Design and Analysis of a Hybrid Solar-Wind Energy System Using CUK & SEPIC Converters for Grid Connected Inverter Application

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Abstract: *This paper introduces design and analysis of a hybrid solar-wind energy system using CUK and SEPIC converters. This design lets two sources supply the load individually or simultaneously depending on the availability of the energy sources. The proposed design deploys a switch mode CUK converter and a switch mode SEPIC converter. The designed CUK and SEPIC converters have been deployed to run a single-phase full-bridge grid connected inverter for residential application. The proposed design has been mathematically modeled which has been simulated via PSIM software as well and finally the results have been presented to confirm the effectiveness of this hybrid system.*

Key words: *Solar system, Wind system, CUK converter, SEPIC converter, Hybrid system, GTI*

1. Introduction

Renewable Energy Sources are those energy sources which are not destroyed rather energy is harnessed. Human use of renewable energy requires technologies that harness natural phenomena such as sunlight, wind, waves, water flow, and biological processes such as an anaerobic digestion, biological hydrogen production and geothermal heat. Among the above mentioned sources of energy there have been a lot of developments in the technology for harnessing energy from the Solar & wind. Solar and wind energy are non-deflectable, site dependent, non-polluting, and potential sources of alternative energy options. Many countries are pursuing the option of wind energy conversion systems as an effort to minimize their dependency on fossil-based nonrenewable fuels [1-3].

Commercial wind turbine generators can be deployed for producing large amounts of power in MW scale at a very low price. But presence of wind is an extremely unpredictable factor as it has very high cut-off point particularly in situations like- tsunami, cyclone, and tornadoes while in general very low the cut-in point to start off a wind mill. In solar energy, inconsistency of irradiation levels is also a concern because of natural conditions such as shadows cast by clouds, rains, objects, trees etc.

Thus intermittent natures of the wind and solar energy make them unreliable sources of energy. Hence, hybrid PV and wind energy system can swell up system efficiency and reliability significantly- when one source is unavailable or insufficient in meeting the load demands, the other energy source can compensate the load demand.

Several alternatives architectures for hybrid PV-wind configuration exit, such as DC/DC boost, DC/DC buck and DC/DC buck-boost converter [1-5]. These configurations inject high frequency current harmonics [HFCH] into the hybrid system. But boost, buck and buck-boost converters do not have the capability to eliminate HFCH. So the system requires passive input filters to reduce HFCH which makes the system more bulky and expensive. Moreover in a conventional inverter, transformer is used to match the inverter output voltage with the utility grid voltage. But the limitations are that transformers are immense, heavy weighted and costly equipment. Otherwise transformer highly influences the enhancement of Total Harmonic Distortion (THD) in inverter [1].

In this paper, PV-wind energy has been integrated together using fusion of CUK-SEPIC converters, so that if one of the sources is unavailable, then the other source can compensate for it and these converters convert unregulated voltage of PV-wind to a fixed high level regulated voltage which is the same as the grid value (312V peak or 220V rms in Bangladesh) [1]. Hence these converters topology has recommended instead of other configurations in order to eliminate the HFCH. They can also support individual and simultaneous operations. PV energy is the input to the CUK converter and wind energy is the input to the SEPIC converter. The average output voltage produced by the system will be the sum of the inputs of these two systems. The inverter control circuit and grid synchronization methods have been portrayed in this paper in detail. The inverter's parameters have been modeled mathematically, and the designed inverter has been simulated via PSIM software to verify the inverter's output performances and viability.

2. Design of proposed solar system

At first, under Standard Test Condition (STC) Sanyo HIP-210HKHA6 panel with 210W maximum output power has been tested [6]. At STC condition of 25^0-30^0 temperature and irradiance of 1000 W/m^2 the panel has been stimulated which output voltage is 48V. Table 1 shows the system parameters of photovoltaic module.

