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RURAL ELECTRIFICATION WITH RENEWABLE ENERGY FED DC MICRO GRID

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Abstract

Surveys and statistics showing a majority of rural areas and remote places in third world countries are far from accessing electricity and facing power shortage. One important reason for this circumstance is power generating plants distant from rural areas. Despite of AC utility grid most of the loads requires power converters to obtain regulated DC. Also power conversions required in DC grids are less when compared with AC grids. Abundant Renewable energy like solar photovoltaic has the potential to provide the solution for rural electrification through DC microgrids. This article presents the design, analysis and simulation of photovoltaic based DC microgrid system with low cost DC household which is not connected to a utility Grid. The proposed system suited for running approximately 125 watts loads useful for daily routine. The Proposed system utilizes a Boost converter as a front-end converter to regulate the required DC bus voltage for forming a DC microgrid. The fly-back converter is used as a point of load converters to meet different load specifications. A simulation study of the proposed system is done in PSIM 9.0.

Keywords : DC micro-grid, Rural Electrification, Solar, Photovoltaic, Front-end Converter, POL Converter

I. Introduction

Renewable energy resources can protect environment and foster nation's economy in greater extent. Solar photovoltaic systems are potential renewable sources to provide sustainable power generation solution to rural areas and remote places. Despite

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the emerging technologies and globalization electrification of rural areas is still lacking and needs attention. Many people in rural areas are living in dark without electricity needs. Higher initial costs and operating cost made traditional utility grids not reachable to remote rural areas. This opens platform to emerge new technologies to fill the gap between electricity and accessibility to remote rural areas. As on today nearly 1.5 billion people do not have accessibility of electricity and 2.8 billion people still using biomass for cooking purpose [I]. Current electricity generation produced from fossil fuels, coal and natural gas arise many problems such as global warming and sustainability issues. Fossil fuels are reserved and one cannot be estimated exactly how much time do they exist. Surveys shows that approximately 50, 60, and 200 years left for Crude oil, Conventional gas, and coal respectively remain as per present consumption rate [VIII]. This is an much important concern to think on particularly highly populated countries like India and China will increase the consumption of fossil fuels even further leading to scarcity of them on Earth.

To obtain the objective of sustainable power generation renewable energy resources are helpful. Sun is the ultimate source of energy but due to intermittent nature of solar power auxiliary energy storage system is needed. In one of the survey at "Virginia Tech's Center for Power Electronics systems, it was shown 85% of all electricity goes through AC-DC conversions and losses occurred at each conversion stage are multiplicative which will degrade the overall efficiency of the system" [VI]. The necessity of DC Appliances usage in residential houses and reduction of power conversion stages in the DC grid is favored with distributed generation [II]. Such grid is shown in Fig. 1. With more than 50% reduction in power converter stages. In tradition AC grid more power converter stages are required, moreover in modern world the power generated, transmitted and distributed in AC, but the utilization takes place in-terms of DC loads and Appliances. Examples of DC loads include LED lighting solutions, Television sets, DC refrigerator, water purifiers, consumer Electronic loads such as Laptops, Mobile phones, smart watches, BLDC motor for fans, air coolers and Pump sets etc.

Most of the rural areas in developing countries like India are receiving power only for few hours and some rural parts are not yet electrified though utility grid is available and connected. Survey shows as on May-2016, there are still 18,452 rural and remote places yet to receive electricity [X]. Scarcity of fossil fuels made power generating sector to look for alterative resources of energy for the power production, Most of the stakeholders accepted the fact of this and started investing in harnessing non-conventional resources [X]. Government of India support such investor and stakeholders with the help of providing subsidy and financial assistance which are helping country economic growth towards sustainability [XV].

"A study on feasibility of the DC distribution in Korean houses for different dc voltage levels is done in article" [IX]. Different research people with common interest had analyzed the low voltage DC micro grid and came to conclusion that 72-V and 48-V DC

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distribution systems for houses stationed adjacent to renewable resources with more cable area and less cable length will be much economical system [VII],[IV],[XVI],[XI].

