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Fuel Cell based Standalone Power System Interfaced with a Semi-Z-Source Inverter through a Non Isolated Boost Converter

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Abstract

The global electrical energy consumption is rising and there is a steady increase of the demand on the power capacity, efficient production, distribution and utilization of energy. The traditional power systems are changing globally, a large number of dispersed generation (DG) units, including both renewable and non renewable energy sources such as wind turbines, photovoltaic (PV) generators, fuel cells, small hydro, wave generators, and gas/steam powered combined heat and power stations, are being used as standalone power systems. Power electronics, the technology of efficiently processing electric power, plays an essential part in the integration of the dispersed generation units for good efficiency and high performance of the stand alone systems. Unique requirements for small distributed power generation systems include low cost, high efficiency and tolerance for an extremely wide range of input voltage variations. These requirements have driven the inverter development towards simpler topologies and structures, lower component counts, and tighter modular design. This paper has successfully developed MATLAB/SIMULINK model of fuel cell standalone power system. Semi-Z source inverter topology is integrated with the fuel cell to form an off grid connected power supply. A non isolated dc-dc boost converter is used as an intermediate between the fuel cell stack and the semi-Z source inverter. The number of fuel cells used in the stack is reduced with the introduction of the boost section into the entire system. The semi-Z source inverter interfaced with fuel cell stack makes it a standalone system.

Index Terms: *Proton Exchange Membrane (PEM) Fuel cell, dc -dc boost converter, semi-Z-source inverter.*

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1. INTRODUCTION

High price and impermanency of major energy resources welcomed the entry of renewable resources in to the power industry. The problems with conventional energy supply and use are related not only to global warming but also to such environmental concerns as air pollution, acid precipitation, ozone depletion, forest destruction, and radioactive substance emissions. To prevent these effects, some potential solutions have evolved including energy conservation through improved energy efficiency, a reduction in fossil fuel use and an increase in environmental friendly energy supplies. Environmental concerns of global warming, fossil fuel exhaustion and the need to reduce carbon dioxide emissions have provided the stimulus to seek renewable energy sources. The interest in distributed generation has increased significantly in recent years. More effort is now being put into the clean distributed power like geothermal, solar thermal, photovoltaic, and wind generation, as well as fuel cells that use hydrogen, propane, natural gas, or other fuels to generate electricity without increasing pollution.

In this context more focus is given to the research of renewable energy. Among these renewable energy resources fuel cell is one of a kind. In today's world there is a growing demand to find greener ways to power the world and minimize green-house gas emission. The application of fuel cell technologies to advanced power generation systems portends the most significant advancement in energy efficiency, conservation, and environmental protection for the next decade.

The output of fuel cell is efficiently conditioned by power converters. The power converter must have high switching frequency in order to achieve small size, light weight, and low noise. In this paper the power converters comprise of a boost converter and an inverter. The number of fuel cell connected in the stack is reduced by introducing a non – isolated dc-dc boost converter as an intermediate between the stack and the dc-ac converter or inverter.

By examining all the advantages of the fuel cell based system, it is turning out to be an emerging power source from the family of renewable energy resources. In near future, when the

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whole world move to other alternatives for power generation this resource will be playing a major role in eliminating the scarcity of power.

This paper presents a standalone fuel cell based power system which is interfaced to an inverter through a dc-dc converter. Since the dc voltage generated by a fuel cell stack varies widely and is low in magnitude, a step-up dc–dc conversion stage is essential for generating a higher regulated dc voltage. Following this stage, a dc–ac inverter is used to supply the ac voltage to the load. Here, in this paper the power conditioning system consists of a non –isolated dc-dc boost converter and a semi-Z-source inverter. The dc power from the fuel cell stack is stepped up using the boost converter and then only given to the inverter for dc-ac conversion. This in turn reduces the number of fuel cells in the fuel cell stack and thus the bulkiness of the entire system. Both the converter and inverter are closed loop controlled. Computer simulation results shows the generation of 230 V single phase ac power from a low voltage fuel cell stack.

The remainder of this paper is organized as follows. In section 2, block diagram of the fuel cell based standalone system is discussed. The closed loop controlled dc-dc boost converter and its simulation results are discussed in the section 3 and 4 respectively. In section 5, the closed loop Semi-Z-source inverter connected to the dc-dc boost converter is presented and the simulation results follows in section 6. Section 7 concludes this paper with some final remarks.