Table1. System parameters of PV module

Parameter	***Value***
Manufacturer	Sanyo
Solar Panel Model	HIP-210HKHA6
Number of cell	100
Voltage at Maximum power	48V
Current at maximum power	3.55V
Series Resistance Rs	0.008Ω
Shunt Resistance Rsh	1KΩ
Short circuit Current (Ix)	3.8 A
Open circuit Voltage	21.5V
Characteristic Constant (b)	0.0773

A.Design of Cuk converter

This section describes the design of a CUK converter for converting unregulated voltage of PV array to a fixed high level regulated voltage [1]. CUK is a type of DC-DC converter which allows the output voltage to be greater than or less than its input voltage. Only the step up capability has been considered here. With respect to common terminal, the output polarity is negative and always works in the continuous conduction mode. When S_1 is turned on, diode D_1 becomes reverse biased and the current through both L_1 and L_2 is increased and the power is delivered to the load. After turned off S_1, D_1 becomes forward biased and the capacitor C_1 is recharged [7]. The design parameters of the CUK converter are listed in Table 2.

Table2. Design parameters of CUK converter

Sym.	**Actual Meaning**	**Value**
V_{in}	Given input voltage	48V
V_{out}	Desired average output Voltage	118V
f_s	Minimum switching frequency	30KHz
ΔI_1	Estimated inductor ripple current of L_1	5.5A
ΔV_{C1}	Desired voltage ripple of capacitor C1	170mV
Is	Average Input current, $\frac{D \times I_{out}}{1-D}$	2.19A

B.Duty Cycle

Maximum duty cycle of CUK converter is,

$$D_{CUK} = \frac{V_{out}}{V_{out}+V_{in}} \times \eta = \frac{118}{118+48} \times 0.95 \approx 65\%$$

C. Inductor Selection

The CUK converter utilizes an input inductor, which enables low voltage ripple and RMS current on the input side. The following equation is good estimates for choosing the right input value of inductors for the CUK converter [7]:

$$L_1 = \frac{D \times V_{in}}{f \times \Delta I_1} = \frac{0.65 \times 48}{30000 \times 5.5} \approx 190\ \mu H$$

D. Capacitor Selection

The input and output capacitor must be rated to handle its RMS current. The following equation is used to adjust the input capacitor value for a desired output voltage ripple [7].

$$C_1 = \frac{I_S \times (1-D)}{\Delta V_{C_1} \times f} = \frac{2.19 \times (1-0.65)}{0.17 \times 30000} \approx 150\ \mu F$$

*E.*The Designed 48-118V CUK Converter

The power converter which consists of PV cell, two inductors, two capacitors and one PWM gate pulses to drive the MOSFETs is shown in Fig. 1. The output of the designed CUK converter simulated in PSIM is shown in Fig.2 which indicates that the output of the CUK converter is118V DC.

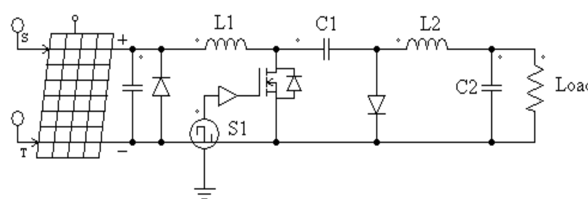

Fig.1. PSIM simulation circuit of the CUK converter using the designed circuit parameters

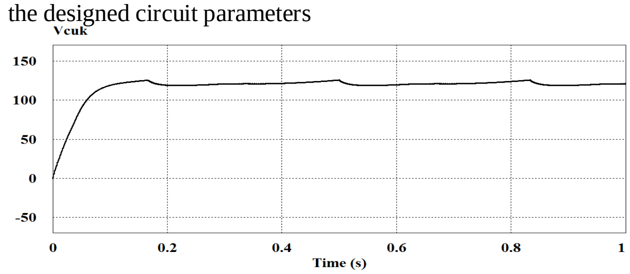

Fig.2. Simulated output of CUK converter

3. Design of proposed wind system

Electricity is generated, when moving air exerts force on the propeller like blades around a rotor of the wind turbines. The rotor is connected to a gearbox which is responsible for increasing the rotational speed from 10-60 rpm to 1200-1800 rpm. A generator which is connected with the high speed shaft is then used for generating electricity [8-10]. The mechanical power from the wind turbine is given by $Pm = \frac{1}{2}[\rho AC_p(\lambda,\beta)V_w^3]$ (1)

Where ρ is air density, *A* is rotor swept area, $C_p(\lambda,\beta)$ is power coefficient function, λ is tip speed ratio, β is pitch angle, v_w is wind speed.

