

A Novel Power Converter Design for Smart Grid

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Abstract : *The Smart Grids for power distribution has increased significantly over the years. Smart grid requires sensors, automatic switches and communication devices etc. for two way communication. These devices require power source for its working. But, as the lifetime of batteries is limited, powering these devices has become main concern of Smart Grids. This paper discusses the benefits of using Energy Harvesting System (EHS) and Power Converters to power the sensors on Smart Grid. It also covers the improvement in efficiency and performance of the Smart Grid by using EHS and Power Converters. Usage of EHS significantly reduces the dependency on batteries and manual involvement and also helps in increasing the robustness. In this paper, a Power Converter design is proposed which boosts the performance of the Smart Grid and reduces dependency on conventional sources of energy.*

Keywords – Battery, Energy Harvesting, MOS, Power Converter, Smart Grid

I. Introduction

Traditional power grids were used to fulfill small power demands which were done using one way interaction. Nowadays, power demand has increased so smart grids have a better role to play. Smart grid uses two way digital communications so that the information can be exchanged between the customers and the providers [1]. Smart grid automatically identifies any problem in the overall grid and reroutes and restores the problem because each device in smart grid network such as power meters, voltage sensors, fault detectors etc. has been given sensors to gather data. Each sensor requires energy for its operation and is powered using batteries [2]. But, as the technology scales down, it is expected that the battery size decreases and with the decreased size of battery its life also becomes shorter. Therefore, there is a need to either replace the battery time to time or to implant a rechargeable battery which can be recharged whenever required. When the area where the application is deployed is hazardous and risky then both solutions become infeasible [3]. Also small size batteries carry low energy density therefore for portable applications; the frequency of battery replacement increases, thus the effort and cost is more in replacing batteries [4]. The most feasible solution for the above stated problems is the Energy Harvesting.

Energy Harvesting is the process of converting ambient energy from environment renewable sources like solar, wind, biomass, tidal, fuel cell, vibration etc. into usable electrical energy. This process is done by means of energy harvesters which transform the ambient energy into electrical energy [5] [6]. Energy Harvesting Systems (EHS) are not able to work without Power Converter circuit. Power Converter is a key element in EHS because energy harvesters like PV cells, thermoelectric and piezoelectric generators etc. do not produce sufficient energy to run portable applications [7] [8].

Integrating EHS in smart grid technologies is very important aspect and it can be used to fulfill two types of energy needs [9].

1. EHS can replace the batteries for small, low power devices such as switches and sensors used in smart grids.
2. By incorporating multiple solar panels and wind turbines, obtained energy can be increased so that it can power low power home appliances also. When the renewable energies are available, it is

stored in batteries and when the power grid is unable to provide the power, the stored power is utilized [10] [11].

There are various topologies available for Power Converters which are broadly classified as Dickson, Cross-Coupled Voltage Doubler and Makowski Power Converters etc. [12]. Dickson topologies exhibit threshold voltage drop and increased bias voltages. Cross-Coupled Voltage Doubler requires $2*N$ PMOS and $2*N$ NMOS where N is no. of stages thus it occupies larger area whereas, Makowski Power Converter has very complex circuit designs as its structure changes for low and high gains [13] [14]. Therefore, there is a need to design Power Converter which overcomes the stated problems with optimized performance and design parameters.

II. Proposed Power Converter

The Proposed circuit is designed combining the two famous topologies Dickson Charge Pump (DCP) and Cross-Coupled Voltage Doubler. Thus, this circuit includes the advantages of both the topologies and their disadvantages are overcome to give the better topology. The output stage of Dynamic CTS DCP is still a diode connected stage thus; the voltage is lost at the output stage. Cross-Coupled Voltage Doubler consists of cross-connected NMOS and PMOS which makes sure that voltage loss doesn't occur but the number of pumping capacitances required for this topology is more. So, this Proposed Power Converter is designed such that the Dynamic CTS DCP improves its output stage. Therefore, output stage is designed using cross-connected NMOS and PMOS so that the Proposed Power Converter provides enhanced output voltage with lesser number of capacitors. The Proposed Power Converter is designed for the following performance parameter and the design parameters are shown in Table 1.2 which is obtained using the automated MATLAB program which is discussed in [15].

