DESIGN OF A WIND POWER GENERATION SYSTEM USING A PERMANENT MAGNET SYNCHRONOUS MACHINE, A BOOST REGULATOR AND A TRANSFORMER-LESS STEP DOWN CIRCUIT

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Abstract

This paper presents a wind power system using a Permanent Magnet Synchronous Machine (PMSM). The whole system consists of a wind turbine, a permanent magnet synchronous machine, a three phase diode rectifier, a boost converter, a transformer-less step down circuit, an H-bridge inverter and a T-LCL filter. The 3-phase AC output from the PMSM is sent to the 3-phase diode rectifier for conversion to DC and a boost regulator is used to step-up this DC voltage to the desired level. This step-upped DC voltage is then converted into AC output by the H-Bridge inverter. The switching technique of the proposed inverter consists of a combination of Sinusoidal Pulse Width Modulation (SPWM) and a square wave along with grid synchronization conditions. As the suggested method is entirely transformer-less, it significantly reduces Total Harmonic Distortion (THD) to less than 0.1% and minimizes its size. The T-LCL Immittance Converter not only reduces the harmonics of the inverter output but also provides a nearly constant output current thereby stabilizing the system. The system setup and the simulation results were obtained using the PSIM software.

***Keywords**: Wind Turbine, Permanent Magnet Synchronous Machine, Boost Converter, Step- down Circuit, T-LCL Immittance Converter, Inverter*

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1. INTRODUCTION

The changing world climate is a serious threat to our planet. The global warming phenomenon, driven by the emission of carbon dioxide (CO_2) from the use of fossil fuels is slowly killing our planet. Moreover, the cost of fossil fuel is also increasing day by day and its sources are gradually becoming exhausted [7]. As a result, the cost of the utilization of the renewable energy systems is on the decreasing trend making them ideal for use in power generation systems. Of the many renewable energy resources such as solar, wind, biomass, tidal etc. solar and wind energy systems are most commonly used.

Wind energy can be used for generating large amounts of power. Wind energy systems are particularly useful in remote areas where grid connection is not accessible or not feasible. In those places, the wind power generation systems can be used for meeting the consumer load demands in a cost-effective manner. In conventional wind energy systems, transformers are used to step-down grid voltages. But transformers are bulky and costly equipment and also contribute to the Total Harmonic Distortion (THD) of the inverter output [4]. Hence, in this paper a transformer-less wind generation topology has been proposed.

The block diagram for the proposed wind power system is shown in Fig1. The design includes 1) a 3–phase permanent magnet synchronous machine which has 3-phase windings on the stator and a permanent magnet on the rotor [2-4]; 2)a three-phase diode rectifier to convert AC output from the PMSM to DC output;3) a boost converter to step up this DC output to the desired level. 4) an H-bridge inverter for converting the DC output of the boost converter into AC output; 5) a T-LCL Immittance converter to suppress the harmonics of the inverter output and produce a pure sinusoidal wave and 6) a transformer-less step down circuit to produce the gate pulses of the inverter using a combination of SPWM and square wave.

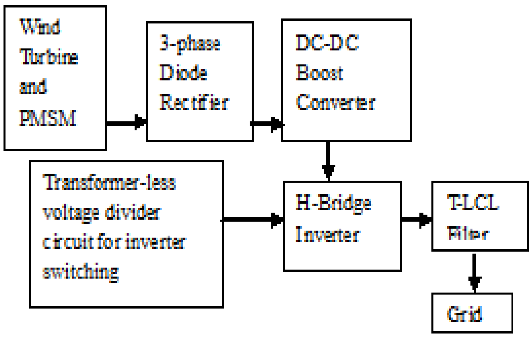

Fig-1: Block diagram of Wind PowerGeneration System

2. WIND TURBINE

When moving air exerts force on the propeller like blades around a rotor of the wind turbines, electricity is generated. The rotor is connected to a low speed shaft which in turn is connected via gearbox to a high speed shaft. The gear box is responsible for increasing the rotational speed from 10-60 rpm to 1200-1800 rpm. The high speed shaft is connected to a generator which is then used for generating electricity [6].

The mechanical power [1] from the wind turbine is given by:

$$Pm=\frac{1}{2}\rho AC_p(\lambda,\beta)v_w^3 \ldots\ldots\ldots\ldots\ (1)$$

Where ρ=air density, A= rotor swept area, Cp(λ, β)=power coefficient function, λ =tip speed ratio, β=pitch angle, vw=wind speed.