The design and the performance of the proposed wind power generation system have been simulated through the PSIM software. The input has been by means of the built-in wind turbine block of the software [9]. It was then connected to the generator via the gearbox and the electrical-mechanical interface. The various features of the whole systems are discussed in details in the following sections. Table 3 shows the system parameters of 2.5KW Aeolos Wind turbine.

Table3. System parameters of wind turbine converter

Parameter	Value
Nominal Output Power	2.5KW
Base Wind Speed	12m/s
Base Rotational Speed	10m/s
Initial Rotational Speed	0.8 rpm

A.AC Synchronous Machine

The generator used for the design is a 3-Phase Permanent Magnet Synchronous Machine (PMSM). A 3-phase permanent magnet synchronous machine has 3-phase windings on the stator, and permanent magnet on the rotor. The variable frequency sinusoidal voltages are produced by the generator and then these voltages need to be rectified into DC and then converted into ac voltages of desired frequency for connecting with utility grid. The rectification is done by 3-phase bridge rectifier [9-10].

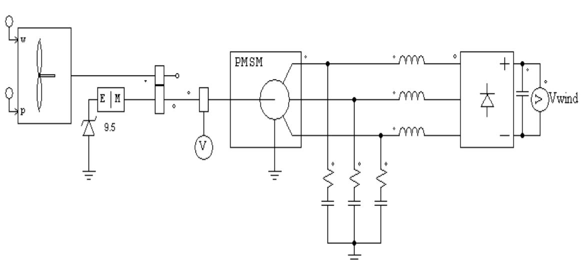

Fig.3. The generator sub-circuit with wind turbine & 3-phase bridge rectifier

B.Design of SEPIC Converter

In this section the design of a SEPIC converter for converting unregulated voltage of wind turbine to a fixed high level regulated voltage has been illustrated. A type of DC-DC converter which provides an output voltage that is less than or greater than the input voltage. Here only the step up capability is considered. With respect to common terminal, output polarity of the converter is positive [11]. Any DC current path between the input and the output is blocked by the capacitor C_3 and the anode of the diode D_3 is connected to a defined potential. Tuning on S_2 causes the input voltage V_{wind} to be appeared across the inductor L_3 and the current I_{L3} is increased. The voltage across the capacitor C_3 is appeared across L_2 and energy is stored in the inductor L_2. During this period the diode D_3 is reverse biased. But D_3 conducts when S_2 is turned off. The energy stored in both L_3 and L_2 is delivered to the output and for the next period C_3 is recharged again by L_3. The design parameters of the SEPIC converter are listed in Table 4.

Table4. Design parameters of SEPIC converter

Sym.	Actual Meaning	Value
V_{in}	Given input voltage	70V
V_{out}	Desired average output Voltage	206V
f_s	Minimum switching frequency	30KHz
ΔI_3	Estimated inductor ripple current of L_3	8A
ΔI_2	Estimated inductor ripple current of L_2	1.28A
ΔV_{C3}	Desired voltage ripple of capacitor C3	0.5V

C. Duty Cycle

Maximum duty cycle of SEPIC converter is,

$$D_{sepic} = \frac{V_{out}+V_D}{V_{in}+V_{out}+V_D} \times \eta = \frac{206+0.7}{70+206+0.7} \times 0.95 \approx 75\%$$

D. Inductor Selection

In the SEPIC converter, a smoothing input inductor is used to reduce current ripple in the input side of the circuit. The following equation is a good estimate for choosing the right inductor value for the SEPIC converter

$$L_3 = \frac{V_{in}D}{\Delta I_{L3} f} = \frac{70 \times .75}{8 \times 30000} \approx 200 \ \mu H$$

Current ripple in inductor is;

$$\Delta I_L = \frac{I_{out} \times V_{out}}{V_{in}} \times 1.3 = \frac{2.06 \times 206}{70} \times 1.3 \approx 8$$

E.Capacitor Selection

The basic selection of the input capacitor is based on the ripple current, ripple voltage and loop stability considerations. In the presented design, the following equation can be used to adjust the input capacitor values for the SEPIC converter:

$$C_3 = \frac{Iout \times D}{\Delta V_{C3} \times f} = \frac{2.06 \times 0.75}{0.5 \times 30000} = 105 \mu F$$

F.Output Inductor and Capacitor Selection

The design of the hybrid system internal compensation assumes L_2 is equal to 200 μH to limit ripple current at output side. The average differential equation for output capacitor C_2 is specified below:

$$C\frac{dv_c}{dt} = (1-D)i_L - \frac{V_{out}}{R} \quad (3)$$

By solving the equation (3) the output capacitor can be selected as C_2=200μF where V_{ripple}=2% of output voltage. Thus, the output capacitor is responsible for desire ripple voltage, ripple current and loop stability.