Table 1.1 Performance Parameter Values for Designing the Proposed Power Converter

Parameters	V _{in}	V _{out}	V _r	f	R _l
Values	3.3V	16V	0.2V	10MHz	10MΩ

Table 1.2 Design Parameter Values Obtained from the Automated Program for the Proposed Power Converter

Parameters	W/L of NMOS	W/L of PMOS	N	c	C _{out}
Values	0.18μm/0.18μm	0.18μm/0.18μm	4	0.8pF	0.6pF

The circuit diagram and output voltage waveform of designed 4-Stage Proposed Power Converter is shown in Fig. 1 and Fig. 2 respectively. The circuit consists of 19 MOS switches, 6 boosting capacitors, a load resistor and an output capacitance. The output voltage provided by the Proposed Power Converter is 16.187V.

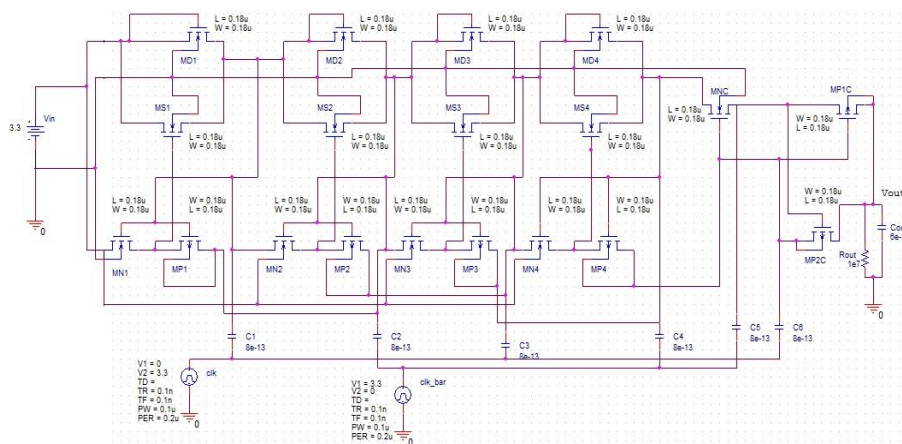


Fig. 1 The Circuit Diagram of Proposed Power Converter

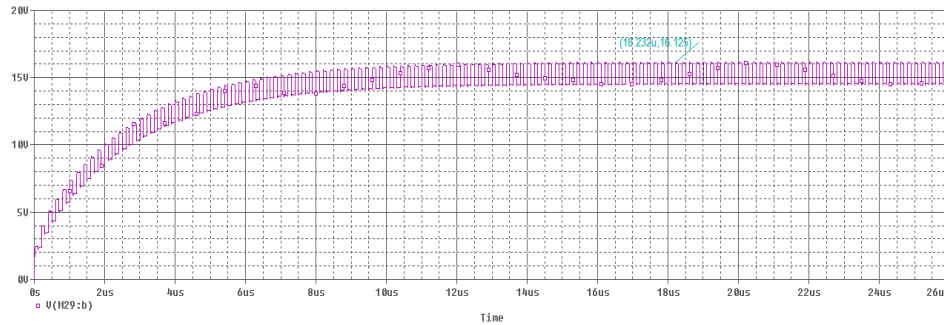


Fig. 2 Output Waveform of the Proposed Power Converter

2.1 Simulation Result and Discussion

The Proposed Power Converter is designed in Orcad 16.5 software using 0.18µm level 3 CMOS process parameters. All the simulations are carried out at 10MHz frequency with clock voltage equal to $V_{in}=3.3V$. The values of boosting capacitors for each stage are same and equal to 0.8pF. The number of pumping stages is $N=4$ with the output capacitor value 0.6pF.

Effect of input supply voltage on output voltage is shown in Fig. 3. It is observed that with increase in input supply voltage output voltage increases. At low input voltage of 1V also the Proposed Power Converter is able to boost the input supply with conversion efficiency of 4.7233. The Proposed Power Converter boosts the input supply voltages with almost constant conversion efficiency of 4.88.