In addition to conductors reduction DC grid enjoys advantages of zero reactive power loss due to zero frequency. No reactive components cause for losses [XVII] and also nullify the issues related to source side harmonics, power factor correction, Ferranti effect and skin effect [XII].

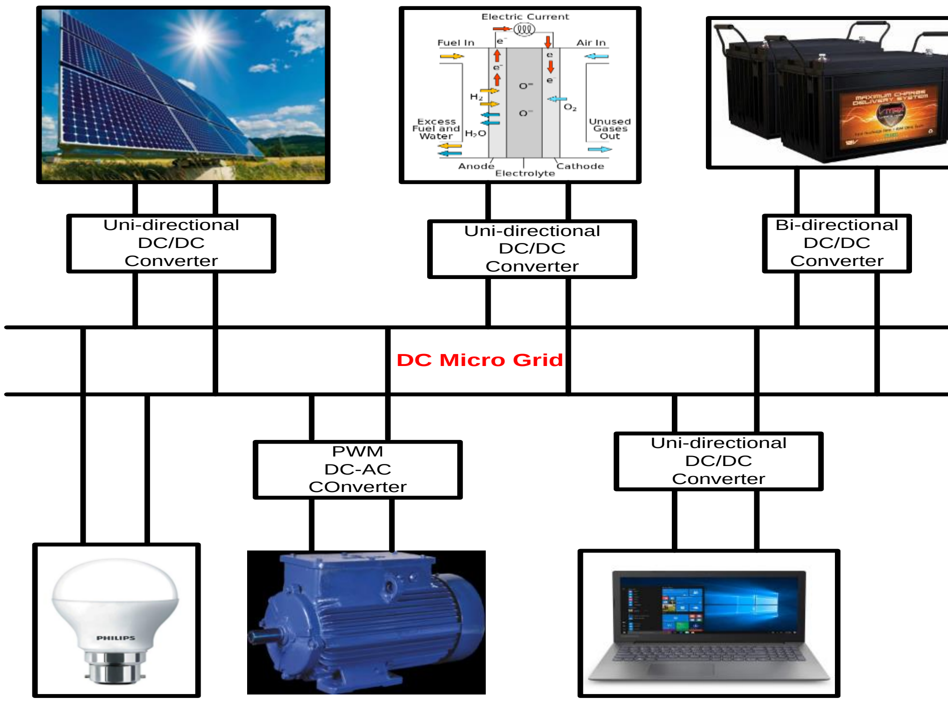

Fig 1. Structure of DC micro Grid

This paper arranged as follows section II discusses the DC bus voltage selection and literature survey of power converters. In section III design and analysis of the converters are present. In section IV simulation results of the proposed converter are discussed. Finally section V ends with conclusion.

II. Literature Survey and DC Bus Voltage selection

The block diagram of the DC micro grid for rural electrification is shown below in Fig. 2. Three power converters are presented in block diagram. The boost converter acts as front end converter to boost the low voltage DC from PV panel to meet the DC grid bus voltage 72V or 48V. Fly-back converter with multiple outputs act as point of load converter to meet multiple voltage levels required for different loads. Synchronous buck-

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boost converter acts as bi-directional DC-DC converter between energy storage system and DC bus. There are several standard distribution voltages in DC grids and these grids having several practical challenges in distributing a regulated power supply [IX]. DC Micro grids generally preferred low level distribution voltages to reduce the converter cable size, cost and also minimize protection issues [XVIII]. As another side of coin to reduce conduction losses distribution system voltages need to be increased for high power loads. In this research 48Volts DC distribution is considered for optimal performance of the system. For High voltage DC grid distribution 380 Volts is preferable.