G. The Designed 70-206V CUK Converter

The power converter which consists of wind voltage, two inductors, two capacitors and one PWM gate pulses to drive the MOSFETs is shown in Fig.4. The output of the designed SEPIC converter simulated using PSIM is shown in Fig.5 which indicates that the output of the SEPIC converter is 206V DC.

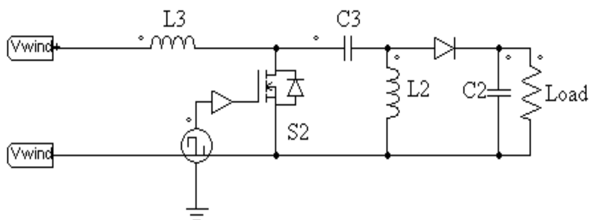

Fig. 4. PSIM simulation circuit of the SEPIC converter using the designed circuit parameters

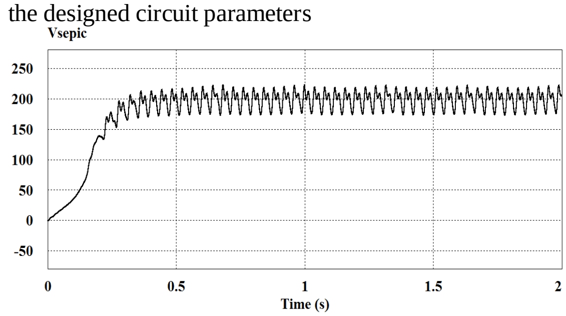

Fig.5. Simulated output of SEPIC converter

4. Proposed Wind-PV Hybrid system

Solar cell is fed to the CUK converter and wind turbine is fed to SEPIC converter. By reconfiguring the two existing diodes D_1 and D_2 from each converter and sharing the CUK output inductor using the SEPIC converter the converters are fused together. Due to this configuration each converter can operate individually when one source is unavailable. From Fig.6 it has been shown that V_{dc} is simply the sum of the two inputs of the Cuk and SEPIC converter and V_{dc} can be controlled by D_1 and D_2 simultaneously.

If only PV source is available, the circuit operates as a CUK converter and the voltage conversion relationship is expressed by:

$$\frac{V_{dc}}{V_{solar}} = \frac{D_1}{1-D_1}$$

If only wind source is available, the circuit acts as a SEPIC converter and the voltage conversion relationship is expressed by:

$$\frac{V_{dc}}{V_{wind}} = \frac{D_2}{1-D_2}$$

Solving this circuit, the output DC bus voltage is given by:

$$V_{dc} = \frac{D_1}{1-D_1}V_{solar} + \frac{D_2}{1-D_2}V_{wind}$$

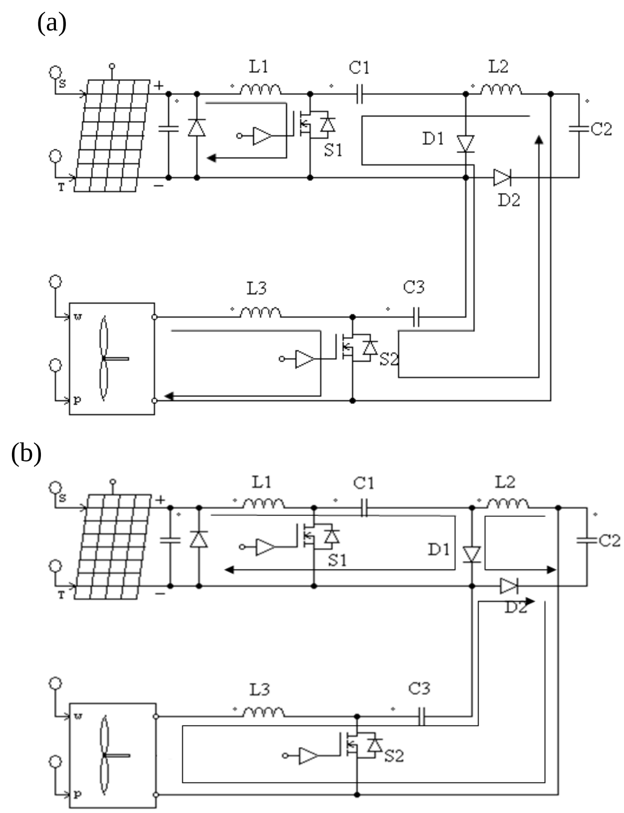

Fig.6. Current direction in hybrid system (a) When S1 and S2 is in on state (b) When S1 and S2 is in off state

A.DC Output of hybrid system

The simulated output of the designed hybrid system using PSIM is shown in Fig.7 which indicates that the output of the hybrid system is 312V DC which is the same as the grid value (312V peak or 220V RMS in Bangladesh).

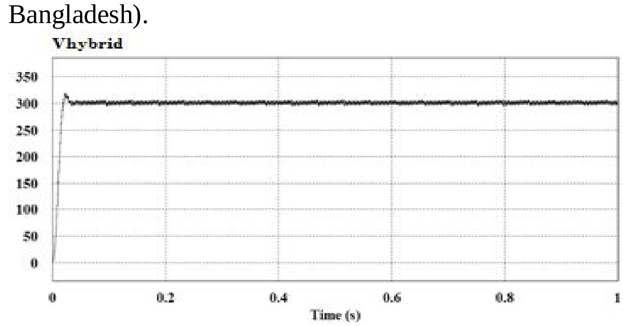

Fig.7. Simulated output of hybrid system

5. Proposed grid tie inverter

A.Grid Synchronization

The output voltage of a grid-tie inverter should maintain some fixed requirements so that it can provide power to utility grid [1], [12]. The requirements are given below:

I The output voltage amplitude of the grid-tie inverter should be same as the grid amplitude.

II The frequency of inverter should be same as the grid frequency (50Hz in Bangladesh).which is

III The phase of inverter should match with the grid.

To fulfill the grid synchronization, the sampled 5V ripple DC is used to generate the SPWM signal which ensures that the output voltage from GTI will have the same frequency as the utility grid. During synchronization, the inverter produces output which is in phase with the grid by employing a 50Hz square-wave pulse taken from the grid and applying AND operation with comparator output which generates four sets of switching signals. With this kind of switching the output voltage and current of GTI is controlled. The CUK and SEPIC converters are designed so that the inverter output amplitude is matched with the utility grid (312V peak or 220V rms). Then the GTI is directly tied with the grid where the load is quite larger than GTI. Therefore, force is transmitted to the GTI for generating power from PV array and wind turbine into the grid.

B.Switching Circuit

In this proposed design, a combination of square wave and SPWM have been deployed, instate of using conventional one type of switching signal to switch the inverter. The switching loss across the switches of the inverter will be greatly reduced with this kind of combination switching [1]. Block diagram of the proposed switching control circuit is shown in Fig.8. For simplifying the synchronizing process, the sine wave which is stepped down into 5V from 220V grid voltage by using the voltage transformer will be sampled. SPWM signal is generated from sampled sine wave. Thus the frequency of the grid and the output from the GTI will be same where this is one of the most significant requirements for the GTI [1], [12].

