

DESIGNING A WIND TURBINE WITH PERMANENT MAGNET SYNCHRONOUS MACHINE

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Abstract: In this study, wind energy that is one of the sources of clean and renewable energy is modeled for generating electrical energy by using PSIM[®]. E- 33 type (ENERCON) wind turbine data sheet is used for the modeling. Wind turbine system is chosen as variable speed instead of fixed one because of the advantage of generating more efficient and higher quality electrical energy. So the generator is connected to the power electronic circuit first and then the step-up transformer. Permanent magnet synchronous machine (PMSM) is chosen as a generator. An uncontrolled rectifier is modeled after the generator in the system and an inverter is also modeled at the grid side for generating electrical energy in the suitable form. Active and reactive power control is achieved by the grid side converter with the indirect current control. Synchronization with the grid is made by Phase Locked Loop(PLL). Both of the power converters are modeled and simulation results are presented. In the last part of study, power quality is evaluated with the harmonic analysis and the total harmonic distortion of the system is in the range of IEC 61400-36 and IEEE 519-1992 Standards.

Keywords: Renewable energy, Wind turbine, Permanent magnet synchronous machine

1. Introduction

There are different generator types that are used in wind turbine systems. Speed control is the main part of the systems. In the fixed speed system such as “Danish concept” wind turbines, an induction generator is connected directly to the grid. However variable speed one is connected through the power electronic circuits which controls the rotor speed of the machine [1]. In this study, variable speed wind turbine system is chosen because of the advantage of generating more efficient and higher quality electrical energy.

Generator type should be decided after choosing the variable speed system. Synchronous and induction generators are widely used for the grid connected variable speed wind turbine system. Switched reluctance and brushless direct current generators are also used in the small applications. There are a lot of advantages and disadvantages which must be considered while choosing the right generator.

Induction machine is not commonly used as a generator except small hydropower plants because

they need reactive power supply such as capacitor banks when they are working as a generator.

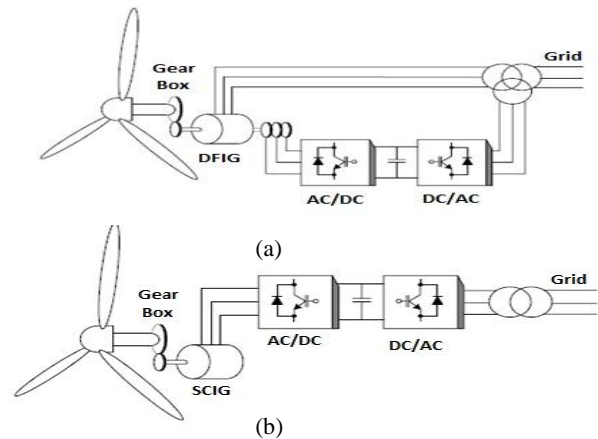


Figure 1. Induction generator topologies for wind turbine system [2]

There are two kinds of induction generator used in wind turbines: squirrel cage (SCIG) type and wound rotor type as given in the Figure 1 [2]. Being reliable and economical makes the squirrel cage induction generator popular. However its control system is

difficult and depends on the generator parameters that vary with temperature and frequency. Also the converters must be oversized %30-50 with respect to the rated power in order to supply the magnetizing of the machine as given in the figure 1 (a) [2]. Wound rotor induction generators are generally used in the doubly fed (DFIG) systems. This system offers some advantages such as reducing the converter and filter costs by reducing the converter power ratings as given in the Figure 1 (b). But they need a periodic maintenance in slip rings [2].

The synchronous generators are commonly used in power plants. They consist of a stator which supplies the load and a rotor that provides the magnetic field. The source of the magnetic field can be a permanent magnet or a direct current in wound field. Wound field synchronous generators (WFSG) have some disadvantages such as necessity of a rectifier between the grid and the generator for the direct current as given in the Figure 2 (a) [3].

In this study, synchronous generator is chosen to eliminate the gearbox problem. Gearbox can be removed from the system by using a permanent magnet synchronous generator (PMSG) since the pole pitch of this generator can be smaller than others to reduce the mechanical losses and improve the reliability of the system [2]. This can be achieved by increasing the number of pole number and decreasing the nominal speed of the generator. In this way, gearbox can be eliminated and the wind turbine system becomes more efficient and reliable.

