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Design of a Hybrid Power Generation System Employing Boost Converters and a Transformer-less Inverter Switching Circuit

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Abstract

This paper presents the design of a transformer-less, hybrid power generation system employing solar and wind energy. The solar energy conversion section consists of a photovoltaic (PV) array, a boost converter, an H-bridge inverter, a transformer-less inverter switching circuit and a T-LCL filter. The wind energy conversion section consists of a wind turbine, a permanent magnet synchronous machine, a three phase diode rectifier, a boost converter, an H-bridge inverter, a transformer-less inverter switching circuit and a T-LCL filter. Both the sections are connected in parallel so that even in the absence of one form of energy, the hybrid configuration can still deliver real power to the national grid. A common transformer-less switching circuit is employed for sending gate pulses to the H-Bridge inverters of both the sections. This is done to ensure proper synchronization. The switching technique of the inverters 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 the Total Harmonic Distortion (THD) of the output voltage to less than 0.2% and minimizes the circuit size. The T-LCL filters not only reduce the harmonics of the inverter outputs but also provide a nearly constant output current thereby stabilizing the system. The hybrid system setup and the simulation results were obtained using the PSIM software. Index Terms : Photovoltaic(PV) array, Wind Turbine, Permanent Magnet

Synchronous Machine, Boost Converter, Inverter, Sinusoidal Pulse Width modulation (SPWM), T-LCL filter.

1. Introduction

Day by day, the natural sources of producing electricity such as coal, oil, etc. are being exhausted. But the demand for energy is increasing. To meet this increased energy demand, more and more efforts are being put into the use of renewable energy sources. There are many sources of renewable energy of which solar and wind are most common.

In photovoltaic (PV) systems, solar energy is converted into electrical energy through PV arrays. There are two mandatory tasks in a PV system (1) extracting maximum energy from PV arrays. (2) Using the most reliable, highly efficient and cost effective configuration for the power converter to supply pure sinusoidal current to the grid [1 and 5]. Wind energy can also be used for generating power. Wind energy systems are particularly useful in remote areas where grid connection is not accessible or not feasible. In those places, stand-alone wind power generation systems can be used for meeting the consumer load demands in a cost-effective manner.

In this paper, a topology has been proposed that that utilizes both these renewable energy sources. Both the systems are connected in parallel so that even if one of the two systems is unable to operate at rated capacity, the hybrid configuration is still able to deliver real power to the national grid. In conventional solar or 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 [3]. Hence, in this paper a transformer-less power generation topology has been proposed.

The block diagram for the proposed hybrid power generation system is shown in Fig-1.

The solar energy conversion section consists of five main parts (1) A PV array for solar energy to electrical energy conversion. (2) A DC-DC boost converter to step-up PV array voltage to grid level. (3) An H-bridge DC-AC inverter to obtain AC voltage. (4) A T-LCL filter to suppress the harmonics of the inverter output and to produce a pure sinusoidal wave. (5) A transformer-less step-down AC-DC conversion circuit which is used to produce the gate pulses for inverter switching by combining SPWM and square wave signals.

The wind energy conversion section consists of (1) a 3-phase permanent magnet synchronous machine (PMSM) which has 3-phase windings on the stator and a permanent magnet on the rotor [6,8,9]. (2) A 3-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 filter to suppress the harmonics of the inverter output and to produce a pure sinusoidal wave. (6) A transformer-less step-down AC-DC conversion circuit which is used to produce gate pulses for inverter switching by combining SPWM and square wave signals. This circuit is the same one that is used in the solar energy conversion section. The same switching circuit ensures proper synchronization between the two systems.