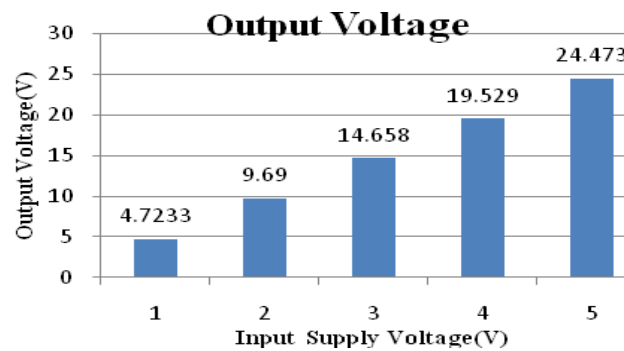


Fig. 3 Output Voltage versus Variation in Input Supply Voltage.

Variation of load resistance on output voltage is shown in Fig. 4. Increased value of load resistance decreases ripple voltage and thus increases output voltage. As load resistance value is low the output voltage is also less due to high ripple. Therefore, when $R_l=0.1M\Omega$ the output voltage deteriorates due to high ripple and gives output voltage of 2.4544V. For low load resistance values conversion efficiency is also low and it increases with increase in load resistance and it saturates after 100MΩ.

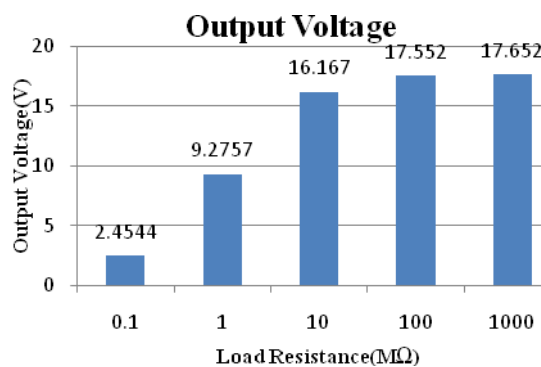


Fig. 4 Output Voltage versus Variation in Load Resistance

Maximum output voltage obtained with different number of stages for the Proposed Power Converter is shown in Fig. 5. It is observed that as number of stages is increased maximum output voltage obtained is also increased. When $N=3$, the maximum output voltage obtained is equal to 16V. Thus, its pumping efficiency is high.

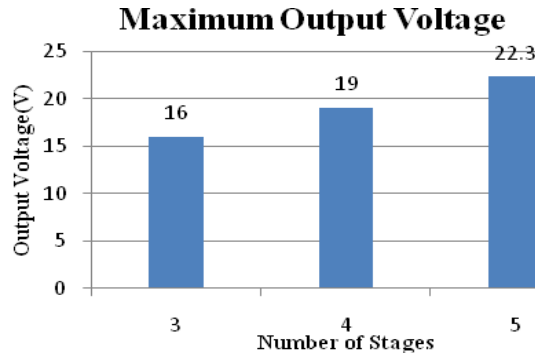


Fig 5 Maximum Output Voltage for Different Number of Stages

Output voltage versus output current graph for different input supply voltage is shown in Fig. 6. It is observed that as output current is increased output voltage value is reduced. As it is observed from the graph that the slope for all the three inputs is same therefore the Proposed Power Converter provides same power efficiency for same output loading current.

