ZETA Converter based charge controller for efficient use of solar energy in street lighting system

Faizan Hameed[1], Khalid Iqbal[2]

[1]Assistant professor, Student (Electrical Power), EE Department, University of Engineering and Technology Taxila, Pakistan.

[2]HOD, Centre of Excellence, College of E&ME, Rawalpindi, Pakistan.

ABSTRACT: The paper presents ZETA converter based solar charge controller with the function to disconnect the battery during overcharging or deep-discharging for efficient use of solar energy in street lighting system. Purpose of circuit's designed is to charge the battery between upper and lower voltage limits in addition to continuously checking the status of charge of battery to add or release current accordingly. The designed circuit will provide alternative path to the power when battery is fully charged. Main difference between the method used in the proposed system and other techniques used in the past is that ZETA converter itself will act as charge controller in addition with this, specific properties of ZETA converter will be used to optimize street lighting system to reduce the power losses and cost. The designed circuit is also implemented in MATLAB using SIMULINK. So in concept of centralize architecture of PV street lighting system this design will provide a best alternative solution.

KEYWORDS: Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Photovoltaic (PV), Direct Current To Direct Current (DC-DC), ZETA converter, Single Ended Primary Inductor Converter (SEPIC), Buck-Boost converter, CUK converter, Buck converter, Boost converter, State Of Charge (SOC), Continuous Conduction Mode (CCM).

I. INTRODUCTION

One of the primary As solar energy is sustainable and available source of energy so it has become the main power source in current situation. It is free, clean and long-lasting. This energy system is one of the best choice for power production because of its low maintenance and operational cost. To increase the efficiency of generation and management/utilization of solar energy we can use different techniques.

An important thing to make the DC generated power more efficient is to use DC-DC converters to store and utilize the energy. The conversion from DC-AC causes a huge loss of power.

Many types of DC-DC converters can be used for the purpose and every converter have its own advantages over others. Aim of this research paper is to make the Centralized architecture of PV LED street lighting system more efficient using ZETA converter as charge controller. Research work includes design, simulation and analysis of the proposed system.

In ZETA converter because of using inductor in series and capacitor in parallel at its output side, this converter gives a smooth and ripple free output voltage. Its second main advantage is that unlike Buck-Boost and CUK converter its output polarity does not changes. It has only one switch while many other DC-DC converters (like charge pump) has multiple switches which make the control system more complicated. Using single switch converter is more preferable because of less power losses. Its efficiency is more than other converters like Buck-Boost converter. It works best in less solar radiation. ZETA converters output voltage polarity is positive that can be more than, same or less than input voltage.

Charge controller's property is that it control the charging and discharging phenomena of battery. There exist a cut-off circuit which charge and discharge battery between the required conditions and it is also used to prevent deep discharging, as a result the life of battery is increased along with reduction of power loss, which indirectly makes the system more efficient. In charge controller we can also give power to alternative load when the battery is fully charged.

II. OPERATION OF ZETA CONVERTER

A simple circuit diagram of a ZETA converter is shown in Figure 2.1, consisting of two coupled inductors "L1.1" and "L1.2", output capacitor "C_OUT", one AC coupling or flying capacitor "C_COUPL", input capacitor "C_IN", also a MOSFET "Q1" and a diode "D1".
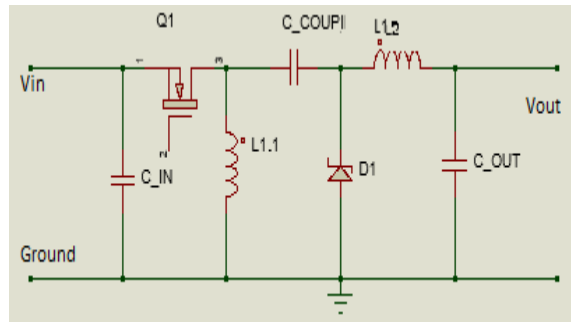

Figure 2.1: ZETA Converter.

Figure 2.2 and 2.3 shows the operation of ZETA converter in continuous conduction mode when Q1 is close/on and off/open. When both switches (Q1 & D1) are off/open and not switching, Capacitor C_COUPL will become in parallel with C-OUT, so C_COUPL is charged up to voltage magnitude that is equal to the output voltage, "Vout". During continuous conduction mode operation the voltages across L1.1 and L1.2 are shown in figure 2.2 and 2.3.
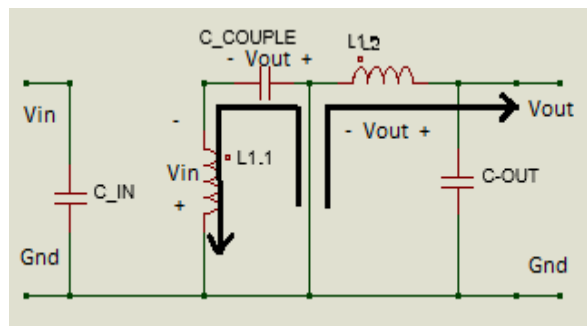
Figure 2.2: When Q1 is off/Open.

When MOSFET is off/open, the voltage across L1.2 will be Vout as it is in parallel with C-OUT. C-OUT will be charged up to the voltage level equal to Vout. When MOSFET will be off/open the voltage across it will be sum of input and output voltages. Because of this the voltage along L1.1 will be –Vout with respect to the drain of MOSFET.
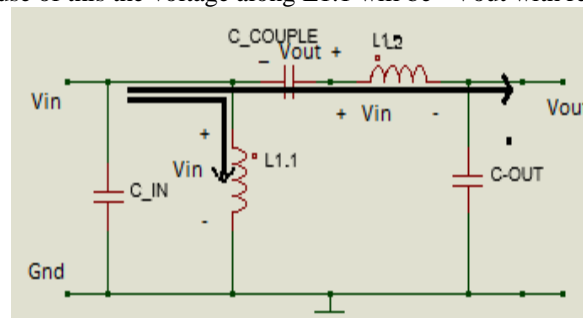

Figure 2.3: ZETA converter when Q1 is on.

