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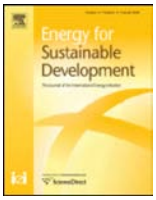

Control strategy of PMSG based wind energy conversion system under strong wind conditions

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ABSTRACT

This paper presents a control approach for the Permanent Magnet Synchronous Generator (PMSG) based Wind Energy Conversion Systems (WECS) under a wide range of wind speeds. Generally, most of the wind turbines are turned-off and disconnected from the power grid, in case wind velocity is gone over 25 m/s. It may cause wind power supply shortage from wind farms. This research introduces a pitch angle controller as well as a rotational speed control system so that the PMSG based WECS can generate power if the wind speeds are above 25 m/s. The proposed method reduces the mechanical stress of the wind turbine by preferential reducing of the rotational speed rather than the mechanical torque during strong wind condition. As a result, the chance of turning-off the is reduced compared to the conventional control system because the PMSG based WECS can temporarily tolerate the wind speed up to 35 m/s. A 2 MW WECS with the electrical and mechanical characteristics is modeled in the MATLAB/SimPowerSystems® to verify the proposed research.

Introduction

Consumption of fossil fuels for generating electric power causes environmental pollutions and possible global warming (Cader, Bertheau, Blechinger, Huyskens, & Breyer, 2016). Alternatively, electric power generation by the nuclear power plants is risky due to the unreliable behavior of the plant and the possible challenges of nuclear waste dumping. Therefore, electric power generation using renewable energies are gaining huge momentum around the world (Kobayakawa & Kandpal, 2016; Oliver, Lew, Redlinger, & Prijyanonda, 2001). Common sources of renewable energies are wind power (Cooney, Byrne, Lyons, & O'Rourke, 2017), solar energy (dos Santos, Canha, & Bernardon, 2018), hydropower (Domenech, Ferrer-Martí, Lillo, Pastor, & Chiroque, 2014), bio-fuel (Shamsul, Kamarudin, & Rahman, 2017) and so on. Among them, WECS has the largest market share and is expected to maintain rapid growth in the coming years (Huang, Li, & Jin, 2015). Usually, WECS uses two types of wind turbines: Variable-Speed Wind Turbine (VSWT) (Chen & Song, 2016) and Fixed Speed Wind Turbine (FSWT) (Rodríguez-Amenedo, Arnaltes, & Rodríguez, 2008). The VSWTs have many advantages such as Maximum Power Point Tracking (MPPT) during operation, better performance and control of the power output (Ajami, Alizadeh, & Elmi, 2016; Wei, Zhang, Qiao, & Qu, 2015). In recent years, the use of VSWTs with the PMSGs have been increased because of their higher efficiency, simpler structure and easy maintenance compared to the other generators (Yao, Liu, Zhou, Hu, & Chen, 2017). Generally, the AC-DC-AC power conversion system is utilized as the basic topology for the PMSG based WECS (Wei, Zhang, Qiao, & Qu, 2016). This kind of topology does not require synchronizing the rotational speed with the grid frequency. Also, the gearbox can be omitted for the directly driven operation of the PMSG (Yoon, He, & Hecke, 2015). Therefore, a PMSG based WECS with AC-DC-AC conversion circuit is a subject of research in this paper, specially its operation in the strong wind conditions.

Mechanical stress due to strong wind conditions is one of the operational challenges for WECS. Japan is a typhoon prone country, more specifically Okinawa prefecture of Japan faces one average 11 typhoons every year. When the wind speed exceeds 25 m/s, most wind turbines stop the power generation and are shut down (Aho et al., 2012; Giallanza, Porretto, Cannizzaro, & Marannano, 2017). It reduces energy utilization efficiency of the WECS. In addition, shutting down of the large wind turbine or wind farm causes severe frequency fluctuations which may lead to the power system instability and a cascaded failure. In Yuan and Tang (2017), an adaptive control

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strategy is proposed for reducing extreme loads and fatigues of the wind turbine when operated under high wind speeds. However, as the wind turbine is operated at the rated speed in the high wind conditions, it could be a matter of safety concern. As the cause of main mechanical stress is centrifugal force rather than the wind pressure, unexpected rise in the rotational speed warrants a serious caution. An Artificial Neural Network (ANN) based pitch angle control is developed in Dahbi, Nait-Said, and Nait-Said (2016). It can operate in the wide range of wind speed, however; mechanical stress at the high wind speeds is not considered in the development of the pitch angle controller.

Considering the research gaps of Yuan and Tang (2017) and Dahbi et al. (2016), a novel control strategy for the PMSG based WECS is presented in this paper. The novelty lies within the consideration that the proposed control strategy reduced mechanical loads the wind turbine by a preferential reduction of the rotation speeds and not by reducing the mechanical torque during strong wind conditions. In the proposed method, the PMSG based WECS can temporarily tolerate wind speed up to 35 m/s. As a result, the WECS can generate power during strong wind conditions which is important for a typhoon prone area like Okinawa. Performance of the proposed control system is verified via numerical simulation results obtained in the MATLAB/SimPowerSyems® environment.