2. BLOCK DIAGRAM OF THE SYSTEM

To effectively utilize energy resources, the development of fuel cell generation systems is becoming increasingly important for global environment. The fuel cell, a clean and renewable energy resource, has recently been revived and shows promising results for applications as small as cellular phones to as large as utility power generations.

The use of fuel cells in both stationary and mobile power applications can offer significant advantages for the sustainable conversion of energy. Benefits arising from the use of fuel cells include efficiency and reliability, as well as economy, unique operating characteristics, and planning flexibility and future development potential. By integrating the application of fuel cells, in series with renewable energy storage and production methods, sustainable energy requirements may be realized.

This paper describes a fuel cell based standalone power system which converts chemical energy in to single phase ac power using the power converters- a boost converter and an inverter.Ac power requirements in army, rural and remote areas and in boats and yachts are met by off grid power systems. Since the output of the fuel cell is clean and free of harmful emissions, demand for this kind of generation is increasing in the above mentioned fields. This kind of backup power is used in industrial and commercial fields also. In developed countries, fuel cell power is used to energize the telecommunication lines and remote areas.

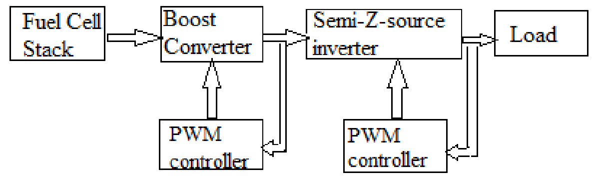

Fig. 1. Basic schematic block diagram for single phase FC system

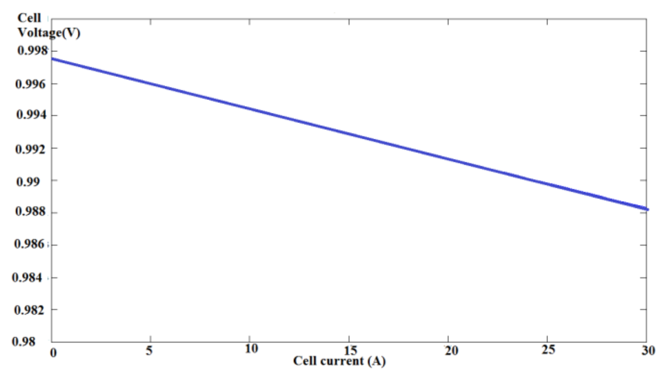

Fig. 2. Voltage vs. current characteristics of a single PEM fuel cell model

Fig.1. shows a basic schematic block diagram for single phase FC based power system for small-scale stand-alone generation plant .The power conditioning system comprises of boost converter and the semi-Z-source inverter. The output power from the fuel cell (Nexa^{TM} 1.2 kW Proton Exchange Membrane (PEM) fuel cell model) is interfaced to semi-Z-source inverter through a non –isolated dc-dc boost converter. The boost converter reduces the number of fuel cells in the stack and thereby reduces the weight of the entire system. Both the converters are PWM controlled. The single phase ac power from the semi-Z-source inverter is given to the load.

3. CLOSED LOOP DC-DC BOOST CONVERTER

Looking into the drooping V-I characteristics given in fig.2, the unregulated terminal voltage of the fuel cell stack cannot be directly interfaced to the DC bus or to dc-ac inverters for residential/grid applications. The fuel cell stack is having a linear region of voltage. For converter design, the linear region

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operation (due to resistance offered by internal components) of the fuel cell stack is only taken into account. Beyond the linear region, the fuel cells cannot be operated as electrolyte membrane of the cell may get damaged. Fig.3 shows a closed loop continuous conduction mode operation of PWM dc-dc boost converter.

