Grid Connected PMSG Wind Turbine Energy Conversion Systems

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Abstract: - A wind energy conversion system (WECS) converts the natural energy available at the system location into electrical energy. Directly interfacing the system to the utility gives rise to problems of voltage fluctuations, flicker and generation of sub-harmonics/harmonics associated with the pulsating torque, characteristic of the vertical axis wind turbine (prime mover) driving the generator. Hence, to overcome these difficulties generally an asynchronous link is used to interconnect the wind energy to the utility. The asynchronous link used consists of rotor side converter, DC to DC intermediate circuit and grid side converter. A case study on a 9 MW PMSG wind turbine is used to explain harmonic mitigation in wind turbine energy conversion systems. In this paper, harmonic voltage and current measurements are taken at different buses of power system model. It presents a comparative simulation study between with and without three phase harmonic filters applied to power system model connected to wind farm. The study is simulated using the MATLAB/SIMULINK software.

Key-Words: - Wind Turbine, PMSG, Power System, Harmonics, Filters, Fault

1 Introduction
The increasing demand of energy from the growing modern society has created a concern in the last few decades. This is made worse by the fact that most of the current energy sources are exhaustible and depleting rapidly. Moreover, the combustion process of most of the current energy sources such as coal and fuel produces a high level or air pollution that causes global warming, which is a currently emerging problem. These issues have prompted the rapid development of many renewable energy sources over recent years, particularly the clean and pollution free wind energy that has an eligible rate of depletion. Thus, many efforts are dedicated to efficiently integrate wind energy into the grid network [1-2]. However, electric utility grid systems cannot readily accept connection of new generation plant without power electronic interface. Recent developments have made the trade-off benefits exceed the cost premium of machine in the power ranges up to several hundred kW. Considering these trends, one of the best topologies for wind power conversion system is the full size AC-DC-AC converter [3-4].

Power quality has also been a growing concern in recent years with many researches done in this area [5-6]. Harmonic emissions are recognized as a power quality problem for modern variable-speed wind turbines (WTs). For this reason, relevant standards require the measurement of harmonics [7-10] and their inclusion in the power quality certificates of WTs, and grid interconnection assessment procedures always comprise provisions for their control [11-12].

Power electronic devices usually inject harmonic and reactive current into the utility system. Harmonics increase power system losses, damage sensitive loads, cause excessive heating in rotating machinery, create significant interference with communication systems, and generate noise on regulating devices and control systems. Therefore, harmonic-compensation has become a major concern for power system specialists. Detection and precise extraction of the compensating signal are the most important parts of a grid connected converter’s control [13-14]. In high power applications, the harmonic content of the output waveforms has to be reduced as much as possible in order to avoid distortion in the grid and to reach the maximum energy efficiency. Many recent works with different multilevel converter topologies have been recently presented showing their good performance for high power applications [15-16].

In order to investigate and mitigate the harmonic content in the WECS; a 9 MW PMSG model was simulated and connected to power system model having voltages ranging from 220KV to 440V and
three phase harmonic filters are also connected to power system model at various busbars. The paper is divided into five sections. In Section 2, wind farm model using PMSG and power system model simulations are discussed. Harmonic filter models are discussed in Section 3 and results and discussions are presented in Section 4. Conclusions are outlined in Section 5 and references are shown in Section 6.

2 Power System Model Integrated with PMSG Wind Turbine

The WECS considered for analysis consist of a PMSG driven by a wind turbine, rotor side converter, DC to DC intermediate circuit and grid side converter. The mechanical power available from a wind turbine is

\[ P_w = 0.5 \rho \pi R^2 V_w^3 C_p(\lambda, \beta) \]  

where,

- \( P_w \) : Power Extracted from the Wind
- \( \rho \) : Air Density
- \( R \) : Blade Radius
- \( V_w \) : Wind Speed
- \( C_p \) : Power Coefficient

\( C_p \) is given as a nonlinear function of the parameters tip speed ratio \( \lambda \) and blade pitch angle \( \beta \). The calculation of the power coefficient requires the use of blade element theory. As this requires knowledge of aerodynamics and the computations are rather complicated, numerical approximations have been developed [17]. Here the following function will be used [18]

\[ C_p = \frac{1}{2} \left( \lambda - 0.022 \lambda^2 - 5.6 \right) e^{-0.17\lambda} \]  

where,

- \( \lambda \) : Tip Speed Ratio
- \( \beta \) : Blade Pitch Angle

The tip speed ratio is given as:

\[ \lambda = \frac{\omega_R}{\omega_b} \]

where,

- \( \omega_R \) : Rotational Speed of Turbine

The torque developed by the windmill is given as:

\[ T_t = 0.5 \rho \left( \frac{C_p}{\lambda} \right) V_w^3 \pi R^2 \]

Following are the equations used in modelling PMSG:

\[ V_d = R_s i_d + \frac{d\varphi_d}{dt} - \omega_r \varphi_q \]

\[ V_q = R_s i_q + \frac{d\varphi_q}{dt} + \omega_r \varphi_d \]

\[ T_e = \varphi_d i_q + \varphi_q i_d \]

\[ \frac{d\omega_r}{dt} = \frac{1}{J} \left( T_e - F \omega_r - T_m \right) \]

\[ \frac{d\theta}{dt} = \omega_r \]

where

- \( V_q, V_d \) : q-axis and d-axis Voltages
- \( R_s \) : Stator Resistance
- \( i_q, i_d \) : q-axis and d-axis Currents
- \( \varphi_q, \varphi_d \) : q-axis and d-axis Fluxes
- \( \omega_r \) : Angular Velocity of the Rotor
- \( T_e \) : Electromagnetic Torque
- \( T_m \) : Shaft Mechanical Torque
- \( J \) : Rotor and Load Inertia
- \( F \) : Rotor and Load Viscous Friction
- \( \theta \) : Rotor Angular Position