When the switch (MOSFET) is on/close, capacitor C_COUPL, will charged equal to the magnitude of output voltage, which (coupling capacitor) is here connected in series with L1.2. Because of this voltage along L1.1 is equal to Vin, so at this time the voltage across diode will be sum of input and output voltage. See figure 2.3.

When Q1 is on/close, power coming from source will be stored in L1.1, L1.2 and C_COUPL. At the same time L1.2 also gives output current "Iout". When Q1 becomes off/open, diode will be forward biased and current from C_COUPL flows through L1.1 and L1.2 again gives Iout.

III. ZETA CONVERTER ALONG WITH CHARGE CONTROLLER

In existing systems there is an extra switch used to isolate converter from load, battery or source which disturbs the power of line. See Figure 3.1
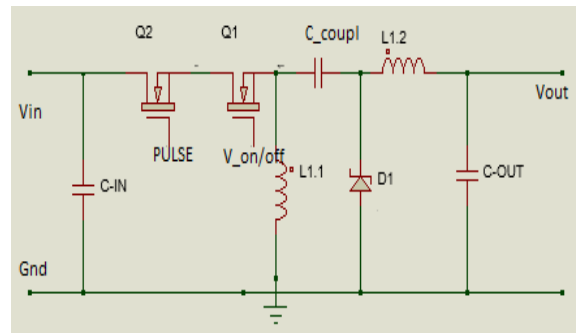

Figure 3.1: Two switches in series with line voltage.

Here ZETA converter is shown with two switches (Q1 & Q2) in series at its input side (according to required condition 2nd switch "Q1" may exist at output side of the converter). One switch is for Pulse (Duty Cycle) and other is for source/load cut-off signal. When both switches will work the converter will pass power.
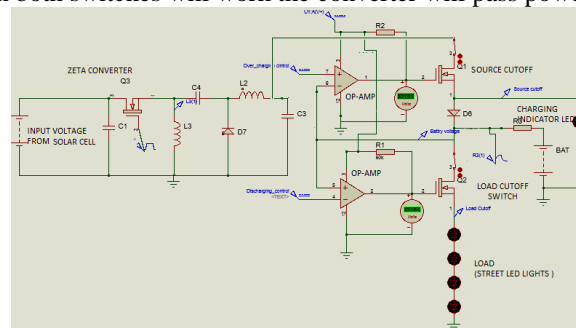

Figure 3.2: ZETA converter with Source/load cut off circuit.

In Figure 3.2 ZETA converter along with charge controller circuit is used. Extra switches requires extra cast and also power loss occurs. Below is the graphical response of circuit.
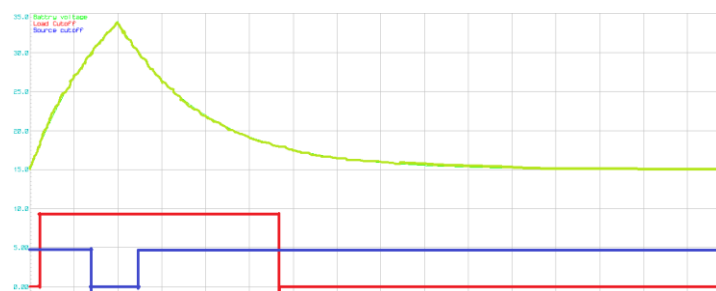

Figure 3.3: Cut off circuit response.

Figure 3.3 shows graphical response of the circuit of figure 3.2. Exponential signal (green) indicates a battery voltage signal while blue signal shows source cut off to prevent battery from over charging at 28.5v and red signal indicate load cut off at 22 volts to prevent battery from deep discharging. This is simplest charge controller we have only as an example when ZETA converter and charge controller are used apart.

In diagram 3.2 LEDs in series indicates load while single LED indicate charging and discharging of battery.

IV. ZETA CONVERTER AS A CHARGE CONTROLLER

ZETA converter can be used as a charge controller. To understand it an example of the circuit is given below in fig 4.1. ZETA converter has the property that it can be used to reduce or boost the output voltage so we can use this converter both at the charging and load side according to our requirements.
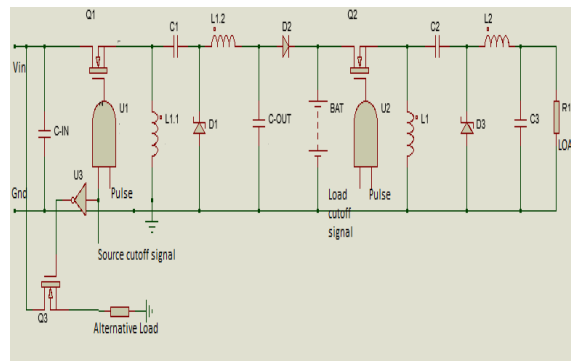
Figure 4.1: ZETA converter as a charge controller.

Using NSS, The diagram 4.1 contains two ZETA converters. One is before the battery and second is after the battery. Left sided converter charge the battery by boosting or reducing the output voltage while right sided converter will give the required power to the load.

AND gates (U1 and U2) shows that when two control inputs (MOSFET switching pulse+Source/load cut off signal) are high, switches Q1 or Q2 will pass power. The compliment of source or load on/off pulse will switch on/off the alternative load switch.

