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Maximum power extraction from wind energy system based on fuzzy logic control

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ABSTRACT

This paper proposes a variable speed control scheme for grid-connected wind energy conversion system (WECS) using permanent magnet synchronous generator (PMSG). The control algorithm tracks the maximum power for wind speeds below rated speed of wind turbines and ensures the power will not go over the rated power for wind speeds over the rated value. The control algorithm employs fuzzy logic controller (FLC) to effectively do this target. The wind turbine is connected to the grid via back-to-back PWM-VSC. Two effective computer simulation packages (PSIM and Simulink) are used to carry out the simulation effectively. The control system has two controllers for generator side and grid side converters. The main function of the generator side controller is to track the maximum power through controlling the rotational speed of the wind turbine using FLC. In the grid side converter, active and reactive power control has been achieved by controlling *q*-axis and *d*-axis current components, respectively. The *d*-axis current is set at zero for unity power factor and the *q*-axis current is controlled to deliver the power flowing from the dc-link to the electric utility grid.

1. Introduction

Wind energy is one of the most promising renewable energy resources for generating electricity due to its cost competitiveness compared to other conventional types of energy resources. Only some specific locations with adequate wind energy resources can be described as being suitable for wind energy electricity generation. Wind energy is not harmful to the environment and it is naturally an abundant resource. Hence, wind power could be utilized by mechanically converting it to electrical power using wind turbine (WT). Various WT concepts have been developed into wind power technologies and led to significant growth of wind power capacity during the last two decades. Variable speed operation and direct drive WTs have been the modern aspects of the wind energy conversion system (WECS) technology. Variable-speed has many advantages over fixed-speed operations such as increased energy capture, operation at maximum power point over a wide range of wind speeds, high power quality, reduced mechanical stresses, aerodynamic noise improved system reliability, providing 10–15% higher output power and less mechanical stresses compared to the operation of a fixed speed systems [1,2]. WTs can be classified into direct drive (DD) and geared drive (GD) according to the type of drive train. The GD type uses a gear box and squirrel cage induction generator (SCIG). The GD configuration can be classified into stall, active stall and pitch control systems in constant speed applications. The variable speed applications used doubly-fed induction generator (DFIG) especially in high power WTs. The gearless DD WTs have been used with small and medium size WTs employing PMSG with higher numbers of poles to eliminate the need for gearbox which can be translated into higher efficiency. PMSG appears more and more attractive, because of the advantages of permanent magnet (PM) machines over electrically excited machines such as its higher efficiency, higher energy per weight, and no additional power supply for the magnet field excitation and higher reliability due to the absence of mechanical components such as slip rings. In addition, the performance of PM materials is improving and the cost is decreasing in recent years. Therefore, these advantages make DD applications in PM wind turbine generator systems more attractive in application of small and medium-scale wind turbines [1,3,4].

Robust controller has been developed in many literatures [5–15] to track the maximum power available in the wind. They include tip speed ratio (TSR) [5,13], power signal feedback (PSF) [8,14] and the hill-climb searching (HCS) [11,12] techniques. The TSR control technique regulates the rotational speed of the generator to maintain an optimal TSR at which maximum power is extracted [13]. For TSR calculation, both the wind speed and turbine speed need to be measured, and the optimal TSR must be given to the controller. The first barrier to implement TSR control technique is the wind speed measurement which adds to system cost and presents difficulties in practical implementations. The second barrier is the need to obtain the optimal value of TSR; this value is different from one system

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to another. This depends on the turbine-generator characteristics results in custom-designed control software tailored for individual wind turbines [14]. In PSF control technique [8,14], it is required to have the knowledge of the wind turbine's maximum power curves to track its maximum power point in these curves through its control mechanisms. The power curves need to be obtained via simulations or off-line experiment on individual wind turbines or from the datasheet of WT which makes it difficult to implement with accuracy in practical applications [7,8,15]. The HCS technique does not require wind speed data, generator rotational speeds measurements or the turbine characteristics. But, this technique works well only for very small wind turbine inertia. For large inertia wind turbines, the system output power is interlaced with the turbine mechanical power and rate of change in the mechanically stored energy, which often renders the HCS technique ineffective [11,12]. On the other hand, different algorithms have been used for maximum power extraction from WT in addition to the three techniques mentioned above. For example, Oghafy [1] presents an algorithm for maximum power extraction and reactive power control of an inverter through the power angle (δ) of the inverter terminal voltage and the modulation index (m_a) based on variable-speed WT without wind speed sensor. Chinchilla et al. [16] present an algorithm for maximum power point tracking (MPPT) via controlling the generator torque through q-axis current and hence controlling the generator speed with variation of the wind speed. These techniques are used for a decoupled control of the active and reactive power generated from the WT through q-axis and d-axis current respectively. Also, Song et al. [17] present a decoupled control of the active and reactive power generated from the WT, independently through q-axis and d-axis current but maximum power point operation of the WECS has been produced through regulating the input dc current of the dc/dc boost converter to follow the optimized current reference. Eltamaly [18] presents an algorithm for MPPT through directly adjusting duty ratio of the dc/dc boost converter and modulation index of the PWM-VSC. Hussein et al. [19] present MPPT control algorithm based on measuring the dc-link voltage and current of the uncontrolled rectifier to attain the maximum available power from wind. Finally, MPPT control based on a fuzzy logic control (FLC) has been presented in [20–22]. The function of FLC is to track the generator rotational speed with the reference speed for maximum power extraction with variation of wind speeds.