The proposed system is shown in Figure 2 (b). In this topology, generator is connected through an uncontrolled rectifier on the generator side and the inverter on the grid side.

The uncontrolled rectifier is used for getting the control system easier. The generator side converter controls the electromagnet torque while the grid side inverter controls the active and reactive power and regulates the direct current bus to control power factor with field oriented control (FOC).

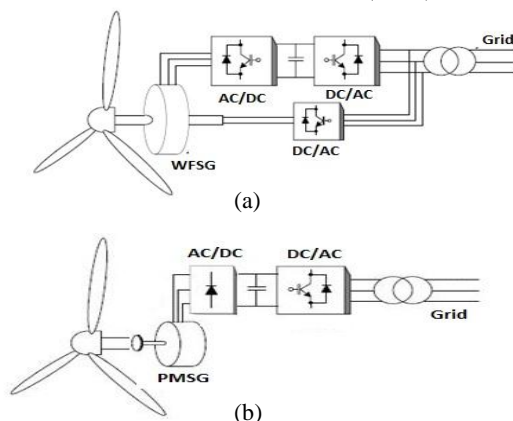


Figure 2. Synchronous generator topologies for wind turbine system [2]

2. Proposed Topology Model in Powersim

The proposed topology is modeled in (PSIM) as given in the Figure 3. Permanent magnet synchronous generator is directly driven by the wind turbine and the output of the generator is connected to the rectifier. At the same time, the current and the voltage are measured and given to the grid-side inverter control unit to control the active and reactive power given to the grid.

2.1. Dynamic Model of the Wind Turbine

In this section, modeling of the wind turbine according to the parameters taken from the datasheet of ENERCON E-33 will be introduced. Power extracted from the wind (P_{wind}) can be calculated as given in equation 1 where A (m^2) = $\pi * R^2$ is the swept area by the rotor blades while R (m) is the radius of the rotor blade, ρ is the air density (kg/m^3) and v (m/s) is the velocity of the air speed.

$$P_{wind} = \frac{1}{2} * \rho * A * V^3 \quad (1)$$

The main problem is the percent of the energy which is converted from the wind energy to mechanical energy to be used in the wind turbine system. This conversion can't be made with 100 % efficiency. In other words, power extracted from the wind energy is the difference between the power of the wind before and after the wind turbine. The ratio between these powers can be defined as power coefficient (C_p).

This ratio is smaller than one and important to determine the characteristics of the wind turbine. So, the mechanical power (P_t) can be calculated as given in Equation 2.

$$P_t = C_p * P_{wind} = C_p * \frac{1}{2} * A * V_1^3 \quad (2)$$

The power coefficient is also a function of the tip speed ratio (TSR) λ . TSR is defined as given in the Equation 3 where u (m/s) is the tangential velocity and w (rad/s) is the angular velocity of the rotor blade [4].

$$\lambda = \frac{u}{v} = \frac{w * R}{v} \quad (3)$$

Another important parameter about the wind turbine characteristic is the torque coefficient (C_T) that is the ratio between the power coefficient and tip speed ratio (TSR) as given in the Equation 4.