In our proposed system ZETA converter based charge controller will be used so the circuit will be designed for Load voltage of 24 volts. The solar panel generally has output of 18 volts to charge the 12 volts battery. ZETA converter has less loss of power in boosting the voltage than reducing it at its output side So, according to our requirement we will use ZETA converter to boost 18 volts output of solar panel to 28 to 30 volts to charge 24 volts battery. We can use this voltage directly to power up street lights without transforming its amplitude with the help of converter. So, power loss will be reduced and with the help of only one converter we can full fill our requirements.

## V. USING OF FILTER BEFORE LED STREET LIGHTS LOAD

A filter may be used to give a smooth power to LED street lights.

First, at output side of battery and between the load an extra filter can be used for the purpose. See figure 5.1.
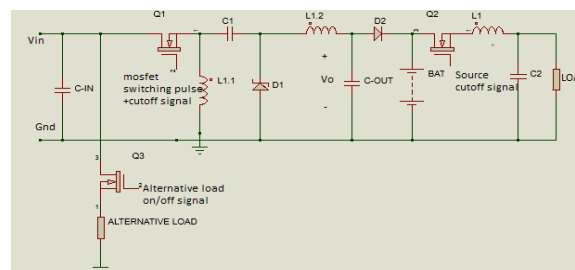
**Figure 5.1:** ZETA converter with extra filter at load side of battery.

Second, we know that solar power is produced at day time and consumed for street lights purpose at night time, so converter will remain off at night time so we can use the ZETA converter capacitor and inductor for our purpose. Second choice is most cost effective. Figure 5.2 shows the circuit diagram for the defined purpose.
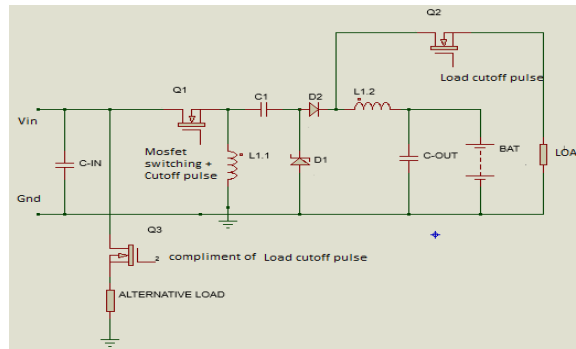
Figure 5.2: ZETA converter with output filter (more optimized).

VI. OPTIMIZED DESIGN

We know that at night time ZETA converter will be off so, there is no disturbance in current flow from battery to the load and because of this, output filter before the load is not required. The most optimized form of the design is in figure 6.1.
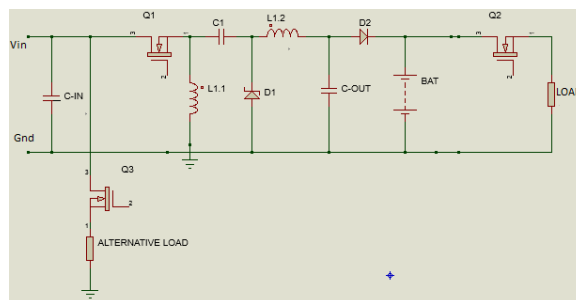
Figure 6.1: Optimized circuit of ZETA converter as a charge controller.

We can use programmable IC for switching of Q1 and Q2 which can further reduce losses.

VII. DESIGN OF ZETA CONVERTER COMPONENTS

Our Design output voltage is 28.5 volts to charge the battery while input voltage is 15 to 20 volts that we have taken from solar panel. Minimum switching frequency (Fsw) is 100KHz.
Maximum and minimum duty cycle (D) for the operation of ZETA converter is

$$Dmax = \frac{Vout}{Vout + Vin\_min} \quad (1)$$

$$Dmin = \frac{Vout}{Vout + Vin\_max} \quad (2)$$

Vout is output voltage while Vin is input voltages of the converter.

$$L1 = L2 = 0.5 \times \frac{Vin\_min \times Dmax}{\Delta IL(pp) \times Fsw} \quad (3)$$

$\Delta IL(pp)$ is inductors peak to peak ripple current.

$$Cout \geq \frac{\Delta IL2(pp)}{8 \times \Delta VCout(pp) \times Fsw} \quad (4)$$

While $\Delta VCout(pp)$ is output peak to peak ripple voltage that is along output capacitor. is peak to peak ripple current of L2.
We can get the value of input capacitor from following equation.

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 6, June 2016

$$Cin = \frac{Iout \times Dmax}{\Delta VCin(pp) \times Fsw} \qquad (5)$$

Where $Iout$ is output current. is input ripple voltage along input capacitor.
The value of flying capacitor can be determined by the following formula.

$$Ccoupl_{min} = \frac{Dmax \times Iout}{\Delta VCcoupl(pp) \times Fsw} \qquad (6)$$

$\Delta VCcoupl(pp)$ is ripple voltage of coupling or flying capacitor.

The switches (MOSFETs in the design) must bear the maximum currents that pass through them.

So, for Vin =15-20 V, Vout=32 V and MOSFET switching frequency Fsw $\geq$100 KHZ, (after calculation) we have got follow-ing values by using equations 1-6.