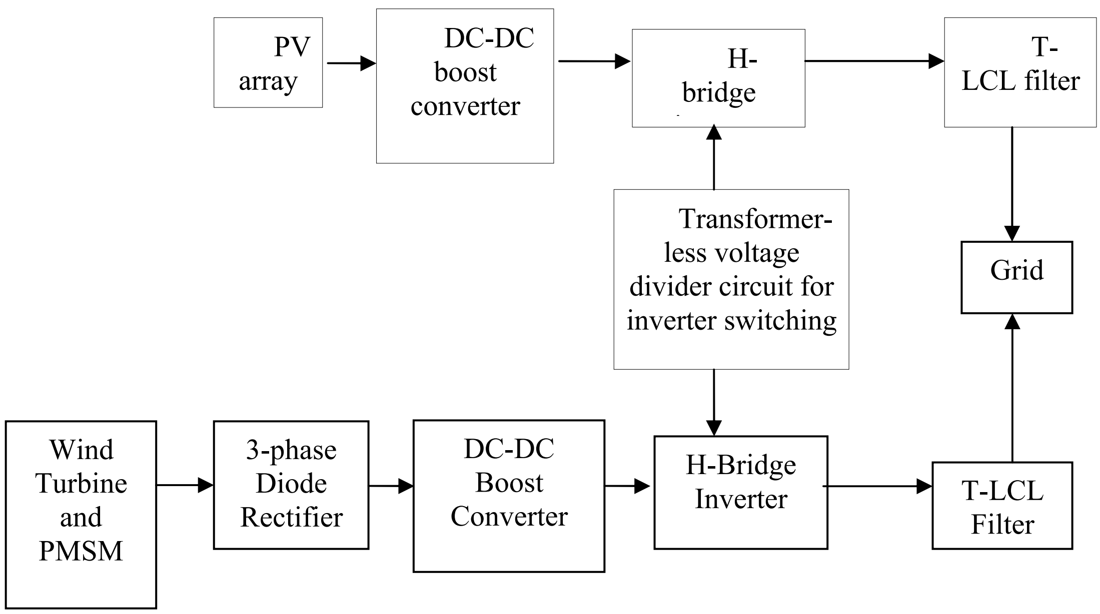

Fig. 1: Block diagram of the hybrid power generation system.

2. Design of the Solar Energy Conversion Section

In this section, design of the components required for the conversion of solar energy to electrical energy is presented. The components essentially include the Boost Converter, the transformer-less circuit for inverter switching and the T-LCL filter.

2.1 Design of the 24-312V DC-DC Boost Converter

In this section, the design of a dual stage DC-DC boost converter is presented which steps up the PV array voltage to a fixed high level grid voltage (312V peak or 220V rms in Bangladesh). The design parameters of the Boost Converter are listed in Table-1

Table 1: Design of the Boost Converter.

Symbol	Actual meaning	Value
Vin	Given input voltage	24V
Vout	Desired average output voltage	312V
fs	Switching frequency of converter	20KHz

IL,max	Maximum inductor current	278A
ΔiL	Estimated inductor ripple current(2% of IL,max)	5.55A
ΔVout	Desired output voltage ripple(0.015% of output voltage)	46mV
Iout	Maximum output current	4.5A

The duty cycle is,

$$D=1-\frac{V_{in}}{V_{out}}=1-\frac{24}{312}\approx 0.923$$

The inductor value is selected using the following equation [7]

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

$$\text{So, } L=\frac{24\times(312-24)}{5.55\times 20000\times 312}\approx 200\mu\text{H and}$$

The capacitor value is selected using the following equation [7]

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

$$\text{So, } C=\frac{4.5\times 0.923}{20000\times 0.046}\approx 4.5\text{mF and}$$

The output of the boost converter using PSIM simulation is shown in Fig-2. The figure shows that 24V has been boosted up to 312V.

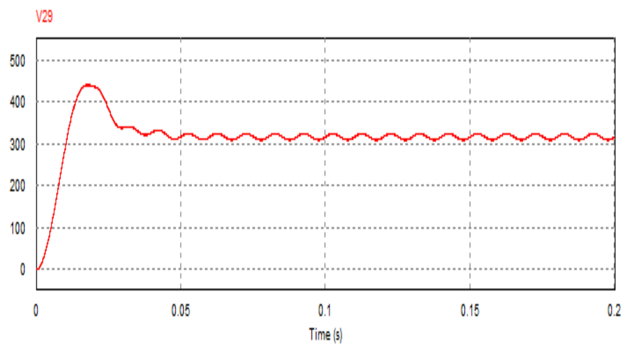

Fig. 2: Boost converter output.