$$C_T = \frac{C_p}{\lambda} \quad (4)$$

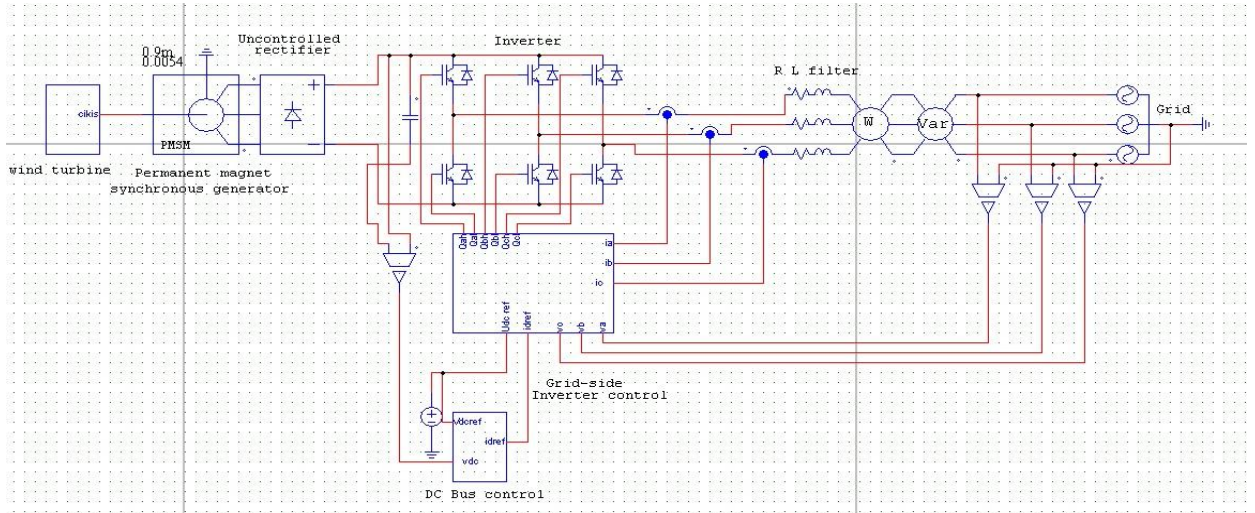


Figure 3. PSIM model of the proposed topology

Torque of the wind turbine can be calculated as given in the Equation 5.

$$T_t = C_T * \frac{1}{2} * \rho * \pi * R^3 * V^2 \tag{5}$$

The power and torque characteristics curves of the wind turbine are given in the Figure 4. The functions of Cp and Cr are obtained by curve fitting technique and given in the Equations 6 and 7 respectively.

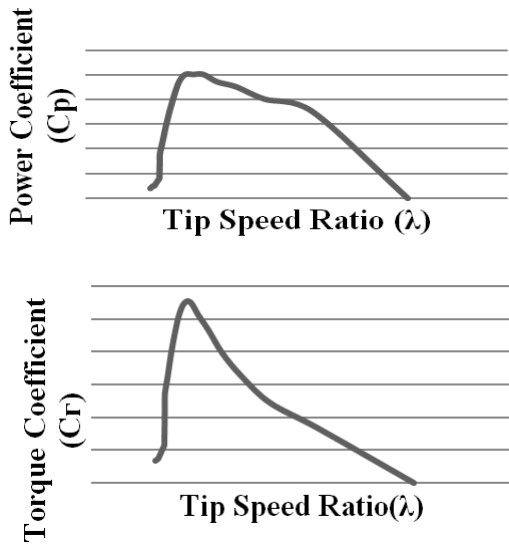


Figure 4. Wind turbine characteristic curves(E-33)

$$C_p = 0.00000003 \lambda^7 - 0.000003 \lambda^6 + 0.0001 \lambda^5 - 0.0017 \lambda^4 + 0.0124 \lambda^3 - 0.0178 \lambda^2 + 0.0056 \lambda \tag{6}$$

$$C_T = 0.00000003 \lambda^6 - 0.000003 \lambda^5 + 0.0001 \lambda^4 - 0.0017 \lambda^3 + 0.0124 \lambda^2 - 0.0178 \lambda + 0.0056 \tag{7}$$

The modeling of the wind turbine is given in the figure 5. Power and torque coefficients are obtained according to the wind speed and then mechanical power,

turbine torque and the angular velocity of the wind turbine and generator can be calculated.

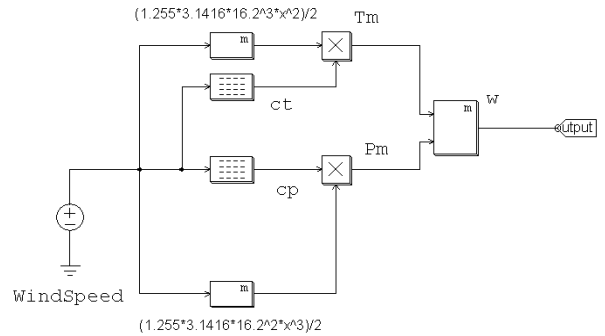


Figure 5. Wind turbine model on PSIM

2.2. Grid Side Inverter Control

Grid-side inverter controller consists of two main parts. One of them is the phase locked loop (PLL) which is used for synchronization with the grid and the other one is indirect current control which is used for controlling the active and reactive power between the turbine and the grid.