The efficiency of the wind turbine to convert wind energy into mechanical energy is given by Cp, which is dependent on λand β. The tip speed ratio, λ, is the ratio of the turbine angular speed to the wind speed as shown in Eq.(2). Maximum power can be obtained for different wind speeds by controlling the rotational speed. The pitch angle, β, is the angle in which the turbine blades are aligned with respect to its longitudinal axis.

$$\lambda = \frac{R\omega_b}{v_w} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

Where R= turbine radius and ω_b=angular rotational speed.

3. PROPOSED DESIGN

The design and the performance of the proposed wind power generation system were performed using the PSIM simulation software. The input was taken by means of the built-in wind turbine block of the software. It was then connected to the generator via the gear box and the electrical-mechanical interface. The various sections of the whole system are discussed in details below.

3.1 Permanent Magnet Synchronous Machine

The generator used for the design was a 3-phase permanent magnet synchronous machine (or permanent magnet synchronous generator)[2]. A 3-phase permanent magnet synchronous machine has 3-phase windings on the stator and permanent magnet on the rotor as shown in Fig-.2, where a,b and c are the stator winding terminals, n is the neutral point and the shaft node is used for establishing connection with the high speed mechanical shaft. The back emf of the machine is sinusoidal.

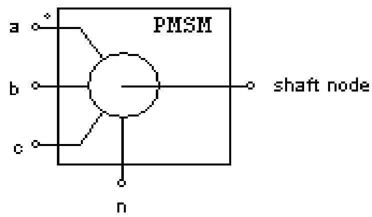

Fig-2: Permanent Magnet Synchronous Machine

3.2 Three-phase Diode Bridge Rectifier

The variable frequency sinusoidal voltages produced by the generator cannot be used for establishing connection with the grid. First, they need to be rectified into DC and then converted into AC voltages of desired frequency and amplitude.The rectification is done by a 3-phase diode bridge rectifier as shown in Fig-3.

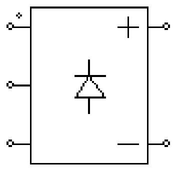

Fig-3: Three phase Diode Bridge Rectifier

3.3 Step-up Boost Converter

The output of the rectifier is then converted into 312V DC by means of a boost converter [8], as shown in Fig-4. The boost converter's output should be 312V since it is the input of the inverter, the output of which should be the same as the grid voltage (312V peak or 220V rms) in Bangladesh. The output voltage of the boost converter is given by:

$$V_{out} = \frac{V_{in}}{1-D} \ldots\ldots\ldots\ldots\ (3)$$

Where Vout=average output voltage, Vin=input voltage and D=duty cycle.

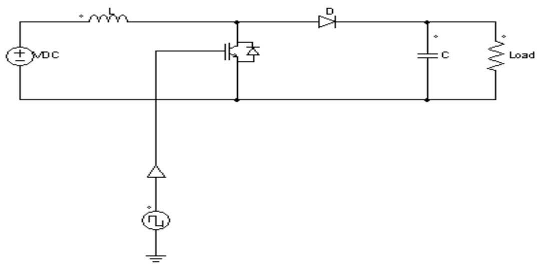

Fig-4: Boost Converter for stepping up voltage to required level

The design parameters of the boost converter are given in Table 1.

Table -1: Design of Boost Converter

Symbol	Actual meaning	Value
Vin	Given input voltage	250V
Vout	Desired average output voltage	312V
fs	Switching frequency of converter	20KHz
IL,max	Maximum inductor current	7.33A
ΔiL	Estimated inductor ripple current(1.75% of IL,max)	0.128A
ΔVout	Desired output voltage ripple(0.021% of output voltage)	65mV
Iout	Maximum output current	4.3A

The inductor value is selected using the following equation [8]

$$L = \frac{V_{in}\left(V_{out} - V_{in}\right)}{I_L \times f_s \times V_{out}}$$

So,

$$L = \frac{250 \times \left(312 - 250\right)}{.128 \times 20000 \times 312} \approx 19.36\text{mH}$$

The capacitor value is selected using the following equation [8]

$$C = \frac{I_{out} \times D}{f_s \times V_{out}}$$

So,

$$C = \frac{4.3 \times 0.198}{20000 \times 0.065} \approx 0.656\text{mF}$$

3.4 Transformer-less Step down Circuit

The step down operation is performed using a voltage divider as shown in Fig-5.

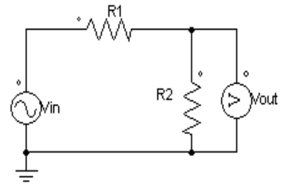

Fig-5: Voltage divider Circuit

Using voltage divider equation, [8]

$$\left|v_{out}\right| = \frac{R2 \times \left|v_{in}\right|}{R1 + R2}$$

Setting $\left|v_{in}\right| = 312\text{V}; \left|v_{out}\right| = 7.07\text{V}; R1 = 100\text{k}\Omega$ and solving for R2, we get R2=2.32KΩ.