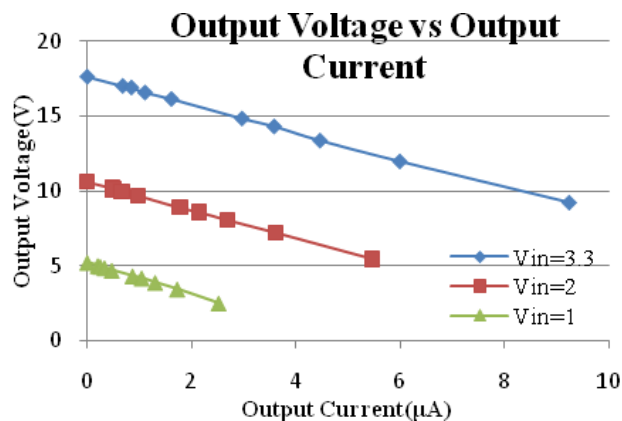


Fig.6 Plot of Output Voltage versus Output Current

2.2 Comparison of the Proposed Power Converter with Previous Work

Conventional DCP, Dynamic CTS DCP, Cross-Coupled Voltage Doubler, Reference [15] Power Converters are designed in [16] by using automated methodology. The automated methodology provides optimized values of design and performance parameters. Comparison of the results obtained from the Proposed Power Converter is compared with these previously designed Power Converters.

2.2.1 Output Ripple

The output ripple with respect to switching frequency, output capacitance and load resistance graphs are shown in Fig. 7, 8 and 9 respectively. By increasing switching frequency, output capacitance and load resistance ripple voltage decreases and after a particular value ($R_l=20\text{M}\Omega$, $C_{out}=6\text{pF}$ and $f=10\text{MHz}$) it remains constant. The Proposed Power Converter has 5 times higher ripple voltage compared to DCP and Dynamic CTS DCP topologies and when it is compared to Reference Power Converter; its ripple voltage is half. But, the equivalent output voltage (i.e. by subtracting ripple voltage from output voltage) of the Proposed Power Converter is higher compared to all the topologies.

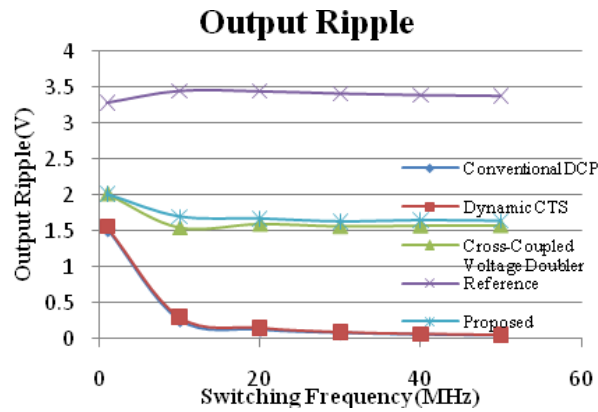


Fig.7 Comparison of Output Ripple Voltage with Variation of Switching Frequency

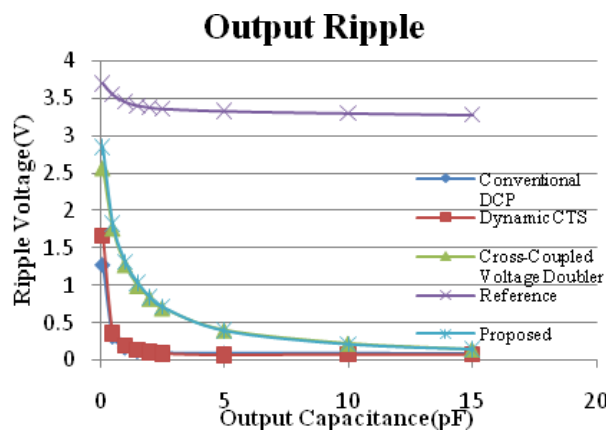


Fig.8 Comparison of Output Ripple Voltage with Variation of Output Capacitance

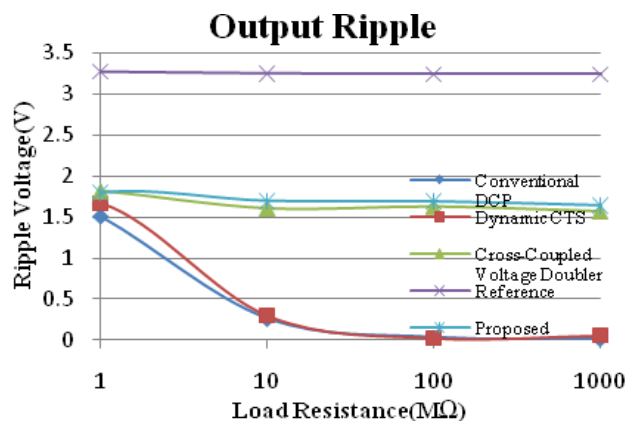


Fig.9 Comparison of Output Ripple Voltage with Variation of Load Resistance

2.2.2 Output Voltage

Output voltage versus input supply voltage, switching frequency, load resistance, number of stages and boosting capacitance for all the designed circuits are shown in Fig. 10, 11, 12, 13 and 14 respectively. The graphs are plotted with the equivalent output voltages.