Grid-side inverter is controlled with linear components to make the system easier. In this step, sinusoidal phase quantities (abc) are transformed to linear components (dq0) with synchronous reference frame. So, the linear components are controlled with PI controller. The phase angle (θ) between the abc and dq0 is given in the figure 6. This angle will be used while transforming sinusoidal abc quantities to linear components dq0 in transform matrix.

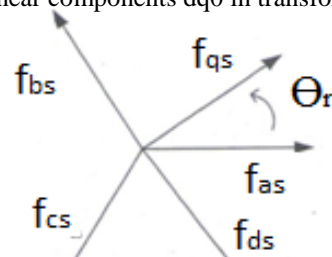


Figure 6. Phase angle (Θ) between reference frames

2.2.1. Phase Locked Loop (PLL)

Synchronization systems must be used in the wind power plant because voltage and frequency are variable according to the wind speed. There are many methods are used so far such as; zero-crossing method, filtering of grid voltages, phase locked loop,etc [5].

In this study, phase locked loop (PLL) synchronization system is preferred since this system is always controlling the grid information while the other ones control the system only half of one period [5].

The principle of the PLL is given in the figure 7. PLL can be defined as a device which is used to find the phase angle (θ) from the grid voltages. The system signal feedback the input one. So, the system provides the inverter with frequency and phase angle. The purpose of that is to synchronize the inverter current angle with the grid voltage angle in order to obtain a power factor so close to unit factor 1.

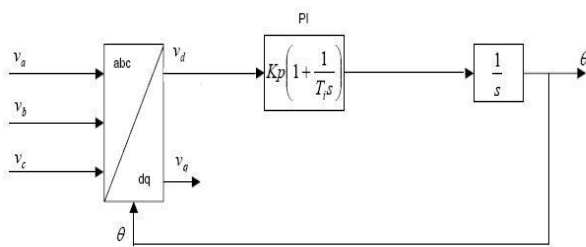


Figure 7. Principle of the phase locked loop

2.2.2. Indirect Current Control

The control aim of grid-side inverter is to keep the voltage constant on the dc bus between the converters, obtain unit power factor and generating the electrical energy suitable for the grid conditions on the aspect of voltage and frequency.

As given in the figure 8, grid-side inverter control has an outer voltage loop to control the active and reactive power given to the grid and inner current loop to control the quality of the power given to the grid. The control system is named as indirect current control because of converting abc sinusoidal quantities to dq0 linear components and using PI controller to make the system easier. At the beginning of the indirect current control, the phase angle (Θ) information comes from the PLL and sinusoidal current (i_{abc}) and voltage (v_{abc}) waveforms are converted to linear current (i_d, i_q, i_0) and (v_d, v_q, v_0) components and given to the control loops.

The aim of the dc bus control is to get the reference d-axis current component (I_d^*) which satisfies the active power given to the grid by keeping the

voltage constant on the capacitor on the dc bus side of the system.

This information is obtained by comparing the reference dc bus voltage (U_{dc}^*) and measured dc bus voltage (U_{dc}) and giving the error as the feedback to the PI controller. The reactive power control is accomplished by comparing the reference q-axis current component (I_q^*) which is obtained by measuring the reactive power on the grid-side and the reactive current component (I_q) of the grid. The error between of (I_q^*) and (I_q) is delivered to the PI controller to be used in dynamic equations of the grid-side inverter in synchronous rotating reference frame.