Parameters	Values
Duty Cycle(D)	62-67%
Coupled Inductors(L1,L2)	72μH
Coupling capacitor(C_COUPL)	23μF
Input Capacitor(C_IN)	50μF
Output Capacitor(Cout)	30μF (min)

Table 1: Components values of ZETA converter.
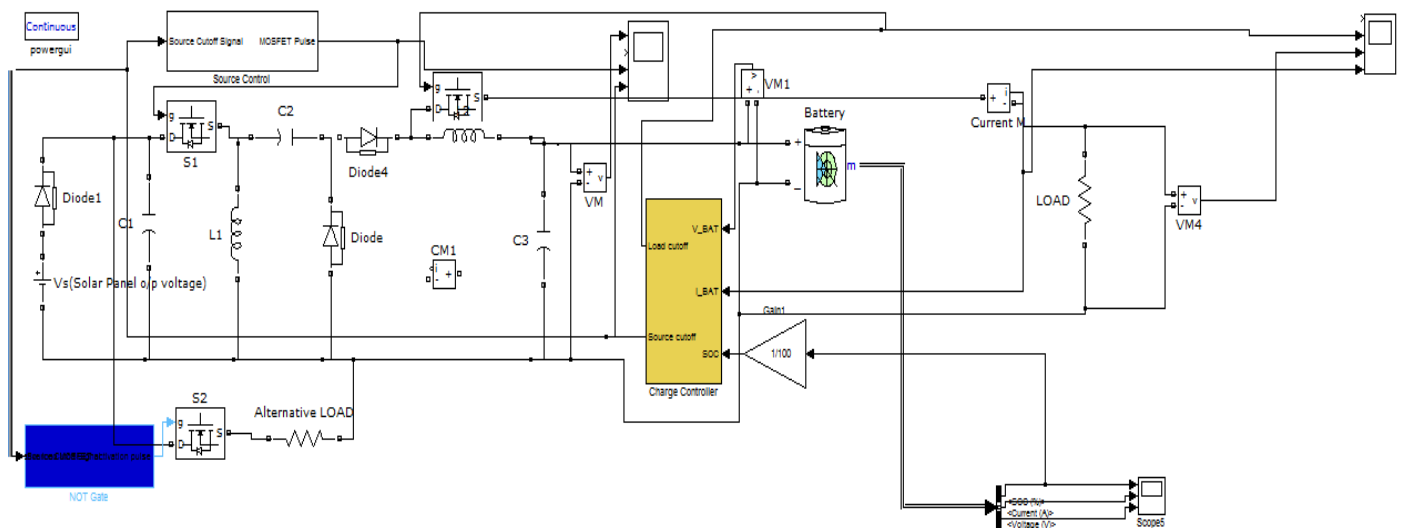

Figure 8.1: Simulink model of Figure 5.2.

The graphical response of designed circuit of Figure 8.1 is shown in figures 8.1.1-8.1.4. A half sine wave is given in place of battery voltage to check the response of load cut off circuit with respect to change in voltage of battery. This analysis is done in specific case when we are using the components of our ZETA converter for filter between battery and load at night time. Figure 8.1.1 shows half sine wave.
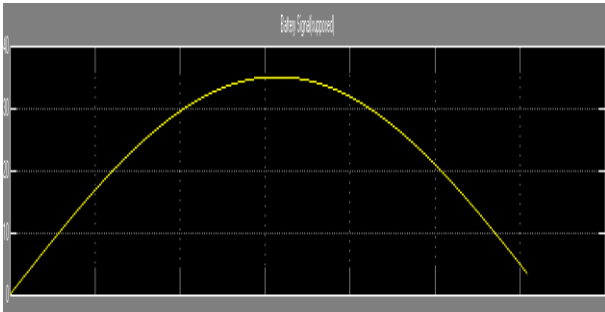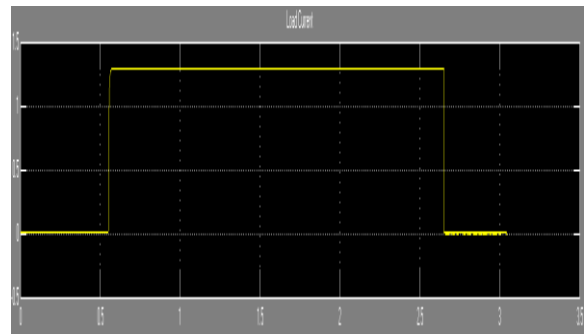
Figure 8.1.1: Battery signal (supposed).

Figure 8.1.2: Load cut off signal.
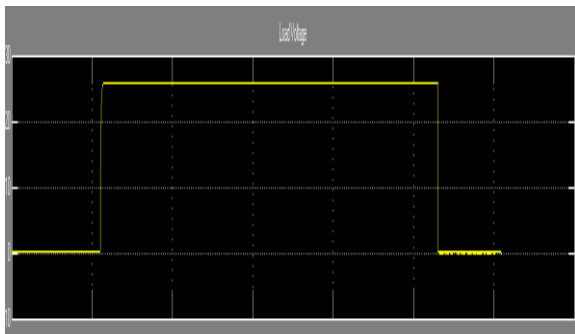
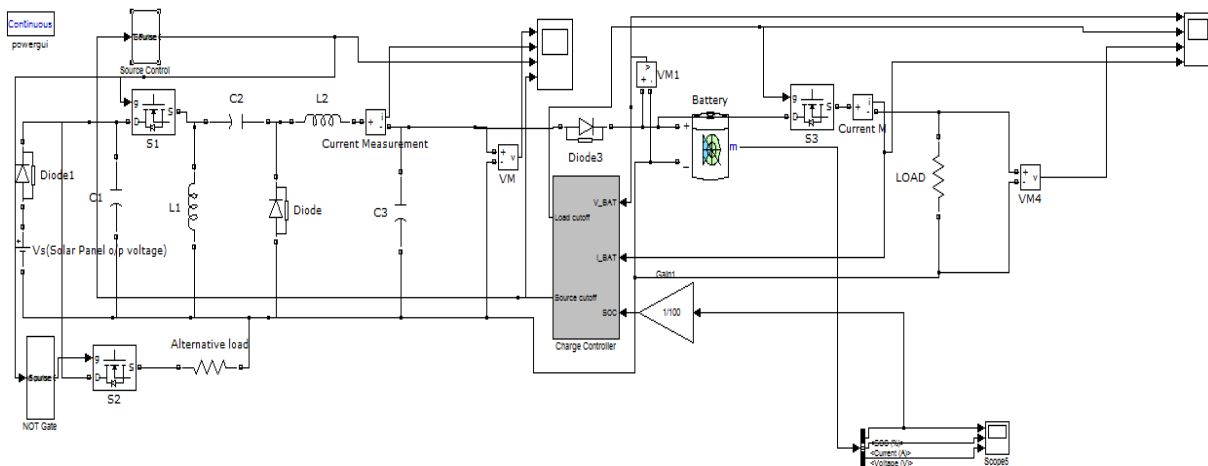**Figure 8.1.3:** Load voltage (25v).