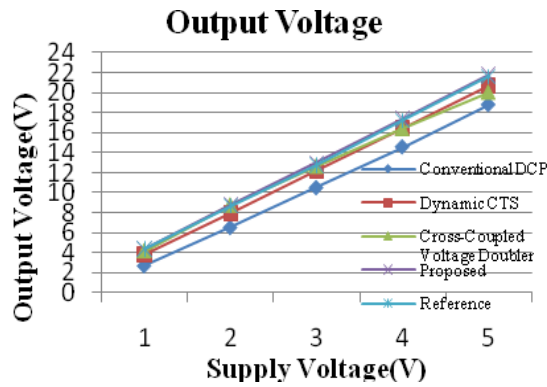


Fig.10 Comparison of Output Voltage with Variation of Supply Voltage.

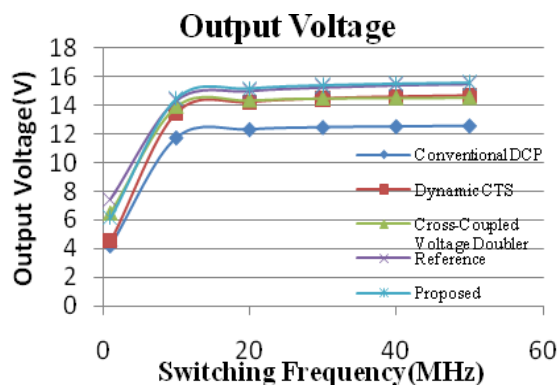


Fig.21 Output Voltage versus Variation in Switching Frequency

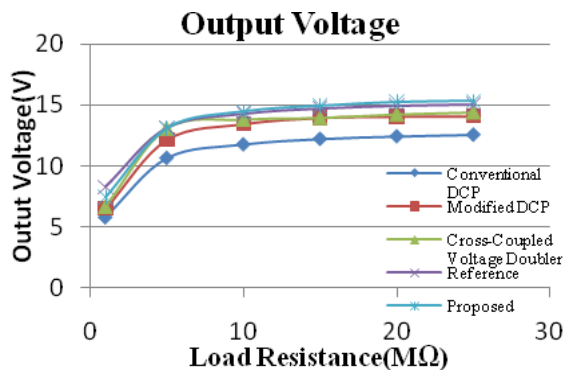


Fig.12 Output Voltages for all Designed Circuits at Different Values of Load Resistance

