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Single-stage AC–AC power conversion for WECS

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ABSTRACT

This paper investigates a novel single stage AC–AC power conversion, as an alternative to multistage AC–DC–AC power conversion topology, for interfacing the wind energy conversion system (WECS) to a grid as a distributed load system. A comprehensive dynamic model of proposed AC–AC converter is developed to satisfy all the functions of the converter. A new time switching pattern and a control mechanism are described to convert a variable frequency input power proportion to the wind power to a constant frequency output power for a distributed load system in a single unit. The converter control functions are adapted to control active and reactive powers injected into the distributed load system. Based on time-domain simulations in the MATLAB environment, a comparative study has been made of the dynamic behavior of wind turbine generation system with the proposed AC to AC converter and conventional AC–DC–AC converter. The study concludes that an AC–AC converter is technically a viable option to interface a wind turbine to a distributed load system or utility grid application. A prototype of the proposed converter is developed in the lab taking variable frequency input voltage and then converting it to a constant output frequency voltage. The performance of the converter has been found satisfactory.

Introduction

Due to the increasing demand of electric energy and environmental concerns, a considerable amount of effort is being made to generate electricity from wind energy sources. Electric generator is one of the most important parts of wind energy system. The generators can be categorized as (1) fixed speed generators (FSGs) and (2) adjustable speed generators (ASGs). Overall, FSGs are more expensive in mechanical construction, especially at high-rated power as compared to ASGs which are widely used in WECS. A detailed description of these generators is available in [1]. Direct-driven permanent magnet synchronous generators (PMSG) have drawn increasingly more interest to wind turbine manufactures due to its advantages over other variable-speed wind turbine generators. These include the possibility of multi-pole design with a gearless construction that offers slow speed operation and reduced maintenance due to absence of brushes, elimination of the excitation system, full controllability for maximum wind power extraction with grid interface and easiness in accomplishing fault-ride through and grid support. Consequently, the efficiency and reliability of a full-scale power converter PMSG wind turbine is higher than that of other variable-speed wind turbine generators such as a doubly-fed induction generator (DFIG) wind turbine [2,3].

A general scheme of the WECS is shown in Fig. 1. Wind energy is transformed into mechanical energy by means of a wind turbine that has one or several blades. The turbine is coupled to the generator system by means of a mechanical drive train. The electronic interface circuit consists of an AC–DC rectifier at the output of PMSG to convert the variable speed AC power to DC power [4]. Typically, the DC output voltage is required to be converted into AC voltage by a DC–AC inverter. Accordingly, the overall power conditioning circuit consists of a rectifier, a DC-link capacitor and a DC–AC inverter [5,6]. However, the Total harmonic distortion (THD) of input currents is much higher in PWM based rectifier system [7]. So, the machine-side PWM rectifier could be replaced by a Diode rectifier cascaded with step-up chopper [8]. The rectifier stage of the power converter causes high distortion of the output current and voltage of PMSGs which generates several undesirable effects to the generator, such as (1) increased heating with the effect of iron and copper losses at higher harmonic frequencies; (2) loss in machine efficiency and reduction in electromagnetic torque; (3) increased audible noise emission and occurrence of mechanical oscillations [9,10]. Additionally, the total efficiency of the two-stage converter is lower because the total power has to be processed twice with two cascade power stages. Each power stage has to be rated as full output power which will increase the size and cost of the circuits. Reliability, efficiency and power factor of the system is also reduced with large input filter and high switching frequency [11,12].

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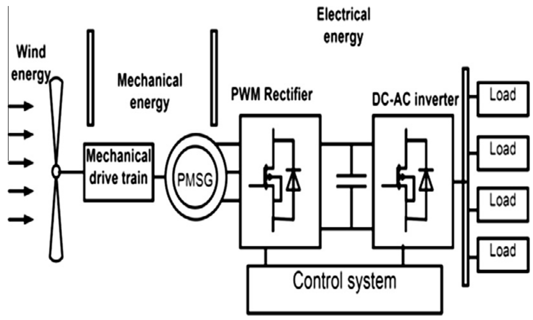

Fig. 1. Wind energy conversion system.