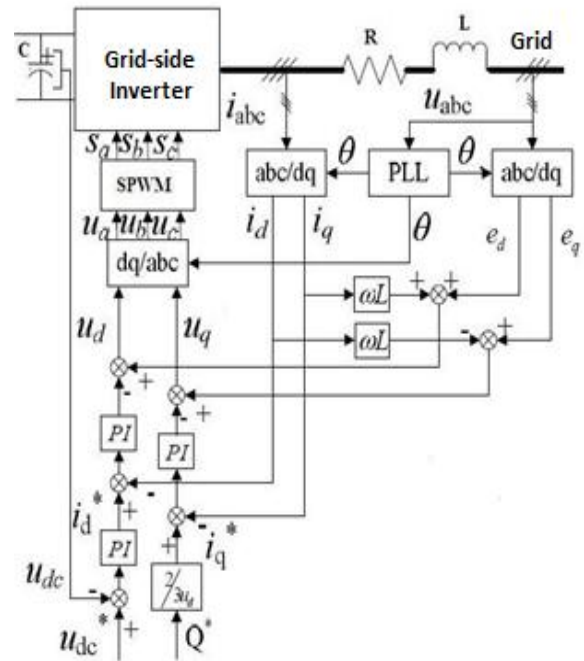


Figure 8. Schematic of the indirect current control

R/L = Stator resistance (Ω) / Stator inductance (H)

w_e = Electrical angular velocity ($w_e = n_p * w_g$)

$e_{d/q}$ = d-axis and q-axis back EMF voltage components respectively (V)

$$u_d = e_d - Ri_d + w_e * Li_q - L * \frac{di_d}{dt} \tag{8}$$

$$u_q = e_q - Ri_q - w_e * Li_d - L * \frac{di_q}{dt} \tag{9}$$

$$P = \frac{3}{2} * u_d * i_d \tag{10}$$

$$Q = \frac{3}{2} * u_d * i_q \tag{11}$$

Active and reactive power control can be made by controlling the current and voltage components in the indirect current control system as given in the Equations 10 and 11.

Eventually, the calculated voltage components (u_d, u_q) are converted back to the three phase sinusoidal (u_a, u_b, u_c) quantities and given to sinusoidal pulse-width modulation (SPWM) to control the gate signals of the inverter.

3. Simulation Results

In this section, the simulation results are given to verify the proposed topology for the wind turbine. Simulation results are given at 13 m/s which is the nominal speed to generate maximum power for this application. The aim of this system is to generate the active power from the mechanical energy. The power factor should be close to 1 to reduce the losses on the transmission lines which cause from reactive power. The customers who need the reactive power must have a system either capacitor bank or static VAR compensator.

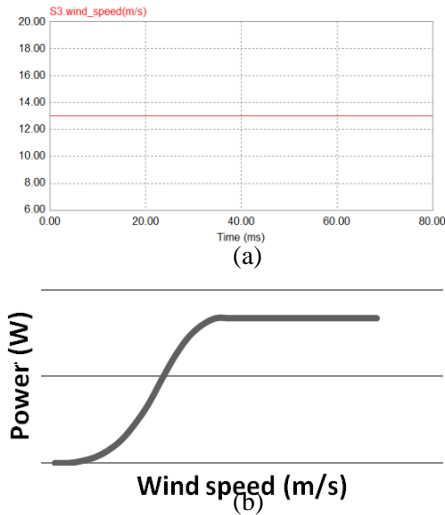


Figure 9. (a) Simulation wind speed
(b) Turbine characteristic from the catalogue

As given in the Figure 10, the turbine's torque is obtained as 110 kNm. The wind turbine rotates at 28.64 min^{-1} at the given wind speed.

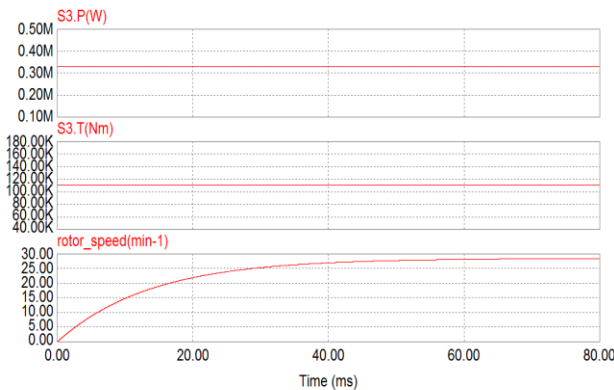


Figure 10. Power, torque and rotor speed curves at 13 m/s

Figure 11 shows the stator current and voltage waveforms of the generator for one phase. As it can be seen, the angle between the phase voltage and current is almost zero. So, the power factor ($\cos\phi$) is almost unit power factor. In other words, the proposed system converts all mechanical power to the active power and gives it to the grid as purposed.