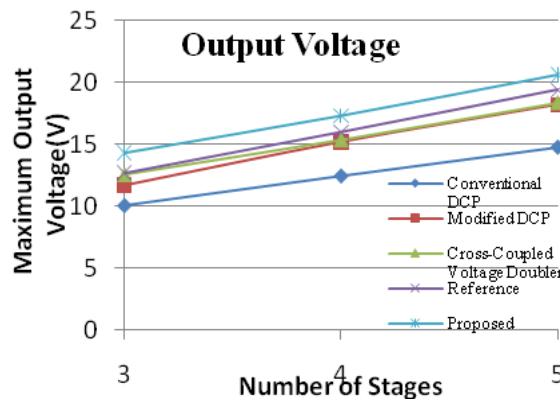


Fig.33 Comparison of Maximum Output Voltages for Different Values of N

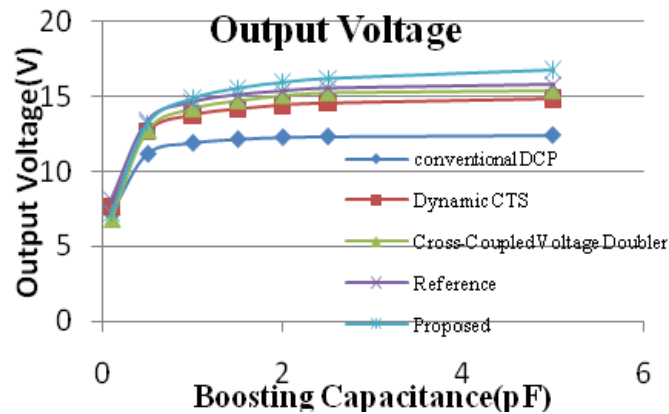


Fig.14 Output Voltage versus Boosting Capacitance for all the Designed Circuits

The Proposed Power Converter provides a higher output voltage for the same input supply voltage, switching frequency, load resistance, number of stages and boosting capacitor value. The increases in Proposed Power Converter output voltage are 23%, 10%, 6% and 2% with respect to Conventional DCP, Dynamic CTS DCP, Cross-Coupled Voltage Doubler and Reference [9] respectively. It indicates that the Proposed Power Converter circuit has better pumping performance.

2.2.3 Voltage Drop versus Number of Switches

Voltage drop versus number of switches graph is shown in Fig. 15. The Fig. shows voltage drop due to switch on-resistance versus number of switches for different topologies. It shows that though Proposed Power Converter requires maximum number of switches, it has lowest switch on-resistance among them thus the lowest voltage drop and higher output voltage.

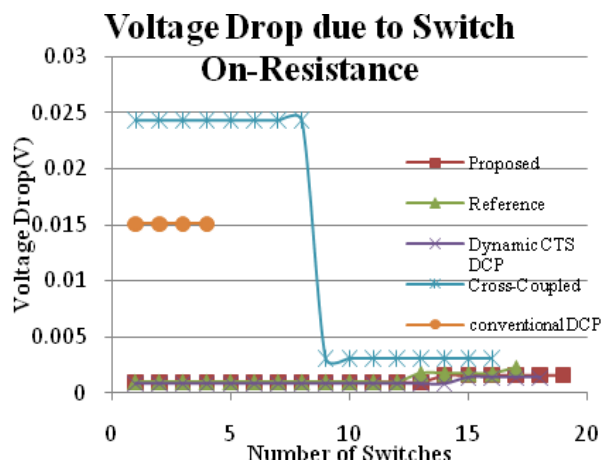


Fig.45 Voltage Drop across Switches versus Number of Switch

2.2.4 Power Efficiency

Power efficiency versus switching frequency and Load resistance plot is shown in Fig. 16 and 17 respectively. It is observed that as switching frequency and load resistance value is increased, power efficiency increases and after 20MHz and 20MΩ the values becomes almost steady. The Proposed Power Converter provides almost 21%, 8.5%, 6%, 1.5% increases in power efficiency with respect to Conventional DCP, Dynamic CTS DCP, Cross-Coupled Voltage Doubler and Reference [9] respectively.