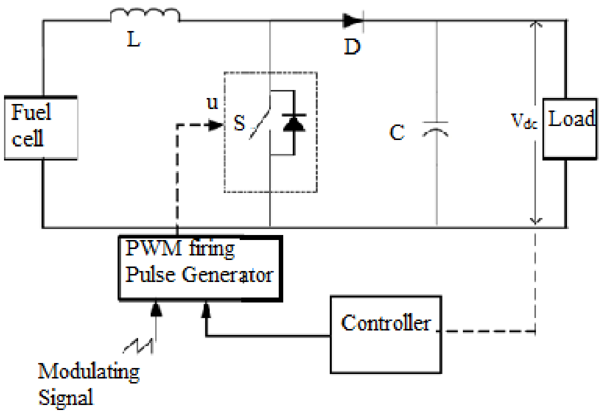

Fig. 3. Closed loop dc-dc boost converter

The main advantages of the dc-dc boost converter are higher efficiency and reduced component count .It converts the unregulated voltage from the fuel cell stack into desired regulated voltage by varying the duty cycle at high switching frequency ,lowering the size and cost of energy storage components. The selection of components like boost inductor value and capacitor value is very important to reduce the ripple generation for a given switching frequency. However large inductance tends to increase the start-up time slightly while small inductance allow the coil current to ramp up to higher levels before switch turns off [1] .

Fig. 4 gives the closed loop control used for the dc-dc boost converter in the FC system. Independent control strategy is used for the converter and the inverter. Pulse width modulation technique is used for both the converters. The fuel cell stack (Nexa™ 1.2 kW PEM fuel cell model) used here is having a maximum voltage of 40 V dc .This low voltage is given to the dc-dc boost converter for boosting to an output voltage of 325 V dc. In the control of dc-dc boost converter, a saw-tooth waveform of high frequency is compared with a reference signal. This signal is the error voltage which is the difference between the reference voltage (325 V) and the actual voltage V_{dc}.

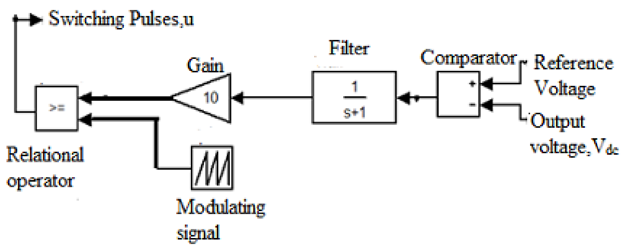

Fig. 4. Control scheme for dc-dc boost converter

4. OUTPUT RESULTS OF CLOSED LOOP DC-DC BOOST CONVERTER

The size of the reactive elements of boost converter can be determined from the rated voltage, current ripple, voltage ripple and switching frequency of the converter based on the equations from [2].Table I enlists the parameters of the non-isolated dc-dc boost converter with Nexa™ 1.2kW PEM fuel cell as power source.

TABLE- I: Simulation parameters of dc-dc boost converter connected to PEM fuel cell

Parameters	Values
Input voltage (PEM Fuel Cell)	40 V
Output Voltage	325 V
Switching Frequency	10kHz
Duty ratio	0.875
Inductance, L	4.8mH
Capacitance , C	2000µF

The input voltage from the fuel cell stack, the current waveform and the output voltage waveform obtained from PEMFC connected to dc-dc boost converter are shown in the Fig.5, 6 and 7 respectively.

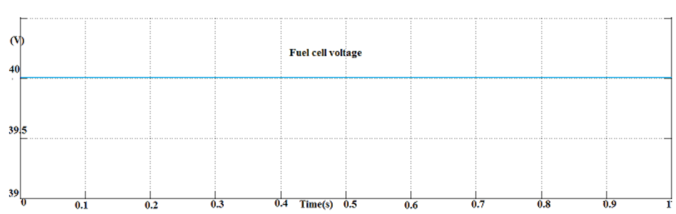

Fig. 5. Source voltage from the fuel cell stack

The fuel cell voltage is having a value of 40 V.The electrochemical model of the fuel cell model is developed according to the [3].

The current waveform shown in fig. 6 is having an average value of 3.5 A. The output voltage from the boost converter is maintained at 325 V.The semi-Z-source inverter outputs an ac voltage having peak value equal to the input voltage. That is why the boost converter is made to deliver an output voltage equal to 325 V dc.