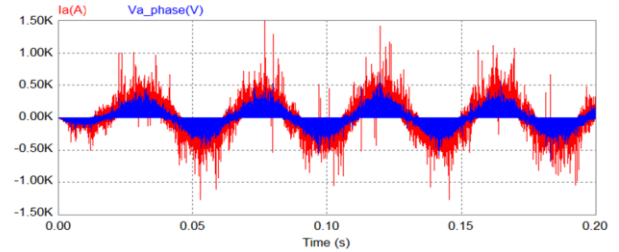


Figure 11. Current and voltage waveform of the generator

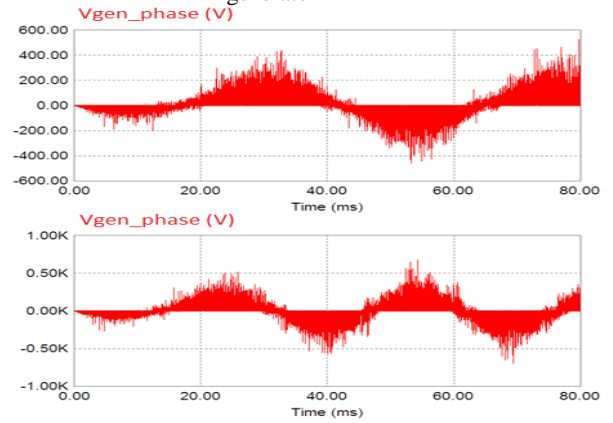


Figure 12. Generator voltage at different wind speeds

Figure 12 shows the results of generator phase voltage at different wind speeds. The aim of giving these waveforms is to show the need of the rectifier in the generator side. The frequency is variable according to the wind speed. The frequency is 20 Hz at 13 m/s while 33 Hz at 25 m/s. Voltage waveforms on the dc bus and capacitor are given in the Figure 13. As it can be seen in the figure, the capacitor voltage is constant. So, the mechanical power and the active power given to the grid are equal as given in the Equation 12 [5]. This is the other proof that power factor is close 1 and all mechanical power is converted to active power and given to the grid.

$$C \frac{dV_{DC}}{dt} = \frac{P_t}{V_{DC}} - \frac{P_g}{V_{DC}} \tag{12}$$

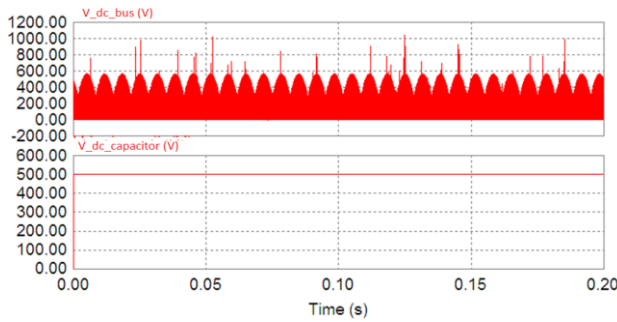


Figure 13. Voltage waveforms of the dc bus and capacitor

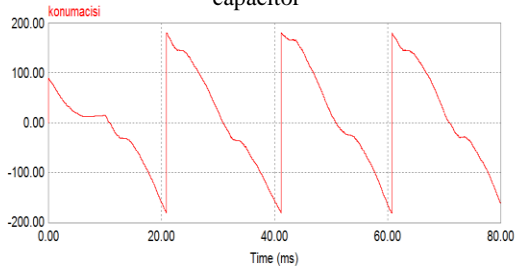


Figure 14. Phase angle with PLL

Figure 14 shows the phase angle result of the phase locked loop (PLL). The loop tracks the grid frequency and gives the signal to the input at every 20 ms (50 Hz).

The first waveform in the Figure 15 shows the comparison the inverter and the grid voltage forms. They are in the same form and this is the other proof that PLL works very well. The second waveform shows the inverter voltage and current. The phase angle between them is almost opposite. This means that power factor is close to 1 and active power is given from the inverter to the grid.