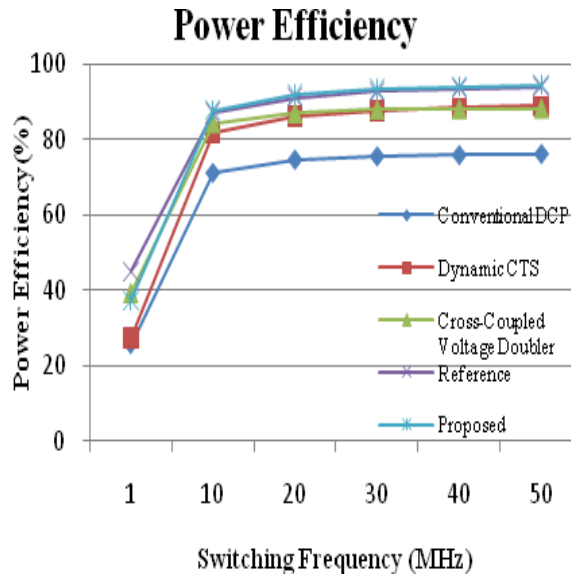


Fig.56 Comparison of Power Efficiency with Variation in Switching Frequency

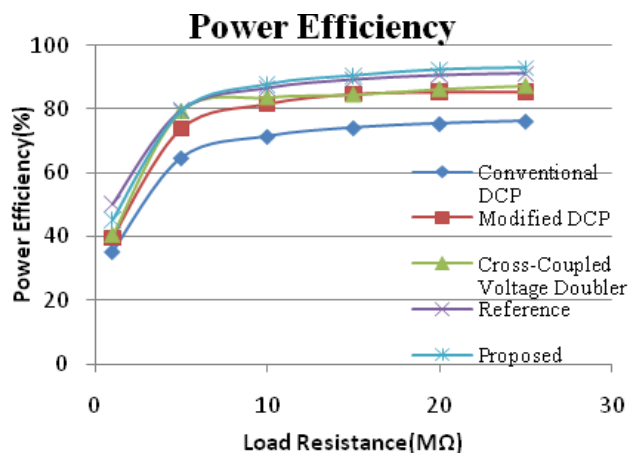


Fig.17 Comparison of Power Efficiency with Variation in Load Resistance

III. Solar Energy Harvesting Application

EHS have become very important these days due to limited reserves of conventional energy sources. Many researchers are working on the Energy Harvesting Systems to harness more and more power from environment. The energy can be harnessed from wind energy, fuel energy and solar energy etc. If solar energy harvesting is considered, the efficiency of solar panel and Power Converter directly affects the efficiency of solar energy harvesting. Efficiency of solar panel cannot be improved since it depends on technology availability and expenses. Thus, improvement in Power Converter design is required.

A complete Energy Harvesting System is designed using co-simulation of Orcad PSpice and MATLAB/Simulink through SLPS interface and is shown in Fig. 18. Solar energy is acquired using solar panel and it is given to SLPS block which consists of the Proposed Power Converter circuit. Power Converter boosts the solar energy value and drives the LED load. Solar Panel is designed in MATLAB/Simulink environment [17].

The irradiance $W=1000 \text{ W/m}^2$ and the open circuit voltage $V_{oc}=3.3V$. The output current provided by solar panel is $0.04213A$ and the output voltage is $3.277V$. The input for SLPS block is the output of solar panel and it is designated as V_{solar} . This input $V_{solar}=3.277$ is boosted by the Proposed Power Converter circuit and it provides output voltage equal to $14.58V$.