Figure 8.1.4: Load current (2Amp).

Load is connected at 21v and above that we have set threshold voltage for load cutoff (Figure 8.1.2). With switching of load we can see output voltage 24 v and current almost 2 A in figure 8.1.3 and 8.1.4 respectively.

VIII. OPTIMIZED DESIGN

Below is the Simulink model of our final and optimized street lighting system.

Figure 8.2: Simulink model of Figure 6.1.

In diagram 8.2.1 MOSFET switching pulse of ZETA converter is shown. Frequency of this pulse is more than 100 KHZ and Duty cycle (D) is 62-67% for our design.
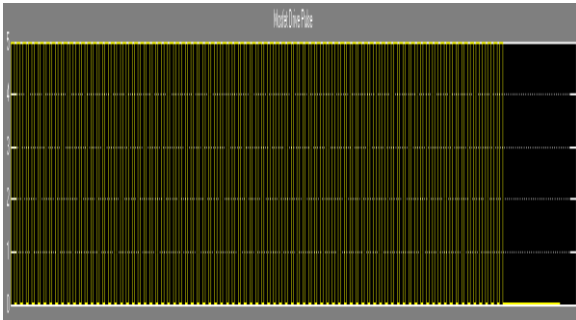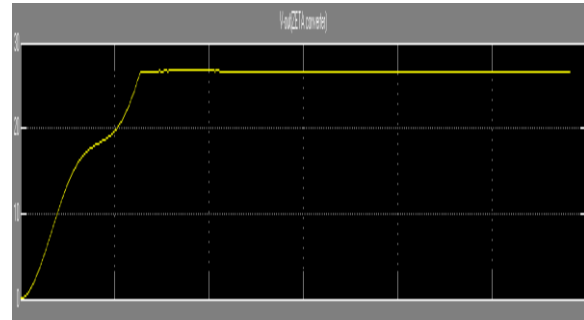
Figure 8.2.1: MOSFET drive pulse.
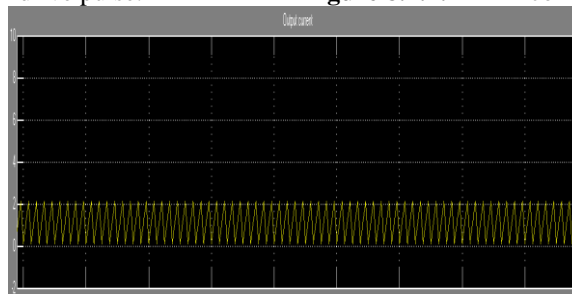

Figure 8.2.2: ZETA converter output voltage.

Figure 8.2.3: ZETA converter output current.

M non Our designed ZETA converter output is almost 28.5 volts to charge the 24 volt battery as we can see in graph of figure 8.2.2, while in Figure 8.2.3 output ripple current is shown. We scaled this current before inductor L1.2 in figure 6.1.

Now we will check the response of the same converter as a charge controller.

8.1. Effect of Voltage on Source/Load cut off:

The A half Sine wave signal is given to check the response of circuit at different voltage levels of battery. See figure 8.2.4.
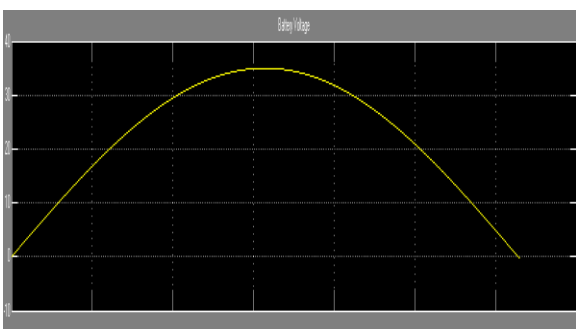

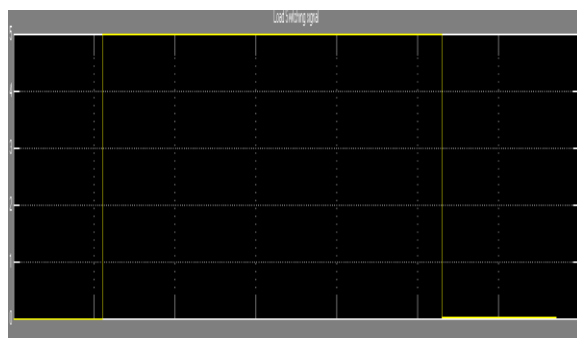**Figure 8.2.4:** Battery voltage (supposed).
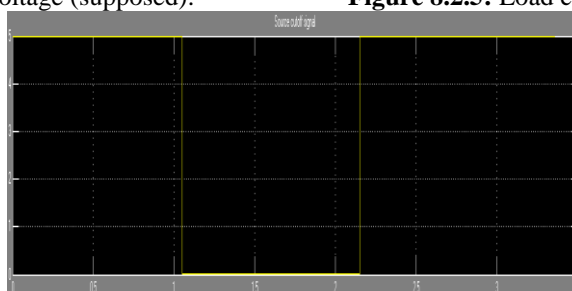

Figure 8.2.5: Load cut off signal.

Figure 8.2.6: Source cut off signal.