The multistage operation can be avoided using a matrix converter (MC) as a direct AC/AC converter. A direct matrix converter has advantages such as compact size, efficient performance and low-input THD [13,14]. Normally, the input supply for a matrix converter has been taken as sinusoidal and balanced with fixed frequency, which is not true for wind energy application [15]. Due to variation and distortion of input supply, the load side output is also influenced which is not solved by matrix converter controller owing to absence of DC link capacitor. Unfortunately, distorted input voltages generate low-order harmonics in the output supply, which have a negative effect on the input supply [16]. The improvement in efficiency is normally achieved by fixed time switching patterns based modulation algorithms such as space vector PWM [17]. The space vector PWM is not a flexible due to its look up table method. Manipulation of duty cycle is typical to create the switching pulses for operating a switch during wind changes [18]. Under the distorted input voltage conditions at variable frequency, a fixed time strategy will not be appropriate because the disturbance in the input side of converter reflects on the output of the converter [19]. The speed (frequency) variation which occurs in variable speed generator affects the duty cycles of time switching patterns and creates a complex controller for controlling parameters [20]. Therefore, it becomes necessary to calculate the duty cycles of switching patterns instantaneously by measuring the output voltages at each sampling period.

In this paper an AC to AC converter has been proposed to interface a variable-speed PMSG connected to a distributed load as an alternative to an AC–DC–AC converter system. The proposed AC–AC converter is flexible for instantaneous change in wind energy. The converter has no electrolytic power capacitors so it has a higher power density in comparison to other converter. A novel control strategy based on variable frequency to constant frequency algorithm is proposed for controller design purpose. The proposed gating signal method is derived by comparing the input voltage with desired frequency signal instantaneously without any tables. It is used to determine the switching status of each of the output phases. A power diode is connected in series with each device to provide reverse voltage blocking capability for the protection and improvement of efficiency. A complete design and simulation of the converter is done based on turbine speed, generator output voltage and a wide frequency variation of input aerodynamic power produced by a variable-speed (turbine) generator for different condition of input wind velocities in real time simulator.

Wind energy conversion system

A typical WECS consists of a wind turbine, generator, interconnection apparatus and control systems. A wind turbine can be designed for a constant speed or variable speed operation. Variable speed wind turbines can produce 8–15% more energy output as compared to their constant speed counterparts. However, they necessitate power electronic converters to provide a fixed frequency and fixed voltage power to their loads.

A permanent magnet synchronous generator (PMSG) converts the mechanical energy of the wind turbine into electrical energy, which is fed to an AC–AC converter. The proposed AC–AC converter converts the variable frequency output of the generator to constant frequency output, which is fed to the grid or local loads without any rectification process. A brief description of each block of the system shown in Fig. 2 is provided in the following subsection:

Wind turbine model

The energy that could be captured from the wind by a specific turbine depends on its design particulars and operating conditions [14]. The power obtained by the turbine is a function of wind speed. The output aerodynamic torque of a wind turbine is defined by Eq. (1).

$$T_t = \frac{P_t}{\omega_t} = \frac{(\rho \times r \times C_P(\beta, \lambda) \times V_\omega^3)}{2 \times \omega_t} \tag{1}$$

Here ρ is the air density,
r is the radius of the turbine,
$(C_p(\beta, \lambda))$ is power coefficient.
V_ω is the wind speed (m/s)
β is the blade pitch angle (degree)
ω_t is the turbine speed,

λ is the ratio between the turbine angular velocity ω_t and the wind speed V_ω This ratio is called the tip speed ratio and is given by Eq. (2).

$$\lambda = \frac{r \times \omega_t}{V_\omega} \tag{2}$$

In order to determine the behavior of turbine model characteristics, generic equations which relate the power coefficient with different coefficients of turbine are given as.

$$C_p(\lambda, \beta) = c_1 \times (c_2/\lambda_i - c_3 \times \beta - c_4) \times (\exp^{-c_5/\lambda_i}) \tag{3}$$

$$1/\lambda_i = \left(\frac{1}{\lambda} + .08 \times \beta\right) - \frac{0.035}{\beta^3 + 1} \tag{4}$$

Here c_1 to c_5 are coefficient of turbine model.

The variation of C_p with tip speed ratio at various value of pitch angle is shown in Fig. 3. It can be observed from this figure, that the maximum value of C_p decreases with an increase in the value of pitch angle [21].

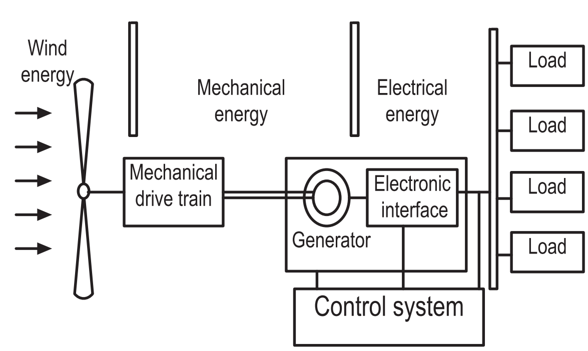

Fig. 2. Single Stage AC–AC converter for wind energy system.