The converter discussed in [XIII] shows the cascading help in achieving high gain without compromising efficiency. The methodology discussed in [III] is useful in building the model of PV array and check the I-V curves for maximum power point.

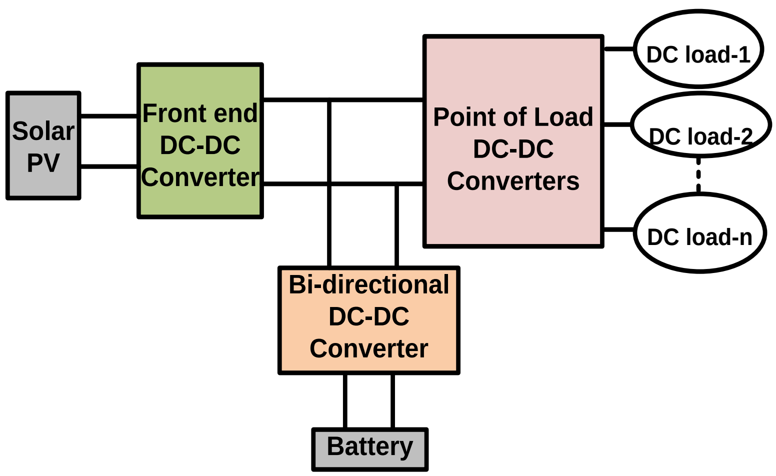

Fig 2. Block diagram of DC micro grid

In [XIX] soft switched converter is implemented to reduce the switching losses, but prevalently conduction losses increases there by degrading efficiency. In [V] auxiliary switch based converter is proposed to clamp the voltage with in limit, but additional switch causes changes in converter dynamics and system becomes complex in implementation for rural electrification application. In this work a simple fly-back converter with multiple outputs is considered as point of load converter taking the advantages of lowest part count and improved efficiency. Also for low power ratings residential dc houses fly-back converter is economical in operation and installation. Boost converter with optimal duty ratio is considered as front end converter to achieve active boosting with lesser space. Synchronous buck-boost converter is suited well for interfacing battery with high voltage DC bus. This converter operates in both buck

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operating mode as well as boost mode based on the switching sequence and current direction.

III. Design and Analysis of the Converters

A. Front-end Boost converter analysis and design

The following assumptions are followed for analyzing the converter performance in steady state a) All the components are ideal b) Input Boost Inductor 'L' and output capacitor 'C' are large enough to have negligible ripple content in inductor current and capacitor voltage. c) Switch ON for DT time and OFF for (1-D)*T time. The equivalent circuit diagram during switch ON time and OFF time is shown in Fig. 3. When the main switch 'S' is in ON condition boost inductor 'L' gets charged and load is supplied by capacitor. When the main switch 'S' is in OFF condition then the inductor 'L' gets discharged with falling current slope.

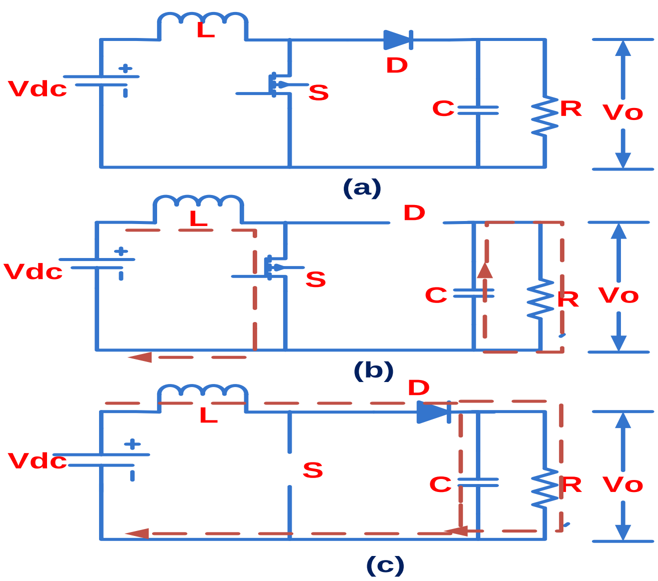

Fig 3. a) Boost converter circuit diagram b) ON state equivalent circuit diagram c) OFF state equivalent circuit diagram