Fig.1 shows a schematic of the wind energy conversion system having PMSG and power electronic interface that will be discussed in this paper. In rotor side converter system, AC voltage and VAR are regulated. DC to DC intermediate circuit consists of two converters: Converter 1 (DC to AC) and Converter 2 (AC to DC). The control system of DC to DC intermediate circuit consists of DC voltage and current regulation and pitch control system. The pitch angle is regulated at zero degree by pitch angle regulator until the speed reaches desired speed. The DC voltage output from intermediate circuit is applied to grid side converter, which consists of an Insulated Gate Bipolar Transistor (IGBT) two-level inverter, generating AC voltage at 50 Hz. The IGBT inverter uses Pulse Width Modulation (PWM) at 2000 Hz carrier frequency.

Fig.2 shows power system model used. The harmonic filters are connected to buses B1 to B4.
A 9 MW wind farm consisting of six 1.5 MW PMSG wind turbines connected to 440V distribution system through power electronic interface. The wind speed is maintained constant at 15 m/s. The reactive power produced by the wind turbine is regulated at 0 MVAR. This model is well suited for observing harmonics and control system dynamic performance over relatively short periods of times. A transient three phase fault is simulated on bus B3 (as shown in Fig.2), which lasts for 50 milli seconds.

3 Harmonic Mitigation by Three Phase Harmonic Filters

Harmonic distortion is the periodic deviation of the voltage or current from the ideal sinusoidal waveform. Harmonic distortion occurs when frequencies of the multiple integers of the fundamental frequency are added to the fundamental voltage or current waveforms. Harmonic distortion can be caused by power electronics in devices such as rectifiers, adjustable speed drives. It may lead to malfunction of computers and excessive heating of motors, transformers and wires. The filter set, used in paper, is made of the following four components:

- One capacitor bank of 100 kVAR
- Three filters
  - One C-type high-pass filter tuned to the 3rd harmonic (100 kVAR)
  - One double-tuned filter 11th & 13th harmonic (100 kVAR)
  - One high-pass filter tuned to the 24th harmonic (100 kVAR)

The total MVAR rating of the filters set is 400 kVAR. A three phase circuit breaker is used to connect the filters set on the AC bus. Fig.3 shows three phase harmonic filters set connected to buses B1, B2, B3 and B4, which are used to reduce harmonic distortion and thus improve power quality.
THD is defined as the root mean square (rms) value of the total harmonics of the signal, divided by the rms value of its fundamental signal. THD can be calculated as follows:

\[
\text{THD} = \frac{I_{an}}{I_{a1}}
\]

(10)

\[
I_{an} = \sqrt{I_2^2 + I_3^2 + \cdots + I_n^2}
\]

(11)

where,

- \(I_{an}\) Phase rms of the \(n^{th}\) Component and
- \(I_{a1}\) Fundamental Component of Phase rms

It follows that the THD has a value between zero and 1. It is null for a pure sinusoidal voltage or current.

4 Results and Discussions

In this section the simulated results for the grid connection of three phase harmonic filters described above are presented. Two cases are considered to investigate the impact of harmonic filters on power grid connected with wind energy. One case (Case 1) is that harmonic filters are not connected to PMSG wind turbine integrated power grid and another case (Case 2) is taken as harmonic filters connected to PMSG wind turbine integrated power grid.
The comparison of magnitude of voltage THD having range 0-1 is presented in Fig.4 to Fig.7 and comparison of current THDs at various buses is shown in Fig.8 to Fig.11. Table 1 and Table 2 shows the effect of adding harmonic filters in terms of voltage THDs and current THDs respectively in the existing integrated wind energy power system model. It is clear from Fig.4 to Fig.11 that values of voltage THD and current THD at various buses is less in Case 2 as compared to Case 1. The %reduction in peak value of voltage THD with harmonic filters at busbar locations B1, B2, B3 and B4 are 50.5%, 51.85%, 43.47% and 37.5% respectively. The %reduction in peak value of current THD with harmonic filters at busbar locations B1, B2, B3 and B4 are 48.1%, 48.18%, 57.6% and 59% respectively. As seen in Fig.4 to Fig.11, harmonics value as well as peak value reduce drastically. Thus power quality is improved by inclusion of abovesaid harmonic filter set in PMSG wind integrated power system model.

5. Conclusions
In this paper, we attempted to compare the impact, in terms of voltage THDs of adding three phase harmonic filters to wind integrated power system consisting of PMSG. Two different cases are considered examining the influence of adding harmonic filters. The results have clearly demonstrated the ability of harmonic filters to reduce transients and harmonic distortion in power system. It has been concluded that with the inclusion of harmonic filters THD reduces noticeably and hence power quality improves significantly.

References:
[1] Z. Chen and E. Spooner, “Grid interface for renewable energy sources,” 2nd International Power Electronics and Motion Control