As in upper model of figure 8.1 it is stated that we design our load cutoff circuit to disconnect load below 21v while here source cut off circuit is design to disconnect source above 29v. So, we can visualize our load and source MOSFET switching signal in diagram 8.2.5 and 8.2.6 respectively according to change in voltage in diagram 8.2.4.

8.2. Effect of State Of Charge (SOC%) on Source/Load cut off:
In the following graph we analyse the effect of state of charge of battery on MOSFET switching signal. We have designed our system to charge the battery between 40% and 90% state of charge to prevent over charging and deep discharging of battery. It controls addition of extra current in battery.

In figure 8.2.7 the signal shows the state of charge of battery.
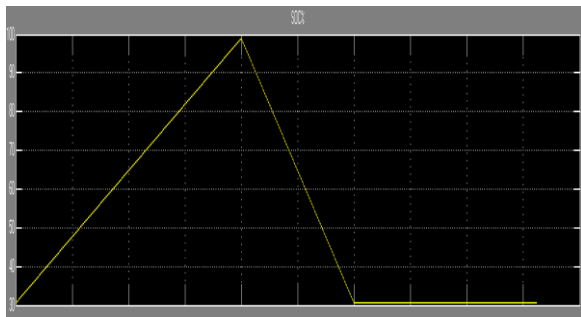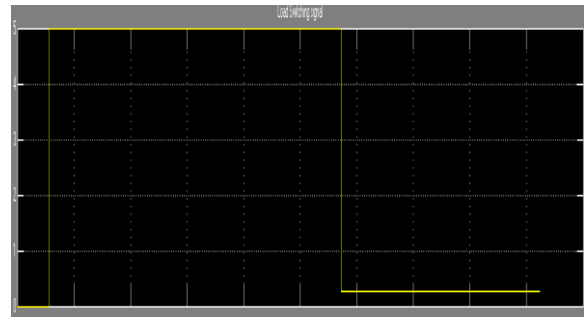

Figure 8.2.7: State Of Charge (SOC%).

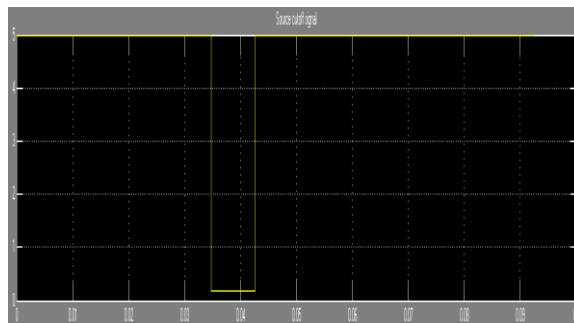**Figure 8.2.8:** Load switching signal.

Figure 8.2.9: Source Switching Signal.

Figures 8.2.8 and 8.2.9 shows the effect of state of charge on load and source cut off signals.
When battery charging reaches at the level of 90% the source is disconnected to prevent battery from over charging and be-low 40% load is disconnected so that battery cannot become deep discharged.

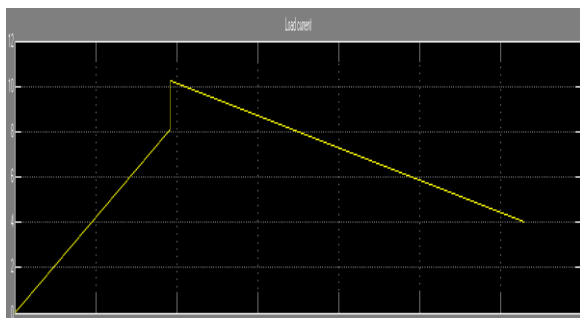### 8.3. Effect of load current on load cut off:

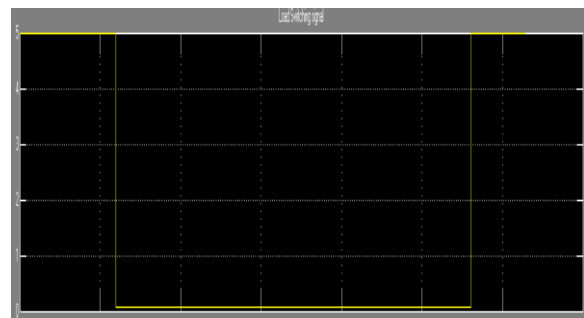**Figure 8.2.10:** Load current signal.

Figure 8.2.11: Load switching signal.

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)
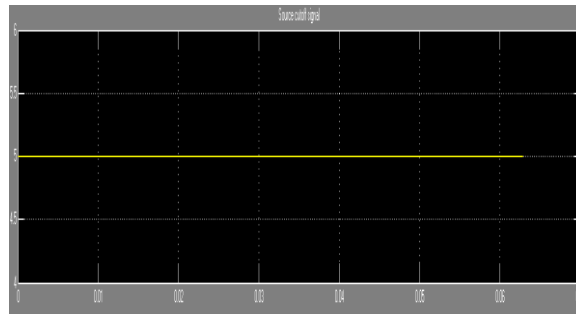
Vol. 5, Issue 6, June 2016

Figure 8.2.12: Source switching signal (5v).

If load current increase more than a limit (5A in this case) than load is disconnected from battery. Figure 8.2.10 shows the current drawn by the load from battery and 8.2.11 and 8.2.12 gives us response of load and source switching signal according to the current. Source will remain on while load is disconnected when current exceeds the limit of 5A and reconnected when load current becomes less than defined value.

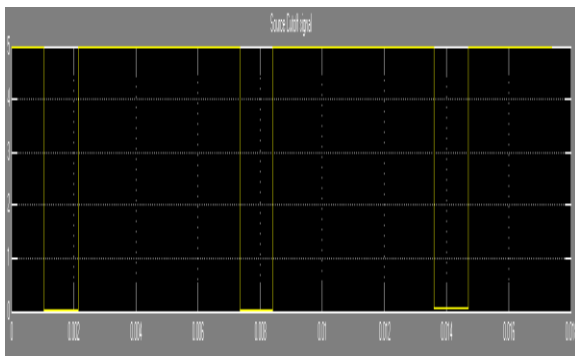**8.4. Output voltages, currents and MOSFET drive pulses with respect to source cut off signal:**

Figure 8.2.13: Source cut off signal.