2.2 Design of the Inverter Switching Circuit

The H-Bridge DC-AC inverter has two parallel MOSFET gates.

This is shown in Fig-3. A combination of analog and digital circuits is used to produce the gating pulses of the MOSFETs.

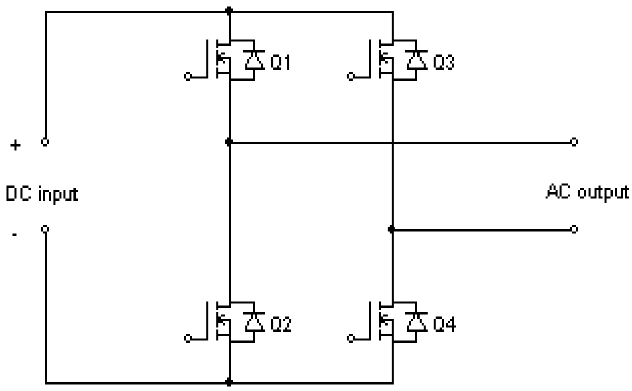

Fig. 3: H-Bridge Inverter.

In conventional inverters, only one type of switching technique is used. But this proposed design 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 voltage divider circuit is shown in Fig. 4.

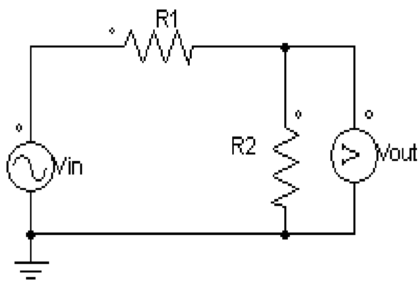

Fig. 4: Voltage divider circuit

Using voltage divider equation, [7]

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

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

The input voltage V_{in} (312Vpeak; 220V rms) and the output voltage V_{out} (7.07Vpeak; 5V rms) are shown in Fig-5 and Fig-6 respectively. The figures show that 312V has been stepped down to 7.07V.

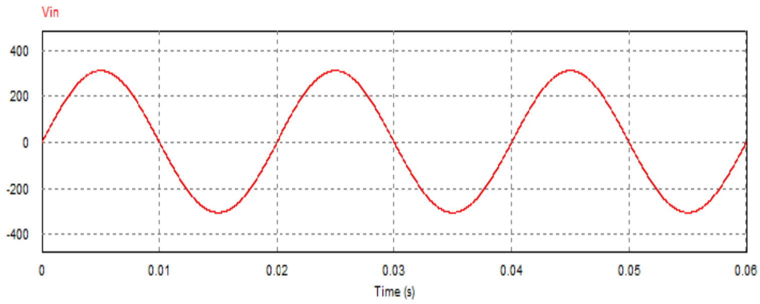

Fig. 5: 312V peak (220V rms) input voltage.

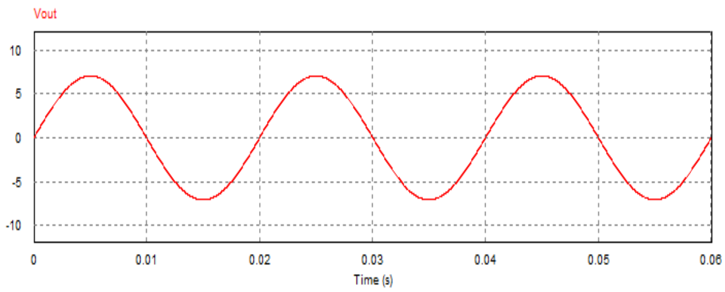

Fig. 6: 7.07V peak (5V rms) output voltage.

The sampled sine wave is used to generate the SPWM signal thus ensuring that the output voltage from the inverter will have the same frequency as the grid frequency [2]. After sampling, the sine wave is rectified with a full-wave rectifier, the output of which is shown in Fig-8.