In this study, the WECS is designed using PMSG connected with the grid via a back-to-back PWM-VSC as shown in Fig. 1. A modified MPPT control algorithm has been introduced using FLC to regulate the rotational speed to force the PMSG to work around its maximum power point in speeds below rated speeds and to produce the rated power in wind speed higher than the rated wind speed of the WT. The input to FLC is two real time measurements which are the change of output power and rotational speed between two consequent iterations (ΔP_m, and $\Delta\omega_m$). The output from FLC is the required change in the rotational speed $\Delta\omega_m^*$. The detailed logic behind the new proposed technique is explained in details in the following sections. Indirect vector-controlled PMSG system has been used for this purpose. The modified MPPT control system shown in this paper is able to track maximum output power via controlling the electromagnetic torque using the two components i_α, i_β of the generator current in simple and effective way. For the grid side converter, active and reactive power control has been achieved by controlling quadrature and direct current components of grid current respectively. Two effective computer simulation software packages (PSIM and Simulink) have been integrated together to carry out the simulation of the modified system effectively. PSIM contains the power circuit of the WECS and Matlab/Simulink contains the control circuit of the WECS. The idea behind integrating these two different software packages is that PSIM is a very effective and a simple tool for modeling the power electronics circuits whereas Simulink is a very effective and a simple tool for modeling the control system especially for FLC and mathematical manipulation. This integration between PSIM and Simulink has never been used in MPPT of wind energy systems in the literature and this approach will help researchers to develop many other control techniques in this area. The interconnection between PSIM and Simulink makes the simulation process easier, efficient, fast response and powerful.

2. Wind energy conversion system description

Fig. 2 shows the co-simulation (PSIM/Simulink) programs for interconnecting WECS to electric utility. The PSIM program contains the power circuit of the WECS and Matlab/Simulink program contains the control of this system. The connection between PSIM and Matlab/Simulink has been done via the SimCoupler block tool in Simulink. The basic topology of the power circuit which has PMSG driven wind turbine connected to the utility grid through the ac–dc–ac conversion system is shown in Fig. 1. The PMSG is connected to the grid via back-to-back bidirectional PWM-VSC. The generator side converter is connected to the grid side converter through dc-link capacitor. The control of the overall system has been done through the generator side converter and the grid side converter. The MPPT algorithm has been achieved through controlling the generator side converter using FLC. The grid-side converter controller maintains the dc-link voltage at the desired value by exporting active power to the grid and it controls the reactive power exchange with the grid.

2.1. Wind turbine model

Wind turbine converts the wind power to a mechanical power. This mechanical power generated by wind turbine at the shaft of the generator can be expressed as:

$$P_m = \frac{1}{2} C_P(\lambda, \beta)\rho A u^3 \tag{1}$$

where ρ is the air density (typically 1.225 kg/m^3), β is the pitch angle (in degree), A is the area swept by the rotor blades (in m^2), u

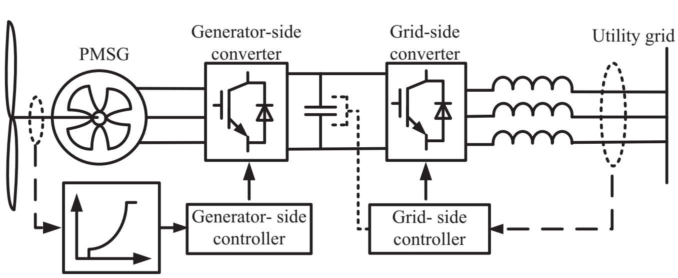

Fig. 1. Schematic diagram of the overall system.

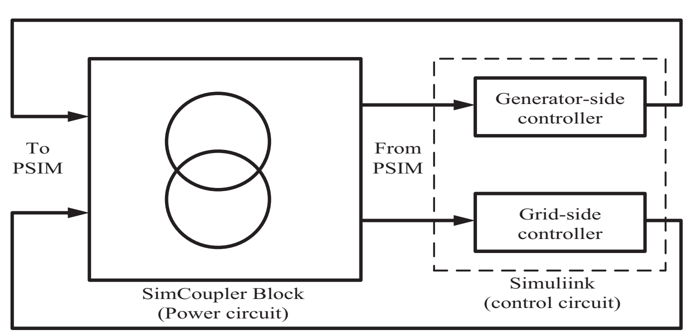

Fig. 2. Co-simulation block of wind energy system interfaced to electric utility.