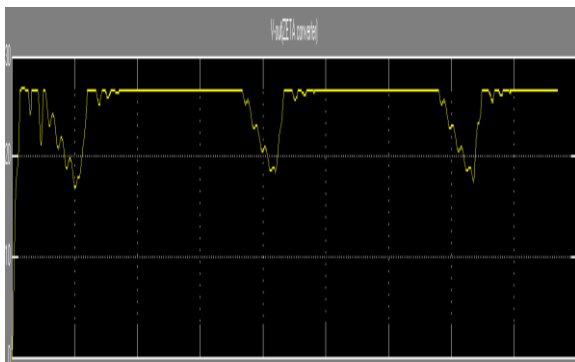**Figure 8.2.14:** MOSFET drive pulse.

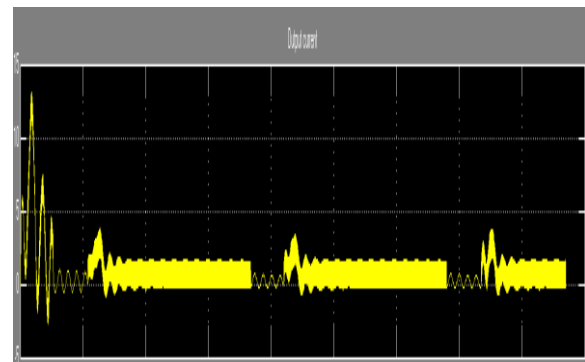**Figure 8.2.15:** ZETA converter output voltage.

Figure 8.2.16: Output current of ZETA converter.

With respect to source cut off signal of figure 8.2.13, MOSFET switching pulse takes the shape shown in figure 8.2.14. So, output voltage of 28.5 volts is shown in diagram 8.2.15. While charging current of 2 Amp can be viewed in Figure 8.2.16. With switching of MOSFET the current is disconnected and reconnected from battery. The output voltage becomes zero when switch is off. Figure 8.2.15 shows only reduction of voltage when switch is off because the switching time is fast. We can observe it more properly when the off spam of switch is more, as in real case.

8.5. Alternative load connection control:

Alternative load MOSFET drive pulse of auxiliary load is compliment of source cut off signal. See figure 8.2.17. So, when the source is cut off with default system alternative load will be connected.
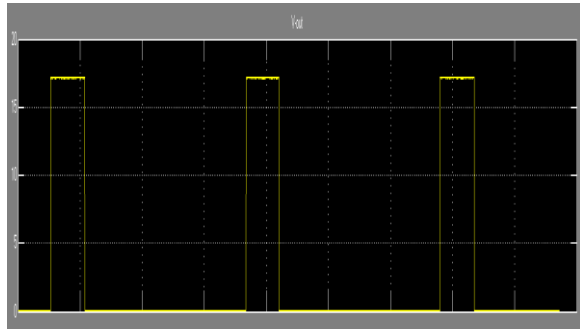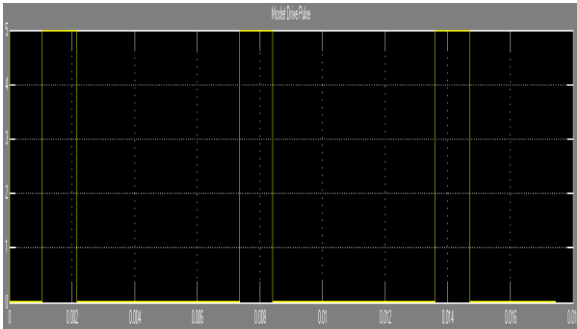

Figure 8.2.17: MOSFET activation pulse of auxiliary load.

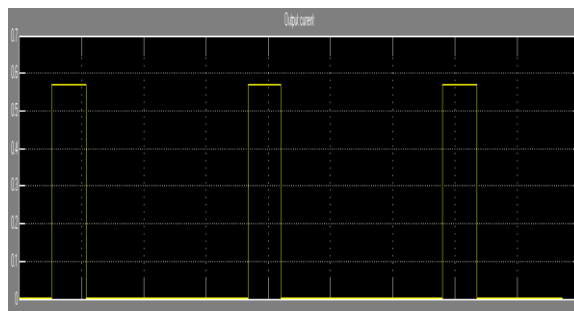**Figure 8.2.18:** Voltage across alternative load

Figure 8.2.19: current across alternative load.

In diagram 8.2.18, voltage of alternative load is shown, which is18v (equal to source voltage) and figure 8.2.19 is graph of current for auxiliary load. Here it draws 0.7A from the source.
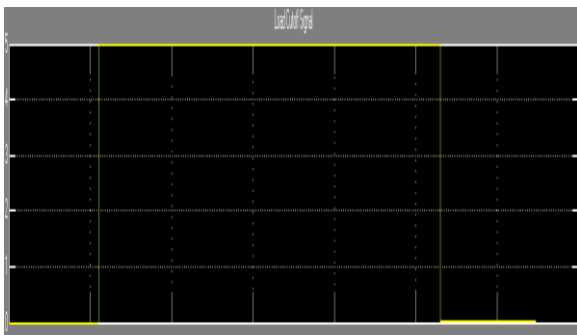
8.6. Load cut off:
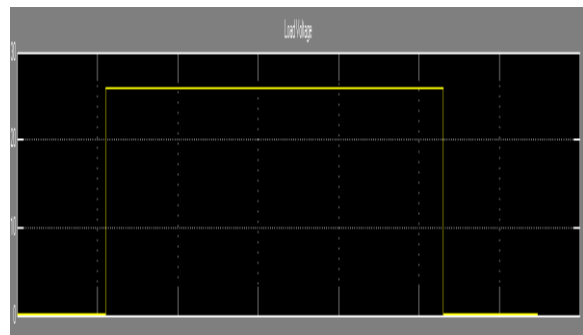

Figure 8.2.20: Load cut off signal (5v).