During ON state VL=Vdc and OFF state VL = Vdc-Vo upon applying volt-sec balance the output voltage is expressed as

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

Capacitor voltage ripple and inductor current ripple are expressed as

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$$\frac{\Delta V_o}{V_o} = \frac{D}{R*C*F} \quad (2)$$

$$\Delta I_L = \frac{V_{dc}*D}{L*F} \quad (3)$$

B. Point of Load (POL) Fly-back Converter analysis and design

The following assumptions are followed for analyzing the converter performance in steady state a) All the components are ideal b) Magnetizing Inductor Lm and output capacitor ‘C’ are large enough to have negligible ripple content in inductor current and capacitor voltage. c) Switch ON for DT time and OFF for (1-D)*T time. The equivalent circuit diagram during switch ON time and OFF time is shown in Fig. 4. When the main switch ‘S’ is in ON condition magnetizing inductor ‘L’ gets charged and load is supplied by capacitor. When the main switch ‘S’ is in OFF condition then the inductor ‘L’ gets discharged with falling current slope and diode conducts on secondary side to supply load.

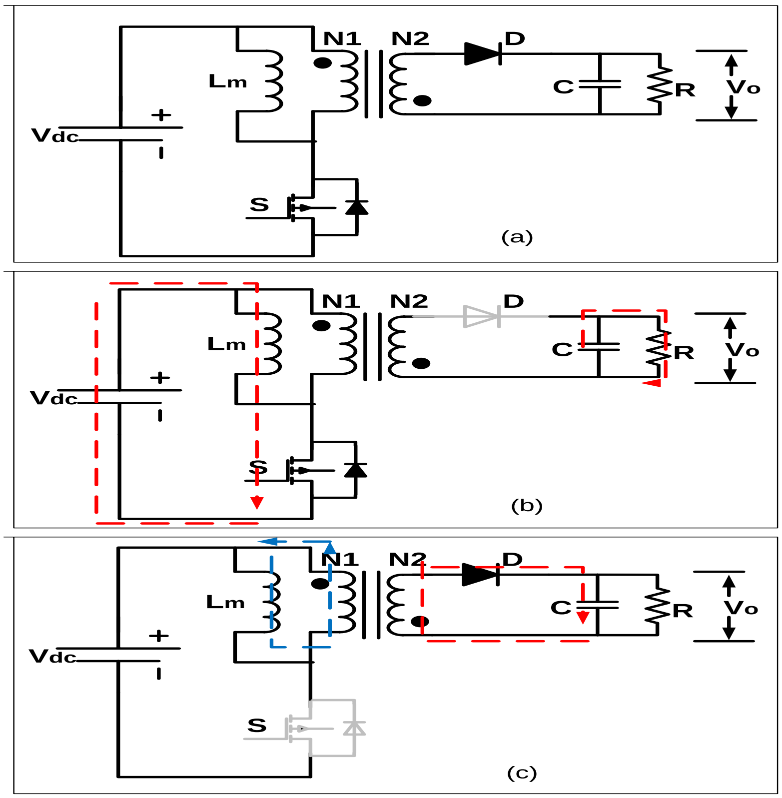

Fig 4. a) Fly-back converter circuit diagram b) ON state equivalent circuit diagram c) OFF state equivalent circuit diagram