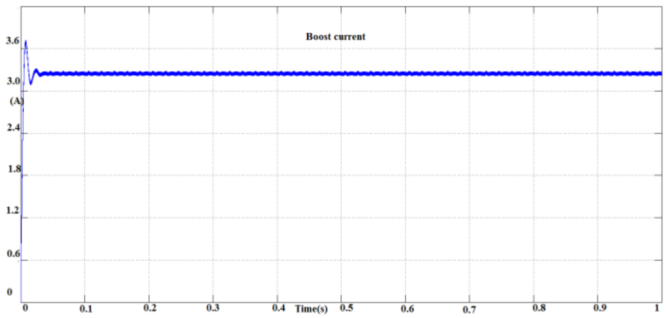

Fig. 6. Current waveform of boost converter

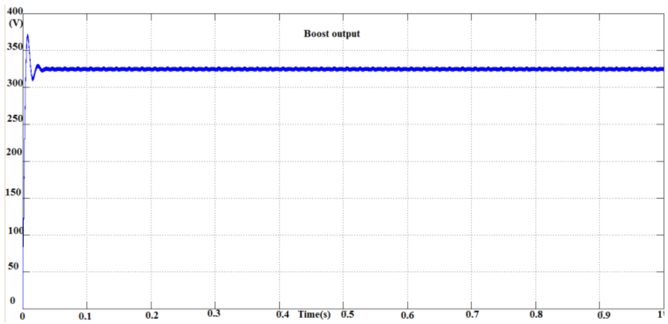

Fig. 7. Output voltage of boost converter

5. CLOSED LOOP SEMI –Z-SOURCE INVERTER

When it comes to the choice of inverters, a numerous topologies are available. Each topology projects its own advantages over other converters. The key points to be remembered while selecting an inverter topology are low cost, low complexity and high system efficiency. The inverter output should be having only acceptable percentage of harmonics also.

Based on the galvanic isolation, these inverters can be divided into two categories: isolated inverters and non-isolated inverters. Isolated inverters usually utilize a line frequency or high frequency transformer for electrical isolation. Due to the size, weight and cost considerations, high frequency transformers are inclined to be used for future applications.

When it comes to standalone system of low voltage and low power levels, non isolated inverters are preferred. The transformer-less inverter topologies can be classified into two categories: two stage inverter topologies and single stage inverter topologies [4]. The two stage inverter topology is an approach with a non- isolated dc-dc converter in the first stage and an inverter in the second stage. The work here focuses on two stage inverter topology. A semi-Z-source converter shown in fig 8 is used as the second or final stage of the power system. The semi-Z-source inverter is nothing but a dc-dc converter giving the alternating voltage by varying the duty cycle of the switches from 0 to 1

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Compared with the traditional single-phase Z-source inverters; the semi-Z-source inverters share the same form of Z-source network. But the Z-source network used in semi-Z-source inverter is in ac side, which is smaller in size than the traditional Z-source network used in dc side. The modulation strategy of the semi-Z-source inverter is also different. The traditional Z-source inverters use sinusoidal reference with extra shoot-through reference to output sinusoid voltage and achieve the voltage boost function. However, in order to output sinusoid voltage, the semi-Z-source inverter has to utilize its non-linear voltage gain curve to generate a modified voltage reference [4].

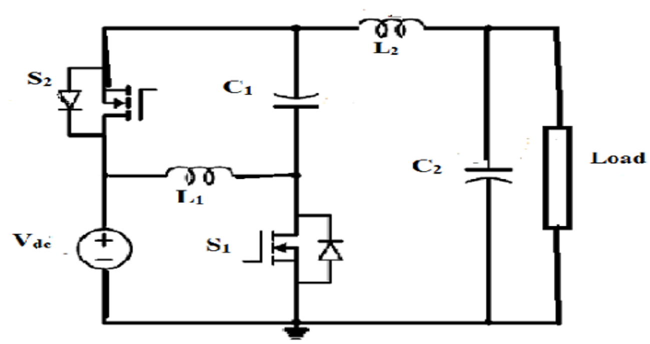

Fig.8 Semi-Z-Source converter

For the dc operation modes of the semi-Z-source converter, the reader could refer to [4].Among the Z- source and quasi-Z-source converters, the input and output of the semi-Z-source inverter topology given in fig.8 shares a common ground. With proper modulation strategy, this semi-Z-source dc-dc converter can be transformed in to an inverter.