The paper is organized as follows: in Wind energy conversion system, the mathematical model of WECS used for the simulation is developed. The conventional control and the proposed control are described in Control strategy for power generation. In Configuration of the control systems, control strategies for AC-DC-AC conversion systems and pitch angle are presented in detail. Simulation results and discussions shows the simulation results and discusses the performances of the WECS with a comparison of the conventional control and the proposed control. Finally, a summary of the discussions is presented in Conclusion.

Wind energy conversion system

A generic single line diagram of a PMSG based WECS is shown in Fig. 1. Wind energy is converted to variable frequency electric power by the PMSG. This power is supplied to the grid after converting it to a fixed frequency electric power via the AC-DC-AC conversion systems which comprises of a Machine-Side Converter (MSC) and a Grid Side Converter (GSC) connected by a DC-link capacitor. The GSC controls the rotational speed, as well as the output power of the PMSG. The system after the DC link is modeled as a voltage source because the system is the same as a conventional system.

Wind turbine model

Fig. 2 shows the wind turbine and the PMSG models. The wind turbine converts wind energy to mechanical power P_w. The mechanical power P_w extracted from the wind is expressed as:

$$P_w = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V_w^3 \tag{1}$$

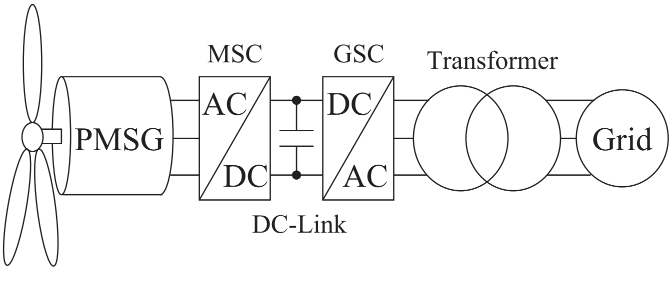

Fig. 1. Block diagram of a variable speed PMSG based WECS.

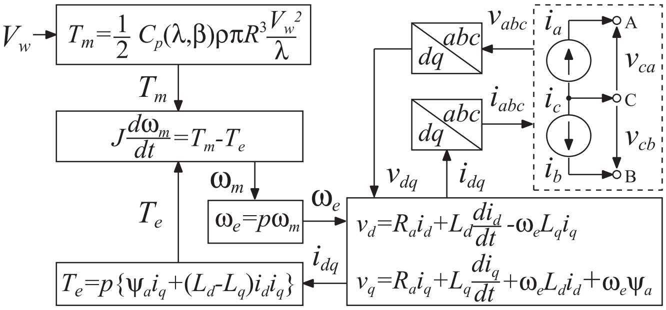

Fig. 2. Block diagrams of the wind turbine and PMSG models.

where C_p is the power coefficient of the wind turbine, $\lambda = \omega_m R / V_w$ is the tip speed ratio, ω_m is the wind turbine mechanical rotational speed, β is the pitch angle, ρ is the air density, R is the radius of the wind turbine blades and V_w is the wind velocity. The wind turbine input mechanical torque T_m is given by:

$$T_m = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^3 \frac{V_w^2}{\lambda} \tag{2}$$

and the power coefficient of wind turbine C_p is given by the following equations (Yin, Li, Zhou, & Zhao, 2007):

$$C_p = 0.22 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) \exp^{\frac{-12.5}{\lambda_i}} \tag{3}$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}} \quad . \tag{4}$$

PMSG model

The mathematical model of a PMSG is the same as the Permanent Magnet Synchronous Motor (PMSM). PMSG is modeled in the synchronous d-q frames by the following voltage and electrical torque equations (Uehara et al., 2011):

$$v_d = R_a i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \tag{5}$$

$$v_q = \omega_e L_d i_d + R_a i_q + L_q \frac{di_q}{dt} + \omega_e K \tag{6}$$

$$T_e = p \{ K i_q + (L_d - L_q) i_d i_q \} \tag{7}$$

where v_d is the d-axis voltage and v_q is the q-axis voltage, i_d is the d-axis current and i_q is the q-axis current, R_a is the stator resistance, L_d is the d-axis inductance and L_q is the q-axis inductance, ω_e is the electrical rotational speed, K is the magnetic flux, and p is the number of pole pairs. The motion equation is expressed as the following (Uehara et al., 2011):

$$J \frac{d\omega_e}{dt} = T_m - T_e \tag{8}$$

where J is the inertia.

Control strategy for power generation

Fig. 3 shows a typical WECS output power curve for the conventional and proposed controls with respect to the pitch angle. First,