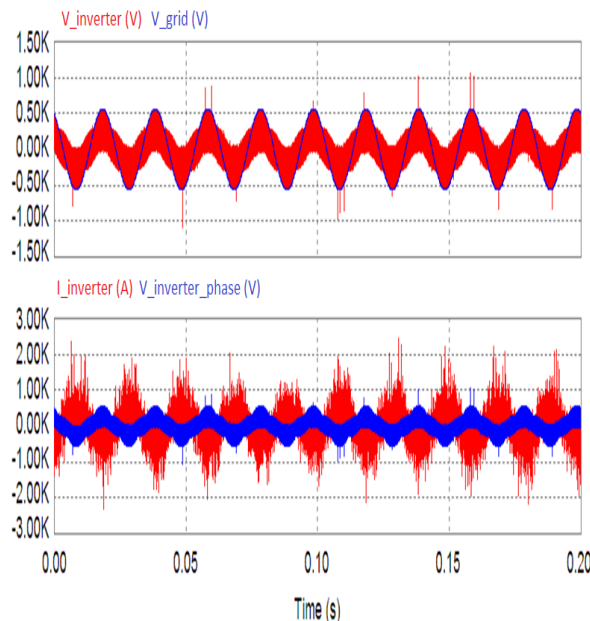


Figure 15. Voltage and current waveforms of the inverter

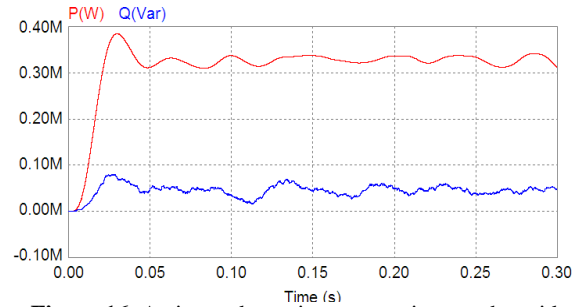


Figure 16. Active and reactive power given to the grid

Figure 16 shows the active and reactive power given to the grid. The reactive power is generated because of RL filter in the system. The wind turbine system generates 326 kW active power and 45 kVar reactive power. This means that the power factor is 0,99.

Power quality is also evaluated with the harmonic analysis. The total harmonic distortion of the system is given in the Figure 17. The current form has 1,2% and the voltage form has 2% total harmonic distortion. According to the IEC 61400-36 and IEEE 519-1992 Standards, THD must be maximum % 5 and these results show that power quality is in the range of the standards.

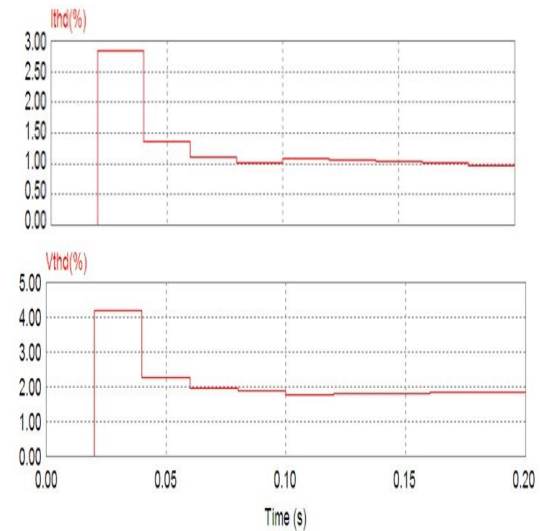


Figure 17. THD of the inverter current and voltage

4. Conclusion

This study presents a control topology of power converter used in a direct-drive permanent magnet system using the real wind turbine characteristics (E-33). The system is able to convert mechanical energy to electrical energy and give it to the grid. Phase locked loop has a very good performance at the synchronization with the grid. Grid-side inverter keeps the power factor close to one and dc bus voltage is kept constant by indirect current control. The results of the simulation and comparison made with similar studies [6, 3] prove that system has a very good performance. At last, good results of this

theoretical study might be the guide for making prototype of a wind turbine system with using a DSP controller.

5. References

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