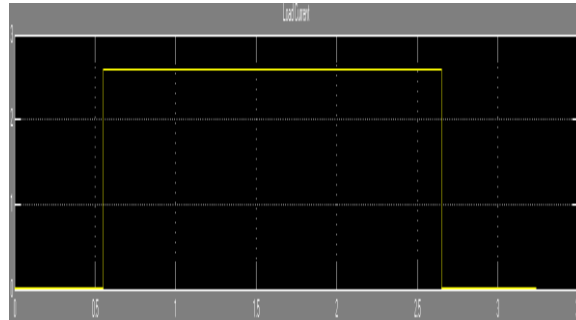**Figure 8.2.21:** Load voltage (24v).

Figure 8.2.22: load current (2 Amp).

So, at the end of this graphical analysis we can visualize the load voltage and current against load switching pulse of figure 8.2.20. The voltage is 24 v while current is almost 2 Amp. Figure 8.2.21 and 8.2.22 show us this voltage and current. Here total power is 48W. We can use/change switch (MOSFET) according to the current required for the load.

IX. COMPARISON OF RESULTS

Four cases of optimization mentioned below have been discussed to reduce losses and cost.

(a) Converter has been used at one side (Load side) instead of both charging and discharging sides of battery which reduced power loss in addition to reduction of components cost.
(b) In case of any requirement of filter to provide continuous current to the LEDs of street lights for their safety, design and analysis of circuit has been discussed by using same components of converter that are used at charging side, as a result extra cost for filter design has been reduced.
(c) An Optimized circuit has been designed without using filter at other side, ultimately reducing the power loss and cost required for components.
(d) Switch of ZETA converter has been used for switching pulse and cut off signal. So ZETA converter is working itself as a charge controller, because of this disturbance, power loss and cost spent on components is also reduced.

X. CONCLUSION

There are three important properties that a converter should have in order to use it in our proposed system.

(a) Its output voltage polarity should not change w.r.t input voltage.
(b) Using it as a charge controller it should have switch in series so that we can use same switch to control flow of energy.
(c) Converter should have property to boost or reduce the output voltage so that we can use it at any place (charging side or load side) according to our requirements.

Amongst Buck, Boost, Buck-Boost, CUK, SEPIC and ZETA converters only three converters such as Buck, Buck-Boost and ZETA converters have switch in series of line voltage (source) whereas only SEPIC, ZETA and Buck-Boost converters can be used to step-up and step-down the output voltage. Generally used Buck-Boost converter's output voltage polarity is opposite to input voltage while SEPIC converter has switch in parallel (between voltage and ground). So, ZETA converter is best choice for solution of our problems because it fulfills all our requirements while its efficiency is also better than many other converters. In short, for street lighting and other solar energy based systems, ZETA converter is best amongst all DC-DC converters because of its special properties. In future non-inverting Buck-Boost converter may be used for the purpose.

REFERENCES

1. J Kamala, K Aishwarya, Centralized Architecture to Improve the Efficiency of PV Street Lighting System, IEEE SPONSORED 2ND INTERNATIONAL CONFERENCE ON ELECTRONICS AND COMMUNICATIONSYSTEMS (ICECS '2015).
2. J Patel(stu.), C Hina (Asso Prof), et al. Bi-directional DC-DC Converter for battery charging - discharging Applications using Buck-Boost switch" IEEE' Conference on Electrical, Electronics and Computer Science, 2012.
3. F Jeff, Designing DC/DC converters based on ZETA topology, Texas Instruments Incorporated.
4. M Mona, A Sarala, et al. Design and Simulation of DC-DC Converters for Photovoltaic System based on MATLAB" International Conference on Industrial Instrumentation and Control (ICIC) Col/ege of Engineering Pune, India. May 28-30,2015.
5. G Srinivas Reddy, KL Vara , A Novel Bidirectional DC-DC Converter with Battery Protection" International Journal of Modern Engineering Research (IJMER),Dec 2012.
6. A Ajan., K Prem Kumar, Performance Analysis of OFF-GRID Solar Photo Voltaic System" 2015 International Conference on Circuit, Power and Computing Technologies [ICCPCT].
7. E Sanchis-Kilders, A Ferreres, et al. Soft Switching Bidirectional Converter for Battery Discharging-Charging.
8. AH El Khateb, AR Nasrudin, et al. Ćuk-Buck Converter for Standalone Photovoltaic System" Journal of Clean Energy Technologies, 2013; 1: 1.
9. JL Durán-Gómez, E García-Cervantes, et al. Analysis and Evaluation of a Series-Combined Connected Boost and Buck-Boost DC-DC Converter for Photovoltaic Application.
10. E Robert and M Maksimovic,, High Efficiency DC-DC Converters for Battery-Operated Systems with Energy Management, University of Colorado.
11. J Viji, PC Thomas, Grid Connected Mode of Micro-grid with Reactive Power Compensation", 2013 International Conference on Advanced Computing and Communication Systems (ICACCS -2013), Dec. 19 – 21, 2013, Coimbatore, INDIA.
12. A Jitty, K Vasanth, Design and Simulation of Pulse-Width Modulated ZETA Converter with Power Factor" International Journal of Advanced Trends in Computer Science and Engineering, 2013; 2: 232- 238.