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M. Sai Krishna Reddy et al

During ON time VLm = Vdc and during, Switch OFF time VLm = -Vo(N1/N2) upon applying volt-sec balance the output voltage is expressed as

$$V_o = \frac{(D*V_{dc})}{(1-D)}\left(\frac{N2}{N1}\right) \tag{4}$$

Capacitor voltage ripple and inductor current ripple are expressed as

$$\frac{\Delta V_o}{V_o} = \frac{D}{R*C*F} \tag{5}$$

$$\Delta I_{Lm} = \frac{V_{dc}*D}{Lm*F} \tag{6}$$

C. Bi-directional DC-DC Converter analysis and design

The following assumptions are followed for analyzing the converter performance in steady state a) All the components are ideal b) Inductor L and output capacitor 'C' are large enough to have negligible ripple content in inductor current and capacitor voltage. c) Switches S1 and S2 ON for DT time and OFF for (1-D)*T time and switching operation is complimentary that is when one switch is in ON condition other switch will be in OFF condition. The equivalent circuit diagram during switch ON time and OFF time is shown in figure-5.

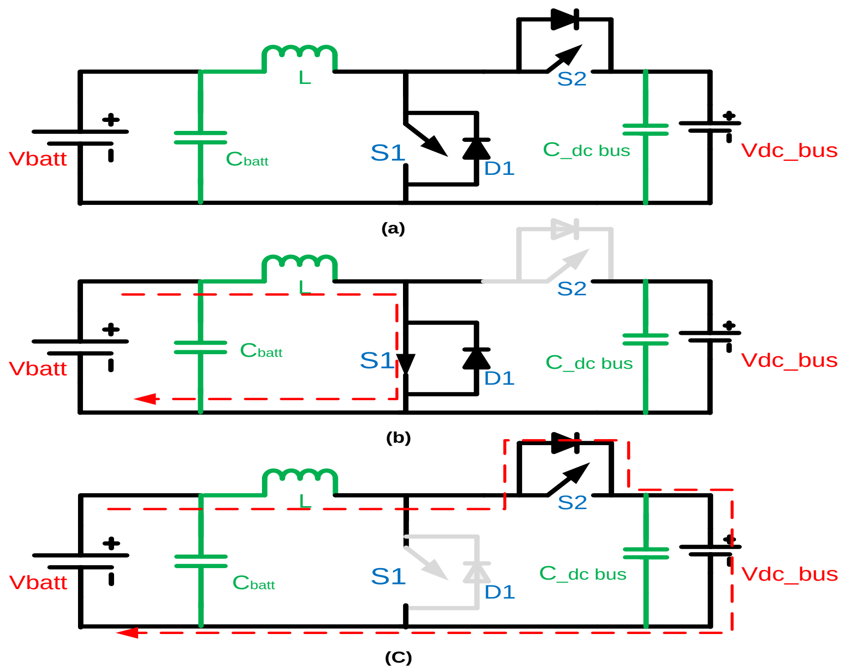

Fig 5. a) Bi-directional Converter circuit diagram b) ON state equivalent circuit diagram c) OFF state equivalent circuit diagram

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For boost operation Capacitor voltage ripple, inductor current ripple and DC gain are expressed as

$$\frac{\Delta V_{dc\_bus}}{V_{dc\_bus}} = \frac{D}{R*C\_dc*F} \quad (7)$$

$$\Delta I_L = \frac{V_{batt}*D}{L*F} \quad (8)$$

$$V_{dc\_bus} = \frac{V_{batt}}{1-D} \quad (9)$$

For buck operation the Capacitor voltage ripple and inductor current ripple are expressed as

$$\frac{\Delta V_{batt}}{V_{batt}} = \frac{1-D}{8*L*C\_batt*F^2} \quad (10)$$

$$\Delta I_L = \frac{V_{dc\_bus}*D}{L*F} \quad (11)$$

$$V_{batt} = D * V_{dc\_bus} \quad (12)$$

IV. Simulation Results and Analysis

The proposed dc micro-grid system for rural electrification is simulated numerically in PSIM 9.0. Five loads are considered for DC home in rural areas, the details of those loads are tabulated in table 1. Solar PV model is used for DC Source. Total Three DC-DC converters are considered for simulation front end boost converter, point of load fly-back converter with multiple outputs feeding multiple loads and auxiliary bi-directional dc-dc converter for battery charging and discharging. The design values and simulation specifications of the frontend converter are tabulated in table 2. The design values and simulation specifications of the point of load fly-back converter are tabulated in table 3. The design values and simulation specifications of the bi-directional dc-dc converter are tabulated in table 4.