3.5 Inverter and Inverter Switching Circuit

The H-Bridge DC-AC inverter has two parallel MOSFET gates. This is shown in Fig-6. A combination of analog and digital circuits is used to produce the gating pulses of the MOSFETs.

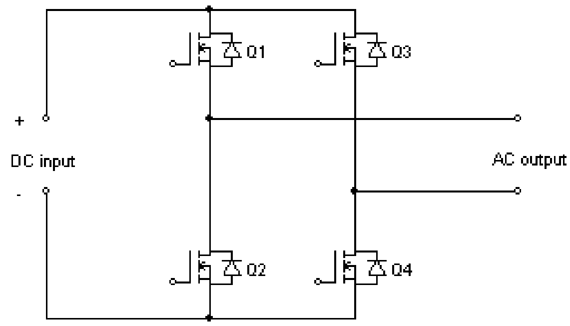

Fig-6: H-Bridge Inverter

In conventional inverters only one type of switching technique is used. But this proposed design instead uses a combination of SPWM and square wave to reduce the switching loss by reducing the switching frequency. Fig-7 shows the proposed switching circuit of the inverter. The sine wave is sampled from the grid by using a transformer-less voltage divider circuit which steps down the voltage from 220V (rms) to 5V(rms).The sine wave sampled is used to generate the SPWM signal thus ensuring that the output voltage from the inverter will have the same frequency as the grid [5]. After sampling, the sine wave is rectified with a precision rectifier, the output of which is shown in Fig-8.

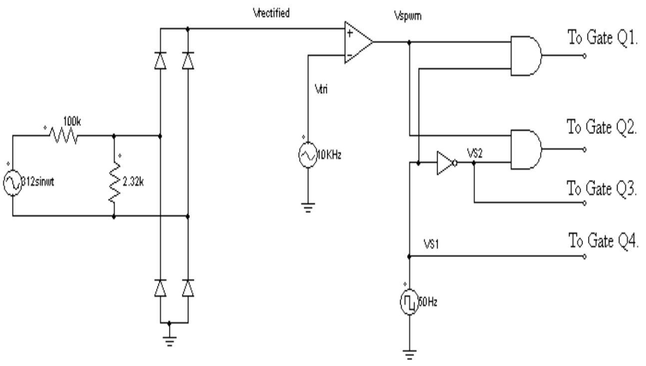

Fig-7: Control Circuit of the Inverter

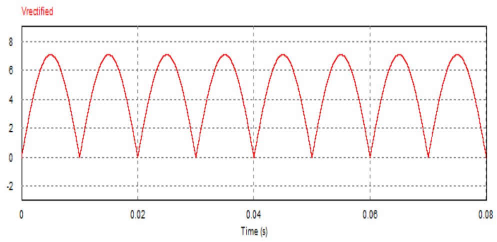

Fig-8: Rectified sine wave

In addition, a high frequency triangle wave of 10 KHz is used. Then the two signals are passed through a comparator to produce the SPWM signal as shown in Fig-9. A square wave signal is used as the line frequency (50 Hz for Bangladesh) and is in phase with the SPWM as shown in Fig-10.The square wave is passed through a NOT gate to produce a signal that is 180 degree out of phase with the original signal.

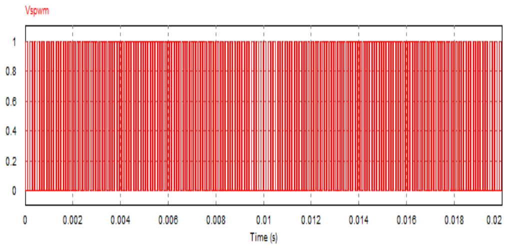

Fig-9: SPWM signal

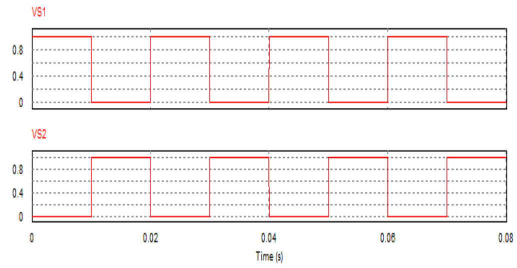

Fig-10: Square wave signals

The inverter requires four switching signals since it has four MOSFETs. To produce the four signals, an AND operation is performed between two sets of square wave signals and the SPWM signal. The four sets of switching signals can be categorized in two groups. The first group contains MOSFETs Q1 and Q4 while the second group contains MOSFETs Q2 and Q3. The gate pulses for switching of MOSFETs are illustrated in Figs 11 and 12 respectively. When Q4 is ON, Q1 is switched ON with the SPWM signal and both Q2 and Q3 are OFF. This produces a positive voltage at the inverter output. When Q3 is ON, Q2 is switched ON with the SPWM signal and Q1 and Q4 are both OFF. This produces a negative voltage at the inverter output.