According to the inductor voltage second balance and the capacitor charge balance equations, [4] gives the following steady state equations.

$$\frac{V_o}{V_{dc}} = \frac{1-2D}{1-D} \quad (1)$$

$$V_{c1} = \frac{D}{1-D} V_{dc} \quad (2)$$

$$I_{L2} = -I_o \quad (3)$$

$$I_{L1} = \frac{D}{1-D} I_o \quad (4)$$

The output voltage of the inverter can be represented by (5). And the modulation index can be defined as (6), plug (5) and (6) into (1) we can get (7), D'=1-D is the duty cycle of S_2 is derived as (8). Because the relationship of the full bridge inverter output and input voltage is linear in terms of switch duty cycle, the sinusoid output voltage can be achieved using a sinusoidal changed duty cycle. But the output voltage and the input voltage of the semi-Z-source inverter are not a linear relationship with the switch duty cycle any more. In order to achieve the sinusoid output voltage, the duty cycle cannot be changed in a sinusoid manner. A corresponding nonlinear changed duty cycle has to be used to generate the correct sinusoid output voltage. A new duty cycle reference, as shown in (7) or (8) has to be used [4].

$$V_o = V \sin \omega t \quad (5)$$

$$M = \frac{V}{V_{dc}} \quad (6)$$

$$D = \frac{1 - M \sin \omega t}{2 - M \sin \omega t} \quad (7)$$

$$D' = \frac{1}{2 - M \sin \omega t} \quad (8)$$

Instead of using the sinusoid voltage reference, a modified voltage reference as derived in (8) is used as the reference signal for the conduction of switch S_2 in order to output the sinusoid voltage. When the reference is greater than the carrier the switch S_2 is turned on, otherwise S_2 is turned off. And the gate signal of S_1 is complementary with the switch S_2. The modified voltage reference as derived in (7) can be also used directly to generate the gate signal of S_1.From the equation (1), it is clear that the converter can be made to give an alternating voltage of the peak value equal to V_{dc}, simply by varying the duty cycle D between 0 and 2/3.This output range (+V_{dc} to-V_{dc}) is same as that of the full bridge inverter. In semi-Z-source inverter with reduced number of switches, it is possible to obtain the same output range as the full bridge inverter by merely varying the duty cycle from (0- 2/3) [4].

When the duty cycle of S_1 changes from (0~0.5), the inverter can output the positive output voltage, and when the duty cycle of S_1 changes from (0.5~2/3), the inverter can output the negative output voltage. When the duty cycle is equal to 0.5 the semi-Z-source inverters are able to output zero voltage [4].

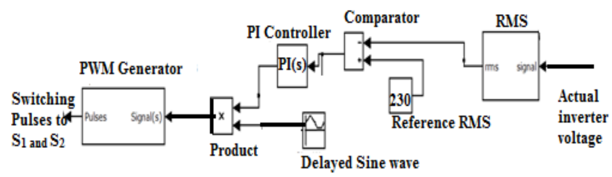

Fig 9. Control scheme for semi-Z-source inverter

The control scheme for the semi-Z-source inverter is shown in fig.9. Instead of a comparing the carrier waveform with a sinusoidal waveform as in sinusoidal pulse width modulation, the triangular carrier waveform of 10 kHz is compared with a delayed sinusoidal waveform whose instantaneous value corresponds to the difference between the actual rms value and the reference rms value.

6. SIMULATION RESULTS OF THE FUEL CELL STAND ALONE POWER SYSTEM

The fuel cell based standalone system input voltage and the intermediate level (non-isolated dc-dc boost converter) output voltage are given in fig.5 and fig.7 respectively. The output voltage of the boost converter i.e. 325 V is the input to the semi-Z-source inverter. Since the output range of the Z-source inverter is same as that of the full bridge inverter, it gives an output voltage of 230 V rms value. The simulation results shown in this section is for a time range from 0.05s to 0.1s.