Table 1: Identified Loads with specifications

Load type (Manufacturer)	**Ratings**
Mobile Phone Charger	10-watts, 5 Volts
Led Bulb (Philips)	9-watts, 12 Volts
Ceiling Fan (Gorilla Renesa-BLDC type)	28-watts, 12 Volts
Water Purifier (Liv Pure)	25-watts, 24 Volts
Led TV (LG)	50-watts, 24 Volts

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Table 2: Design Values and simulation Specifications of Front-end Boost Converter

S. No	Parameter	Values
1	Input Voltage from PV	24V
2	Output Voltage for DC bus	48V
3	Boost inductance (L)	1.5mH
4	Output side Capacitor	109uF
5	% Duty Cycle	50%
6	Switching Frequency	50kHz

Table 3: Design values and simulation specifications of POL Fly-back Converter

S. No	Parameter	Values
1	Input Voltage from dc bus	48V
2	Output Voltage levels for different loads	5V, 24V and 12V
3	Magnetizing inductance (Lm)	2.02mH
4	Output side Capacitor values for different loads	50uF,155.6uF, 34.7uF, 69.4uF and 320uF
5	Different resistor values for representing different loads	16Ω,5.14Ω,23.04Ω, 11.52Ω and 2.52Ω
6	% Duty Cycle	40%
7	Switching Frequency	50kHz

Table 4: Design Values and simulation Specifications of bi-directional DC-DC Converter

S. No	Parameter	Values
1	Input Voltage from PV	48V
2	Output Voltage for DC bus	24V
3	Output side inductance (L)	3.47mH
4	Output side Capacitor	0.72uF
5	% Duty Cycle	50%
6	Switching Frequency	50kHz
7	Load Resistance (based on battery charging current)	2.304Ω

PSIM schematic depicting proposed configuration with sub systems is shown in Fig. 6. The DC bus voltage obtained 48 Volts with 2% ripple is shown in Fig. 7. Front-end Boost

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converter input inductor current with 3% ripple of average inductor current is shown in Fig. 8. Voltage and current waveforms of mobile phone charger load with a ripple of 1% and 2% respectively is shown in Fig. 9. Voltage and current waveforms of led bulb load with a ripple of 1.66% and 2.5% respectively is shown in Fig. 10. Voltage and current waveforms of ceiling fan load with a ripple of 2.5% and 2.1% respectively is shown in Fig. 11. Voltage and current waveforms of water purifier load with a ripple of 1.66% and 1.88% respectively is shown in Fig. 12. Voltage and current waveforms of led TV load with a ripple of 2% and 1.8% respectively is shown in Fig. 13. Voltage and current waveforms of battery during charging with a ripple of 0.88% and 0.66% respectively is shown in Fig. 14.

