotive force E can be described as

$$E = k_E\cdot\omega \tag{6}$$

where k_E denotes the electromotive force coefficient.

The rectified DC-side voltage V_{dc} can be mathematically described as [20]

$$V_{dc} = \frac{3\sqrt{6}}{\pi}\left(E - \frac{\sqrt{6}}{6}k_L\cdot\omega\right) \tag{7}$$

where k_L denotes an electrical constant of the 3-phase bridge rectifier.

The following relationships can be derived from Eqs. (6) and (7)

$$\begin{cases} V_{dc} = \frac{3\sqrt{6}}{\pi}\left(k_E - \frac{\sqrt{6}}{6}k_L\right)\cdot\omega \\ V_{dc\_opt} = \frac{3\sqrt{6}}{\pi}\left(k_E - \frac{\sqrt{6}}{6}k_L\right)\cdot\omega_{opt} \end{cases} \tag{8}$$

where V_{dc_opt} denotes the optimum DC-side voltage at the maximum power point.

Combining Eqs. (5) and (8) yields

$$P_{max} = k_{Pm}\cdot V_{dc\_opt}^3 \tag{9}$$

where k_{Pm} is the optimum power coefficient and is a constant.

The DC-side power at the maximum power point P_{dc_opt} can be described as

$$P_{dc\_opt} = P_{max}\cdot\eta = V_{dc\_opt}\cdot I_{dc\_opt} \tag{10}$$

where η is the transmission efficiency from the generator to the DC side and is assumed to be a constant. I_{dc_opt} denotes the optimum DC-side current.

Combining Eqs. (8) and (10) yields

$$V_{dc\_opt} = \sqrt{\frac{I_{dc\_opt}}{k_{Pm}\cdot\eta}} \tag{11}$$

As described in Eqs. (10) and (11), the maximum mechanical power can be captured by the wind turbine when the DC-side voltage is well kept around its optimum value. The optimum DC-side voltage