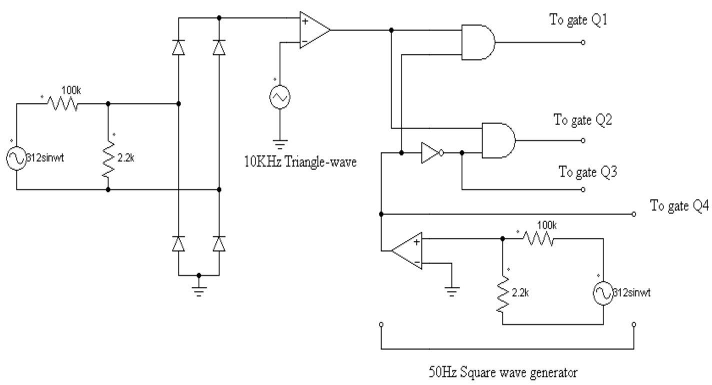

Fig. 7: Control circuit of the proposed inverter.

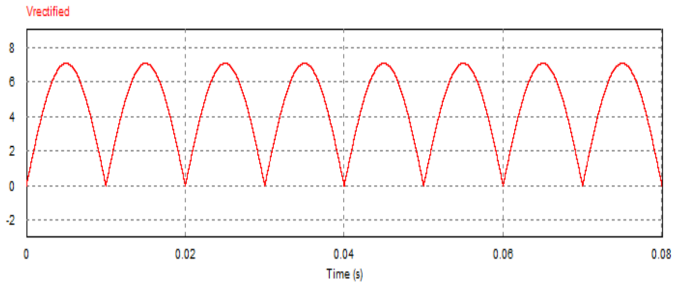

Fig. 8: Rectified sine wave.

In addition, a high frequency triangle wave of 10KHz is used. Then the two signals are passed through a comparator to produce the SPWM signal as shown in Fig-9. A 50 Hz square wave, also produced by sampling the grid voltage, is used 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.

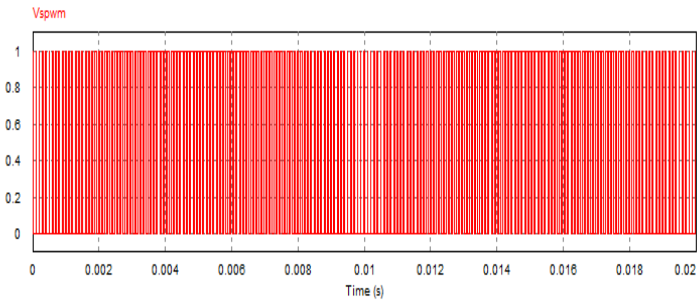

Fig. 9: SPWM signal.

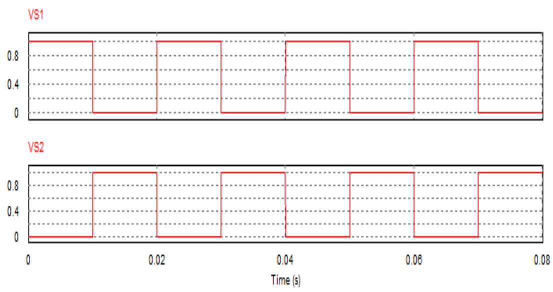

Fig. 10: Square wave signals.

The inverter requires four switching signals since it has four MOSFETs. To produce the four signals, a logic 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.

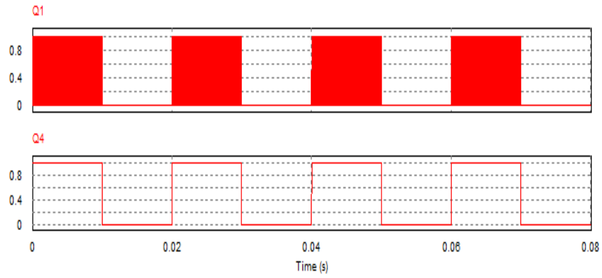

Fig. 11: Switching signal from control circuit for MOSFETs (Q1 and Q4).

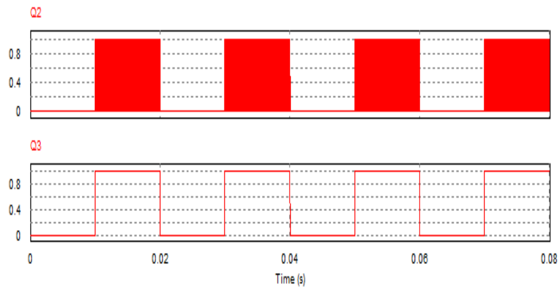

Fig. 12: Switching signal from control circuit for MOSFETs (Q2 and Q3).