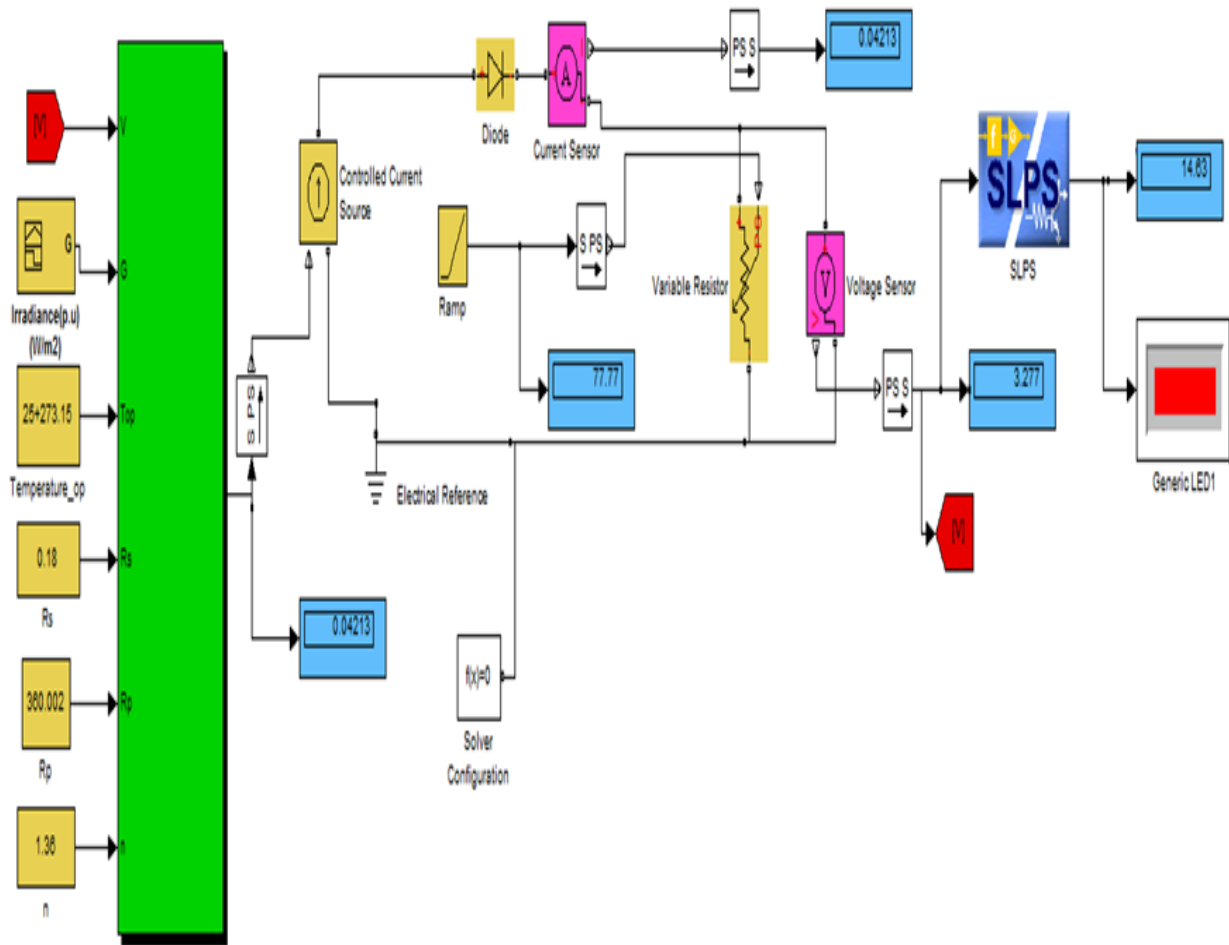


Fig. 18 The Solar Energy Harvesting System Design

The Proposed Power Converter is tested with solar panel input and the results are shown in the following table. It is observed from the above table that the Proposed Power Converter boosts the solar energy with 89.27% power efficiency and voltage conversion efficiency of 4.46.

Table 1.3 Comparative Result for all the designed Power Converters in Solar EHS at $W=1000W/m^2$

Parameters	Proposed Power Converter
Vin(V)	3.277
Vout(V)	14.63
Power Efficiency (%)	89.27

To check the effectiveness of the designed Power Converter circuits for low intensity of input signal, irradiance of the solar panel is varied to 100, 400, 600 and 800 W/m^2 and the output voltages and power efficiency have been found out. The Table 1.4 shows the comparative result.

Table 1.4 Comparative Result for all the Designed Power Converter Circuit in Solar Energy Harvesting System

W (W/m ²)	Vin (V)	Proposed Power Converter	
		Vout(V)	η (%)
800	3.02	13.5	89.40
600	2.68	12	89.55
400	2.25	9.99	88.80
100	1	4.48	89.60

The comparative result shows that the Proposed Power Converter provides consistent power efficiency of 89.60% and is able to maintain high power efficiency even at low input supply of 1V.

IV. Conclusion

Smart Grid has lot of sensors which are powered using batteries which requires regular maintenance and manual intervention. The usage of EHS in Smart Grid circuits is increasing day by day. The Power Converter plays a crucial role in EHS system which houses it. In this work, a new Power Converter circuit design is proposed which has advantages of both Dickson and Cross-Coupled Voltage Doubler Power Converter. The simulated results show that it also overcomes disadvantages such as threshold voltage drop, operation with low supply voltage and low conversion efficiency. The 4-stage Proposed Power Converter circuit is optimized to provide output voltage of 16.167V, power efficiency of 87.65% and voltage conversion efficiency of 4.9 with minimum area.

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