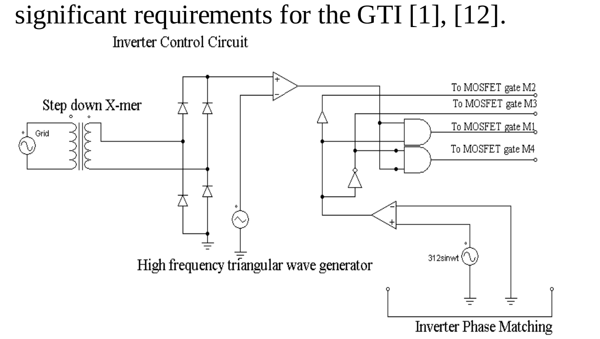

Fig. 8. Control circuit of proposed grid-connected inverter

The sine wave is rectified with a precision rectifier after sampling and an additional high frequency triangle wave of 20 KHz frequency is used. For generating the unipolar SPWM signal, the two signals are passed through a comparator which has only positive values. The unipolar signal changes from +5V to 0V and again back to +5V. A square wave which is in phase with the SPWM signal is used as the line frequency (50Hz for Bangladesh). Then the square wave signals is passed through a NOT gate to produce a 180 degree out of phase signal of the original signal. Since inverter has used four MOSFET switches, it requires four switching signals. Two AND operation is performed between square wave and the SPWM signals for generating four switching signals. The switching signals are categorized in two groups. The first group contains MOSFETs M_1 and MOSFETs M_2, while second group contains MOSFET M_3, and MOSFETs M_4. For M1 and M2 pair, positive voltage emerges across the load while for M3 and M4 pair, negative voltage emerges across the load [13]. Thus the inverter produces a full square wave output as shown in Fig. 9.

C. Filter circuit

Unlike conventional LC filter, a T-LCL immittance converter is employed to eliminate harmonics. This T-LCL circuit not only reduces the harmonics but also stabilizes the output current [1], [14-15]. The value of *C* and *L* of T-LCL filter (considering Butterworth type) is calculated using the condition of cut-off frequency of low pass filter. Here, the cutoff frequency, f_C is 50Hz and the characteristic impedance, Z_0 is assumed to be 60Ω. So, the values of *C* and *L* are calculated using the following equations as,

$$C = \frac{1}{2 \times \pi \times f_C \times Z_0} = \frac{1}{2 \times \pi \times 50 \times 60} \approx 105\ \mu F$$

$$L = CZ_0^2 = 105 \times 10^{-6} \times (60)^2 \approx .180\ mH$$

6. Simulation results & analysis

A.Output of AC synchronous generator

Fig.9 shows the output voltages of the PMSM, the frequencies of which are 20 Hz. As a result the 3-phase rectifier is needed to convert it into dc voltage and then for the conversion of the dc to ac voltage of 50 Hz.

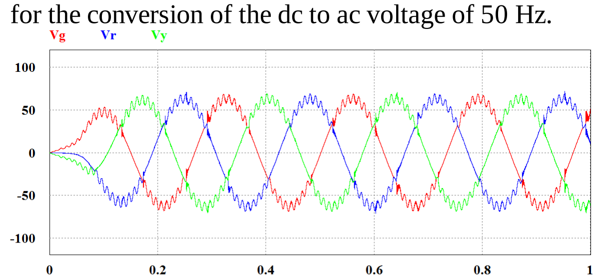

Fig. 9. Output of AC Synchronous Generator at 12m/s Wind speed

B.Inverter Output Voltage

Fig.10. shows the simulated output voltage waveform

which is non-sinusoidal, distorted and contains excessive amount of harmonics. After filtering, 312V peak (220V RMS), 50Hz pure sine wave output voltage is obtained as shown in Fig.11. It is observed that the output voltage of the proposed inverter becomes stable after a couple of cycles since it is connected to the grid.

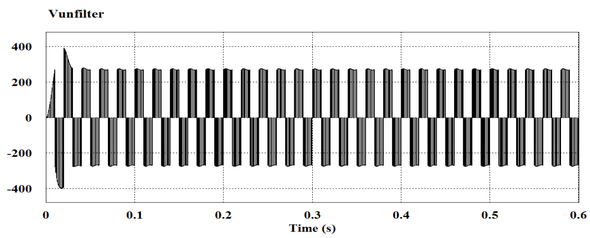

Fig. 10. Output voltage waveform without filtering in PSIM

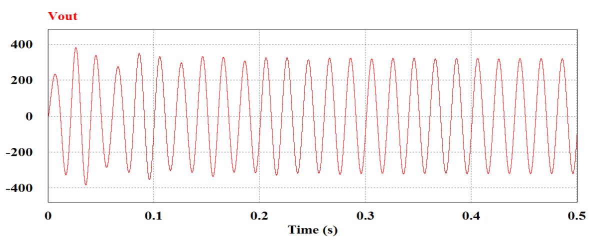

Fig. 11. Output voltages after filtering in PSIM

C.Inverter Output Current

Fig.12. shows the inverter output current which becomes stable within a couple of cycles (0.04sec.).