2. 3 Design of the Filter Circuit

To remove the harmonics from the inverter output, a filter circuit is employed. In conventional inverters, LC filters are used but this design employs a T-LCL filter. 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.

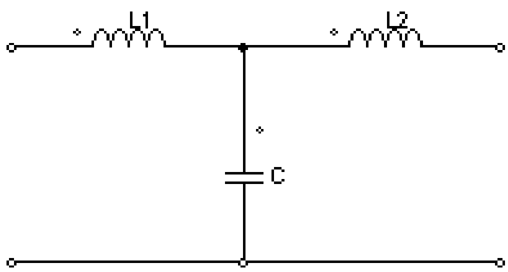

Fig. 13: T-LCL Filter.

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

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

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

$$Q=\frac{\omega L}{r}..........(2)$$

With ω=2πf as the angular frequency, r is the internal resistance of the inductor and Z_0 is the characteristic impedance determined by L and C,

$$Z_0=\sqrt{\frac{L}{C}}\ \cdots\cdots \qquad (3)$$

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

$$I_2 \ =\frac{V_1}{Z_0}........(4)$$

From eq. (4), it is observed that the output of the T-LCL filter is independent of load. Therefore this filter, besides reducing harmonics, can also provide a constant current to the load.

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

$Z_0=\dfrac{1}{2\pi f_c C}........(5)$ where Z_0 is the characteristic impedance given by Eq. (3).

Assuming Z_0 as 30Ω and choosing f_c=50Hz, we get the values of L and C using Eqs. (3) and (5),

$$C=\frac{1}{2\times\pi\times 50\times 30}\approx 106\mu\text{F}$$

And $L=CZ_0^2=106\times10^{-6}\times30^2\approx 95.40\text{mH}$

3. Design of the Wind Energy Conversion Section

In this section, design of the components required for the conversion of wind energy to electrical energy is presented. The components essentially include a 3-phase Permanent Magnet Synchronous Machine (PMSM), a 3-phase Diode Bridge Rectifier, a Boost Converter, a transformer-less voltage divider circuit for inverter switching and a T-LCL filter.

3.1 Permanent Magnet Synchronous Machine

A 3-phase synchronous generator (or permanent magnet synchronous generator) has been used in this design [8]. A 3-phase permanent magnet synchronous machine has 3-phase windings on the stator and permanent magnet on the rotor as shown in Fig-14, where a,b and c are the stator winding terminals, n is the neutral point and the shaft node is used for connecting with the high speed mechanical shaft. The back emf of the generator is sinusoidal. The 3-phase AC output of the PMSM is shown in Fig-15.

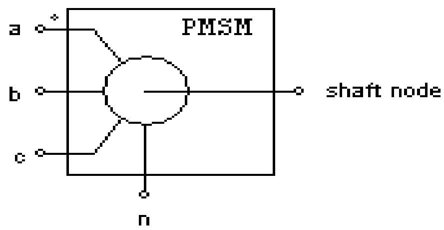

Fig. 14: Permanent Magnet Synchronous Machine.

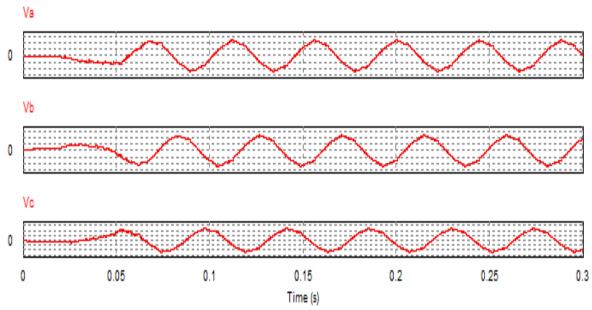

Fig. 15: Output phase voltages of Synchronous generator.