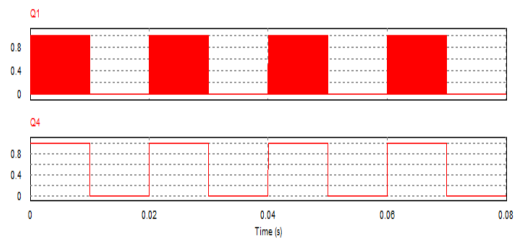

Fig-11: Switching signal from control circuit for MOSFETs (Q1 and Q4)

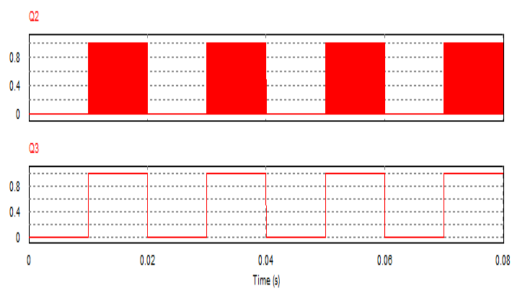

Fig-12: Switching signal from control circuit for MOSFETs (Q2 and Q3)

3.6 Filter Circuit

To eliminate harmonics from the inverter output, a filter circuit is employed. In conventional inverters, LC filter is used but this design employs a T-LCL Immitance Converter. The filter circuit consists of two inductors L_1 and L_2 and a capacitor C in the shape of a T as shown in Fig-13.

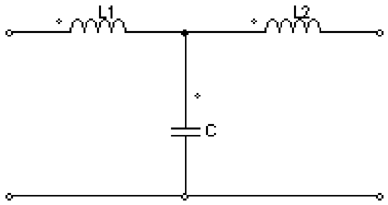

Fig-13: T-LCL Filter

From the derivation of the equation of the output current of the filter, I_2 is found as [4]:

$$I_2 \cong \frac{V_1}{Z_0}\left[1-\frac{Z_2}{QZ_0}\right].....(4)$$

Where V_1 is the input voltage, Z_2 is the load impedance and Q is the quality factor,

$$Q=\frac{\omega L}{r}..........(5)$$

With $\omega=2\pi f$ as the angular frequency, r is the internal resistance of the inductor and Z_0 is the characteristic impedance determined by L and C,

$$Z_0=\sqrt{\frac{L}{C}}\;....... \qquad (6)$$

When *r* is negligible or zero, the quality factor becomes infinity. Under this condition,

$$I_2=\frac{V_1}{Z_0}........(7)$$

From eq. (7), it is observed that the output of the T-LCL filter is independent of load. Therefore this filter is capable of not only reducing harmonics but is also helpful in providing a constant current to the load.

The values of L and C of T-LCL filter (considering Butterworth type) is calculated using the cut-off frequency condition of low pass filters, i.e.

$$Z_0=\frac{1}{2\pi f_c C}........(8)$$

Where Z_0 is the characteristic impedance given by Eq. (6). Assuming Z_0 as 30Ω and choosing f_c=50Hz, we get the values of L and C using Eqs. (6) and (8),

$$C=\frac{1}{2\times\pi\times 50\times 30}\approx 0.106\text{mF}$$

And L=C Z_0^2 =0.106$\times 10^{-3}\times 30^2\approx$95.4mH

4. POWER TRANSMITTING

The real power supplied by the inverter is given by [2]

$$\text{Real Power } P=\frac{|V_{inv}|\times|V_{grid}|}{Z_t}\sin\ \phi,$$

Where,
Z_t= Linking line impedance
V_{inv}= Output voltage of inverter
V_{grid}= Grid voltage
ϕ= Angle between V_{inv} and V_{grid}.

From the above equation, it is clear that maximum real power can be transmitted into the grid for ϕ=90 degrees. Since the voltage angle of the inverter must lead grid voltage angle to transmit power into grid, the sampled sine wave from the grid is passed through a phase shifter circuit to make the leading adjustments. As mentioned earlier, to send maximum power into the grid, the leading angle must be 90 degrees. But in practice, due to stability reasons the angle is kept somewhat less than 90 degrees. [5]

5. SIMULATION RESULTS

The PSIM simulation results are provided in this section. the simulation results are given at the nominal speed of 12m/s to generate maximum power.