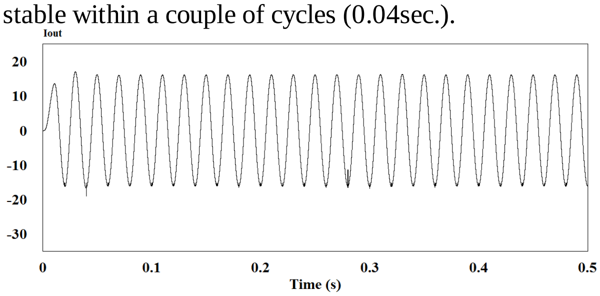

Fig. 12. Output voltages after filtering in PSIM

D. Output voltage & current in Phase condition

Fig. 13 represents the simulation result of grid-connected hybrid system, where it is observed that both the output current and voltage are in same phase.

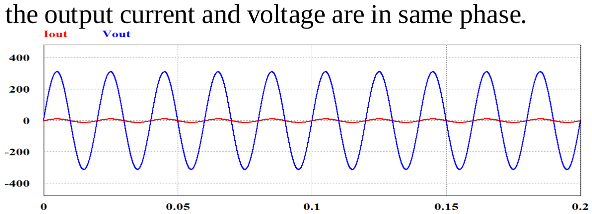

Fig. 13 Output voltages and current are in phase of GTI in PSIM

E.Performance analysis of GTI

The performance of proposed grid tie inverter (GTI) is analyzed in two states (a) before connecting with grid (b) after connecting with grid in Table 5 and Table 6.

Table 5.Inverter performance before connecting with grid

Parameters	**Value**
Proposed Hybrid Voltage	326V
Inverter Output Voltage (RMS)	230.62V
Inverter Output Current	11.53A
Inverter Output Power	2650Watt
Total Harmonic Distortion (THD)	0.01171643
Efficiency of this Proposed System	97.75%

Table 6.Inverter performance after connecting with grid

Parameters	***Value***
Proposed Hybrid Voltage	312V
Inverter Output Voltage (RMS)	220.40V
Inverter Output Current	12.25A
Inverter Output Power	2694Watt
Total Harmonic Distortion (THD)	0.009297646 4
Efficiency of this Proposed System	99.40%

F.FFT Analysis

Fig.14 presents the Fast Fourier Transform (FFT) of output voltage in unfiltered and filtered conditions. The FFT analysis ensures that the unfiltered output voltage has harmonics with mentioned value but after filtering THD is reduced to 0.0092976464.

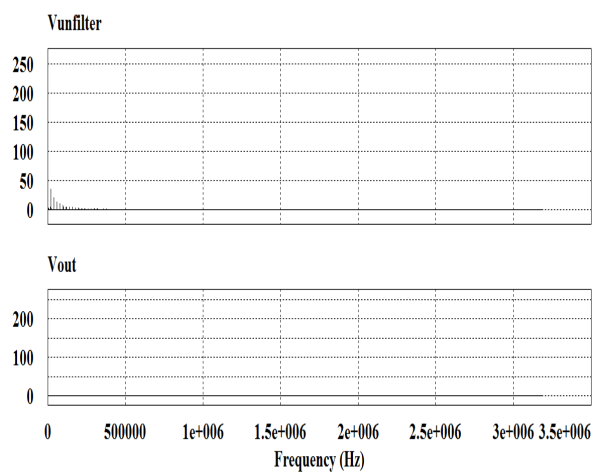

Fig.14. Output Voltage's FFT unfiltered and filtered condition in PSIM

7. Conclusion

Mathematical model, analysis and computer simulation of this proposed hybrid system is presented in this paper. The simulation results ensure that the frequency of the inverter output voltage is exactly 50Hz with a magnitude of 312V peak (220V rms) and is in same phase with the utility grid voltage. The total harmonic distortion (THD) of the inverter output is less than 0.03 which is much lower than the IEEE519 standard, and the efficiency of the inverter also increases up to 99% when connected with utility grid.

Therefore, the simulation results confirm the utility of CUK & SEPIC converters for the proposed PV-wind hybrid energy system to feed the sinusoidal output voltage and current to the utility grid.

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