3.2 3-phase Diode Bridge Rectifier

The variable frequency sinusoidal voltages produced by the generator cannot be directly supplied to the grid. They first 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-16. The rectified DC output of the diode bridge rectifier is shown in Fig. 17.

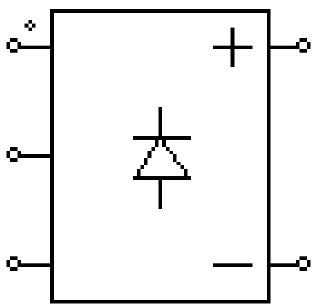

Fig. 16: 3-phase Diode Bridge Rectifier.

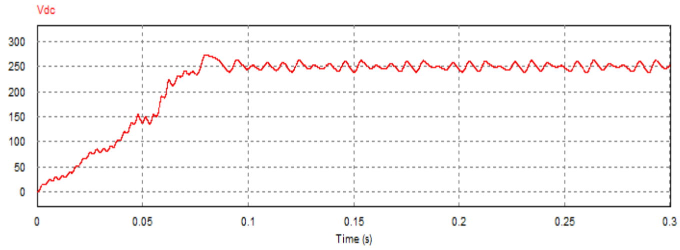

Fig. 17: The DC output voltage of the Rectifier.

3.3 Design of the 250-312V DC-DC Boost Converter

The rectifier output is then converted into 312V DC by means of a boost converter [7], as shown in Fig-18. The boost converter's output should be 312V since the grid voltage in Bangladesh has an amplitude of 312V (220V rms). The output voltage of the boost converter is given by:

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

Where V_{out}=average output voltage, V_{in}=input voltage and D=duty cycle.

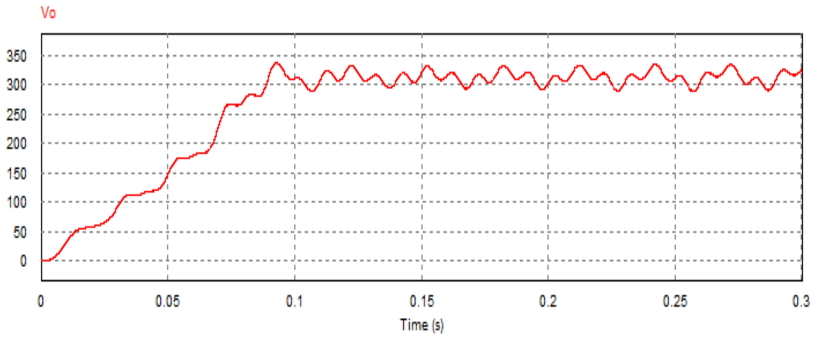

Fig. 18: The DC output voltage of the Boost Converter.

The design parameters of the boost converter are given in Table 2.

Table 2: Design of the 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	6.4A
ΔiL	Estimated inductor ripple current(2% of IL,max)	0.128A
ΔVout	Desired output voltage ripple(0.022% of output voltage)	69mV
Iout	Maximum output current	4.5A

The duty cycle is,

$$D = 1 - \frac{V_{in}}{V_{out}} = 1 - \frac{250}{312} \approx 0.20$$

The inductor value is selected using the following equation [7]

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

$$\text{So, } L = \frac{250 \times (312 - 250)}{.128 \times 20000 \times 312} \approx 19.40\text{mH}$$

The capacitor value is selected using the following equation [7]

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

$$\text{So, } C = \frac{4.5 \times 0.2}{20000 \times 0.069} \approx 652\mu\text{F}$$

3.4 Design of the Inverter Switching/Control Circuit

This is the same transformer-less switching circuit that has been described in section 2.2. A common switching circuit has been used to ensure proper synchronization between the two sections

3.5 Filter Circuit

To reduce the harmonics from the inverter output, a T-LCL filter circuit is employed. 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-19.

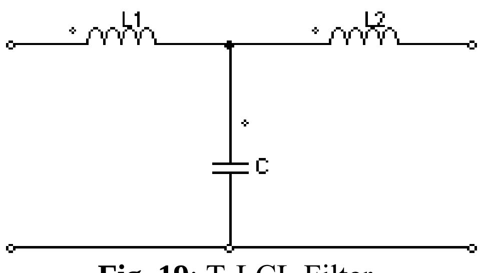

Fig. 19: T-LCL Filter.