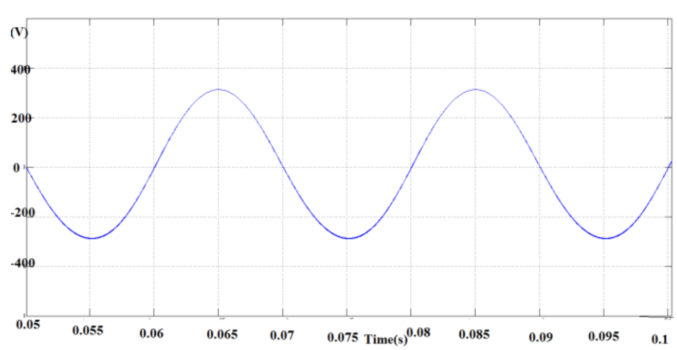

Fig 10. Inverter output voltage

The output voltage waveform is given in fig 10. The load current is same as the current through inductor L_2.The current waveform is shown in fig 11.

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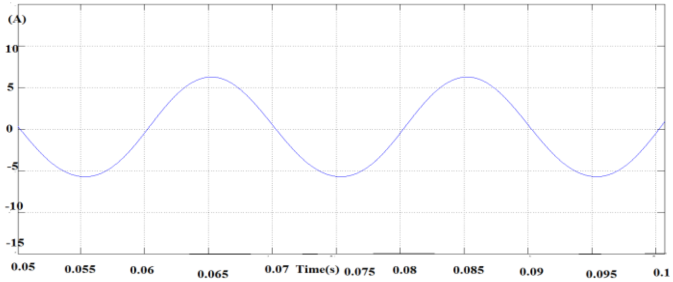

Fig 11. Inverter output current

The capacitor stress and inductor currents of the semi-Z-source inverter are given by the equations (1), (2), (3) and (4).

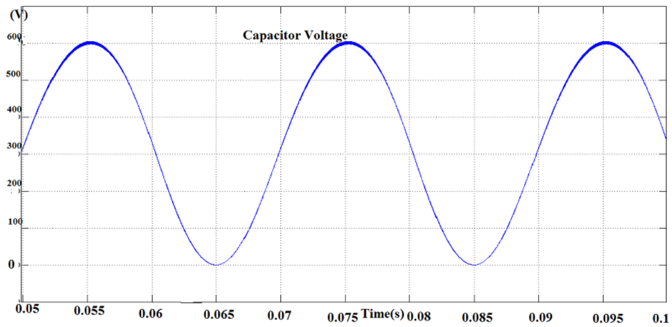

Fig 12. Capacitor voltage VC_1

The inductors and capacitors of the semi-Z-source inverter is so selected according to the criteria given in [4].The designed values of the capacitors C_1 and C_2 are 4μF and the inductors L_1 and L_2 are 400μH.The capacitor stress VC_1 and inductor current IL_1 are shown in fig 12 and fig 13 respectively.

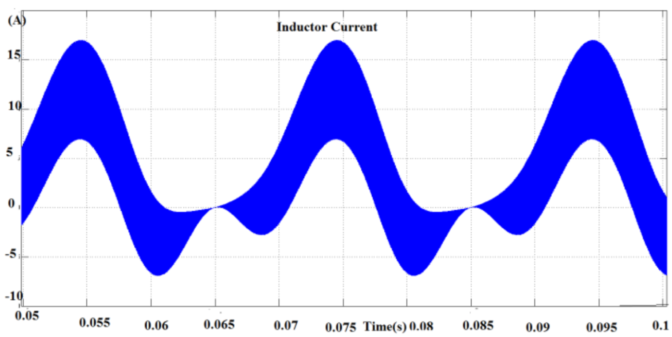

Fig 13. Inductor current, IL_1

7. CONCLUSION

In this paper, single phase fuel cell powered standalone power system which generates alternating power through two stages is simulated. Dc-dc boost converter converts the unregulated fuel cell power to regulated DC power and the next section which is a semi-Z-source inverter converts the regulated dc power to alternating power. Comparing with conventional inverters, the semi-Z-source inverter system has only two active switches thereby reducing switching loss and giving same output as a full bridge inverter. The harmonics present in the output voltage from the semi-z-source inverter is only 2.5%.This percentage is under the allowable harmonic limits.

The world is using up all the resources to meet the daily demands of energy and it is quite expectable that in the near future we will run out of any naturally occurring ore/mineral/petroleum. As a result, renewable energy solution is a way today to save the natural resources and also to tackle the crisis of energy. This type of small low power, off grid power systems using renewable resources mitigates energy scarcity and also offers a greener solution to the environmental pollution.

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BIOGRAPHIES

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