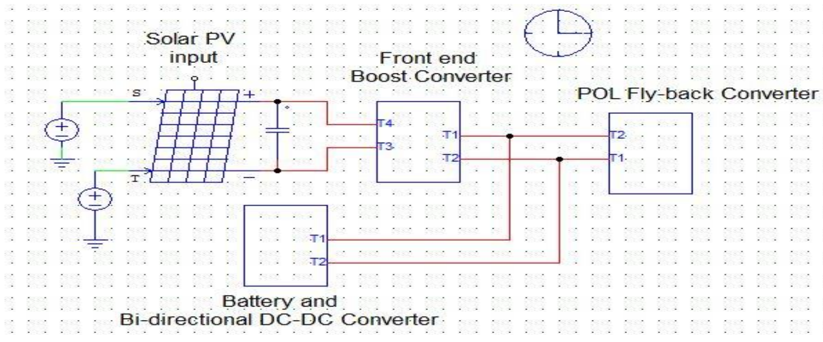

Fig 6. PSIM Schematic of the proposed system

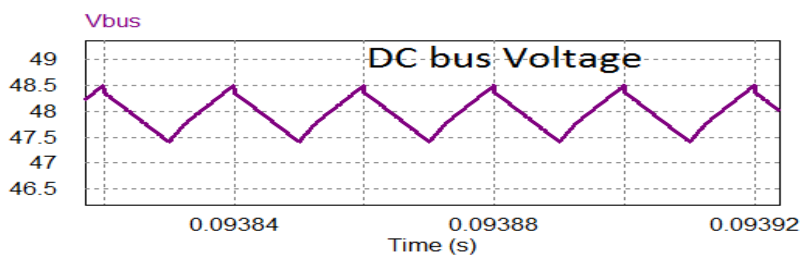

Fig 7. DC bus voltage of the proposed system

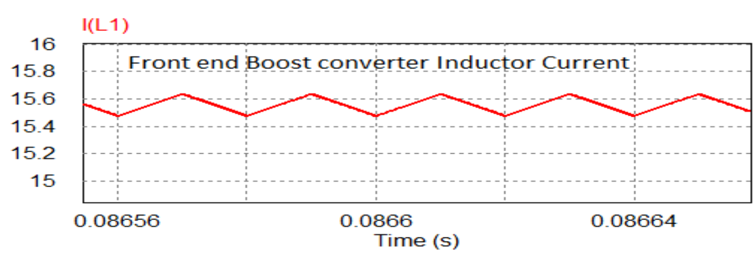

Fig 8. Front end Boost Converter Inductor Current

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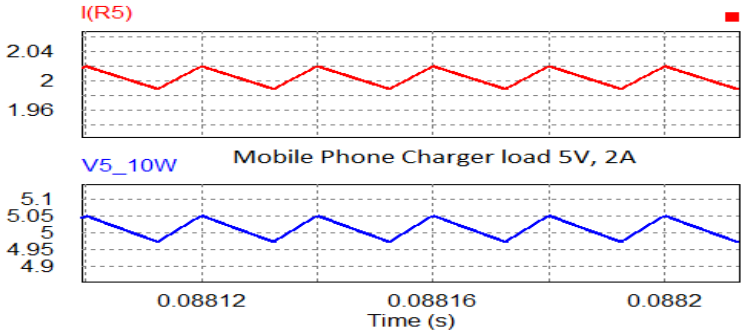