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

$Z_0 = \dfrac{1}{2\pi f_c C}$........(8) where Z_0 is the characteristic impedance given by Eq. (8). Assuming Z_0 as 30Ω and choosing f_c=50Hz, we get the values of L and C as

$$C = \frac{1}{2 \times \pi \times 50 \times 30} \approx 106\mu\text{F}$$

And $L = C Z_0^2 = 106 \times 10^{-6} \times 30^2 \approx 95.40\text{mH}$

4. Power Transmitting

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

Real Power $P = \frac{|V_{inv}| \times |V_{grid}|}{Z_t} sin \quad \phi$, 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 □=90 degrees. Since the voltage angle of the inverter must lead the 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. [2]

5. Simulation Results

The PSIM simulation results are provided in this section. Fig-20 shows the output voltage waveform in the absence of any filter. The waveform is non-sinusoidal and contains plenty of harmonics. To remove these harmonics, low pass T-LCL filters are employed at the output of the inverters which produce a pure, sinusoidal voltage.

After filtering, we obtained a pure sinusoidal voltage of frequency 50Hz and of rms value 220V as shown in Fig-21.

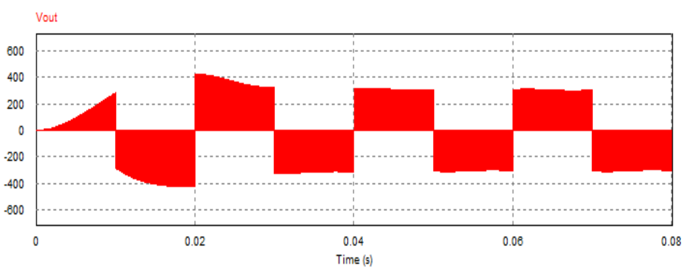

Fig. 20: Output voltage without filtering in PSIM.

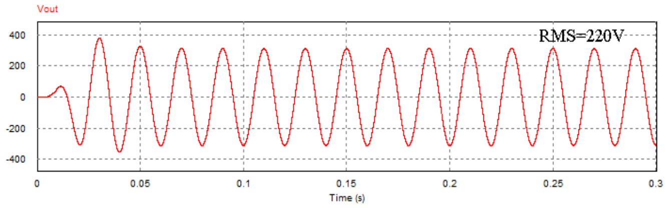

Fig. 21: Output voltage after filtering in PSIM.

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 0.015% which is much less than the IEEE 519 Standard.

Table-3 shows the amount of real power delivered to the grid by the hybrid system with the variation of load. The contributions of the individual sections (solar and wind) are also presented in the table.

Table 3: Power delivered for different loads.

Load	**Total power delivered by the hybrid system (KW)**	**Contribution of the solar energy conversion section (KW)**	**Contribution of the wind energy conversion section (KW)**
5Ω	0.72	0.46	0.26
10Ω	1.37	0.77	0.60
15Ω	1.96	1.05	0.91
20Ω	2.48	1.28	1.2
25Ω	2.9	1.48	1.42
30Ω	3.14	1.65	1.42

6. Conclusion

This paper presented the design of a hybrid power generation system combining solar and wind energy. Since the system was designed to supply real power to the grid, it needed to satisfy the grid synchronization conditions. That means that the inverter outputs must had an rms value of 220V at a frequency of 50Hz. The PSIM simulation results confirm these. The power loss in the transformer-less circuit is only 473mW which is much lower than the loss incurred with a transformer. The total harmonic distortion of the output voltage is 0.015% which is much lower than the IEEE 519 standard. Further, because the solar and wind power conversion sections are connected in parallel, even in the absence of one form of energy the system is able to deliver real power to the grid. Therefore the proposed design is highly efficient, cost-effective and is worthy of practical implementation.

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Biography

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He has been working as a Lecturer in the Department of Electrical and Electronic Engineering f Independent University, Bangladesh (IUB) since September 2012. His research interest includes power systems, power electronics and renewable energy.