Fig-14 shows the output voltages of the permanent magnet synchronous generator. The frequency of the distorted sinusoidal waves is 20 Hz and hence the need for the rectifier arises for converting it into DC voltage and then the conversion of DC to 50Hz(grid frequency) AC voltage.

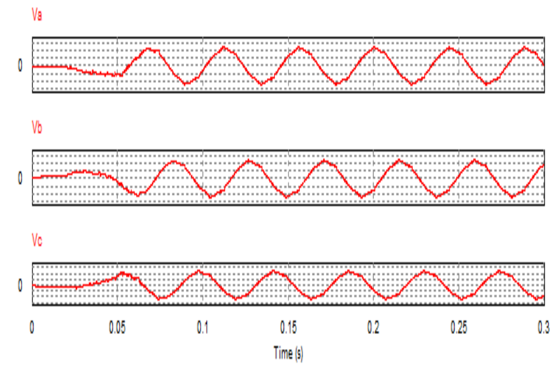

Fig-14: Output phase voltages of Synchronous generator

Fig-15 shows the DC output of the rectifier which is 250V. Fig-16 shows the output of the Boost converter which steps up 250V to the desired 312V.

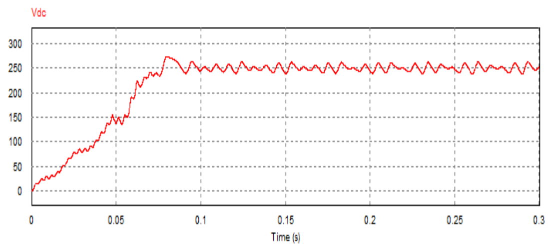

Fig-15: The DC output voltage of the Rectifier

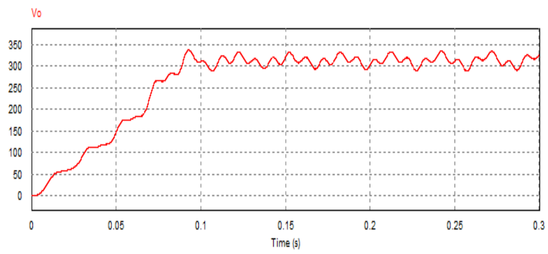

Fig-16: The DC output voltage of the Boost Converter

Fig.-17 shows the AC output voltage waveform in the absence of any filter. The waveform is non-sinusoidal and contains lots of harmonics. To eliminate these harmonics, a low pass T-LCL filter is employed at the output of the inverter which produces a pure, sinusoidal voltage.

After filtering, we obtained a pure sinusoidal voltage of frequency 50Hz and of rms value 220V as shown in Fig-18.

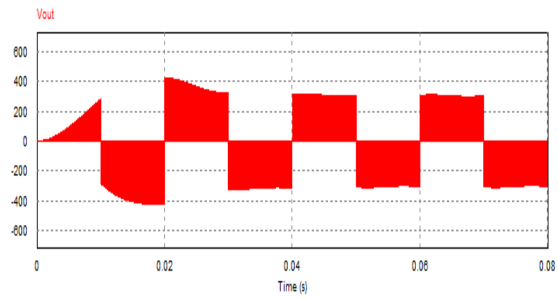

Fig-17: Output voltage without filtering in PSIM.

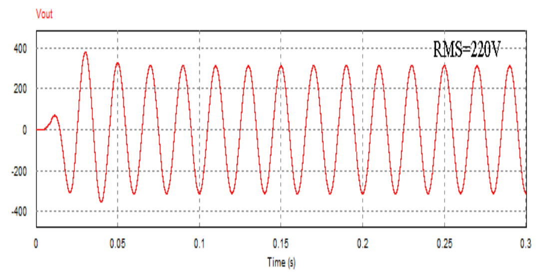

Fig-18: Output voltage after filtering in PSIM

Since this waveform has an amplitude of 312V (220V rms) and a frequency of 50 Hz, this output can be used for sending real power to the grid. The Total Harmonic Distortion (THD) of this inverter output is 0.01% which is much less than the IEEE 519 Standard.

CONCLUSIONS

In this paper, the design of a wind power generation system using a permanent magnet synchronous machine along with a boost regulator and a transformer-less Step down circuit has been presented. The PSIM simulation results show that a 220V, 50Hz output voltage can be obtained using the particular set-up. The total harmonic distortion (THD) was found to be 0.01% which is much lower than the IEEE 519 standard. Thus the proposed wind power generation system can be used for sending power to the grid.

In future, the simulation results would be expanded and variable wind speeds would be taken into account.

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