Fig 9. Voltage and Current waveforms of Mobile phone charger load

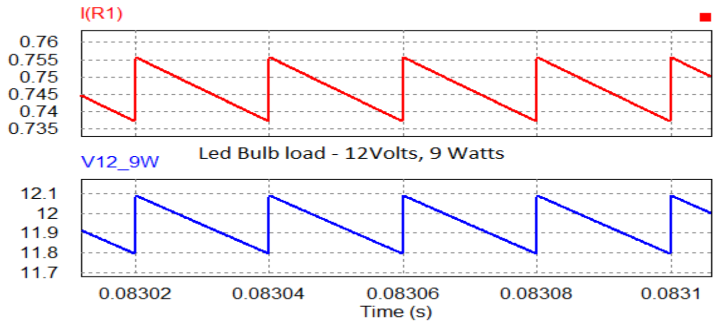

Fig 10. Voltage and Current waveforms of Led bulb load

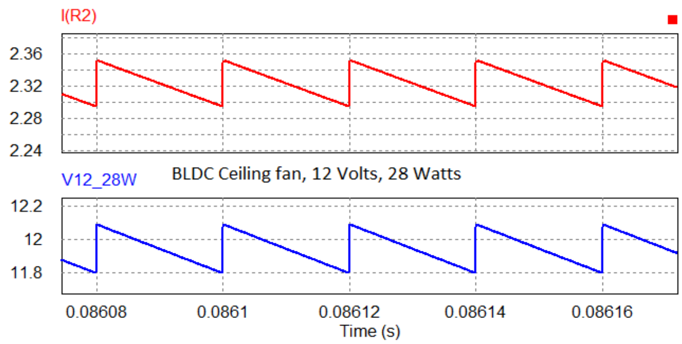

Fig 11. Voltage and Current waveforms of BLDC Fan load

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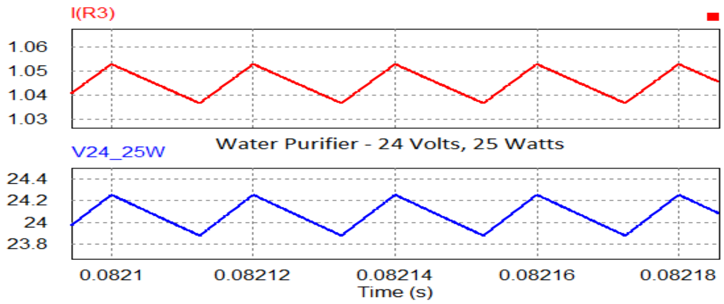

Fig 12. Voltage and Current waveforms of water purifier load

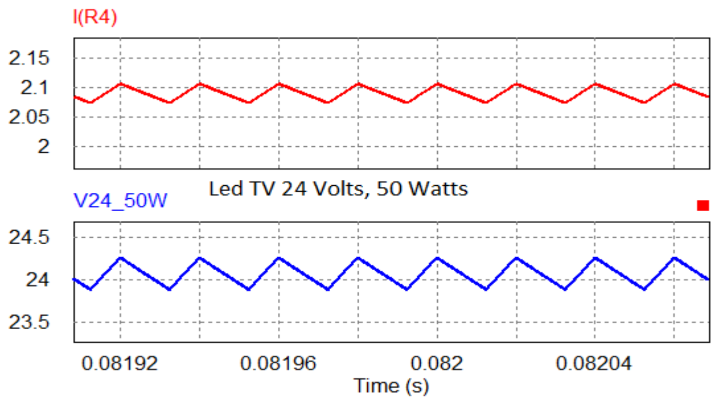

Fig 13. Voltage and Current waveforms of Led TV load

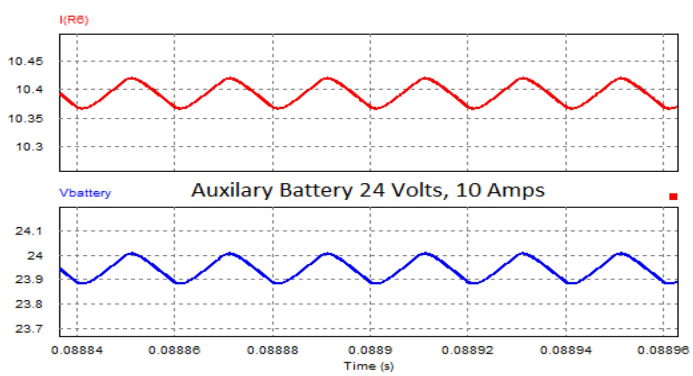

Fig 14. Voltage and Current waveforms of Auxiliary Battery

V. Conclusion

This research proposed a DC micro-grid system for electrifying rural households. Five essential loads are considered in the system and modeled. The proposed system able

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to meet loads of 125 watts continuously through Solar PV and auxiliary battery system. The converters employed in this work are simple to control and able to meet the load requirements. DC bus voltage is maintained at 48 V, which satisfies the low voltage grid standards in India. The design of the system show that current and voltage ripples of all converters are very low and negligible. By realizing the proposed system on a higher scale, the further scope of this research can be commercialized to see that goal of achieving 100% electrified villages.

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