A DC-DC VOLTAGE REGULATOR BASED BATTERY STORAGE USED IN RENEWABLE SYSTEM APPLICATIONS

Jalla Upendar[1], Samala Sreenivasulu[2], Sapavath Sreenu[3]
[1,2 and 3]*Department of Electrical Engineering, University College of Engineering, Osmania University, India.*

ABSTRACT : *The In DC –DC converter with energy storage system is proposed for renewable energy systems such as solar and wind energy applications. In case of solar energy the unprocessed DC output from the solar panels is connected to the proposed DC –DC converter, in case of wind energy, the induction generator output is connected to diode rectifier and then connected to this DC –DC converter. In both cases an energy storing element i.e battery is used to maintain the continuity of supply to the load. The proposed DC-DC converter topology has the merits of protection against outage, compensation for power fluctuation, peak power leveling and also good voltage regulation. Modeling, simulation, design aspects and hardware implementation of the proposed power converter is discussed in detail in this thesis. From the simulations and hardware implementation the operation of the proposed converter topology with battery storage system is found to be satisfactory. The detailed analysis with experimental results and simulation results are presented.*

Keywords: *Buck converter, boost converter, voltage regulation, power leveling.*

1. INTRODUCTION

The Uninterruptible Power Supplies (UPS) are one application where battery energy storage has been extensively used. These systems are the go-to choice when compensating for power sag or total outages[1]-[5]. The study of using renewable energy sources to produce electrical electricity, such as wind and solar energy has attracted interest during the past few decades. However, the amount of electricity produced varies because the wind has an unpredictable nature and the amount of solar energy is dependent on the weather. Energy can also be kept in a battery bank as an alternative. Utilizing battery storage to cap at maximum the amount of electricity provided by the supply grid is another expanding application. A utility grid is connected to a bidirectional converter for battery energy storage, which runs in both peak-cut and energy-storage modes[6]-[10].

The two power sources are an engine driven alternator and battery bank. That make up the load-adaptive variable-speed producing system. When the energy from the alternator is not enough to meet unanticipated spikes in load demand, energy is pumped from the battery to the dc link. The battery's energy is replenished when the engine's capacity is overextended[11-13].

Battery charger and DC/DC converter combined in an integrated dc UPS topology. When there is a power outage, the battery feeds the load naturally via a diode linked between the battery and output capacitor. The battery charger stage is a buck converter[14-15].

For renewable energy systems, a DC-DC converter with energy storage battery is suggested in this thesis. Voltage Regulator Battery Energy Storage System is the name of this system. The suggested system connects a generator-turbine for wind energy to an unregulated rectifier. This system is immediately connected to a photovoltaic (PV) array in the case of solar energy[16]. Switch-mode DC/AC converter connects the Voltage Regulator Battery Energy Storage System(VR-BESS) to the ac utility source.

2. DC-DC CONVERTERS

2.1 Buck Converter

2.1.1 Principle of Operation

Buck converter generates an average output voltage that is lower than the DC input voltage.

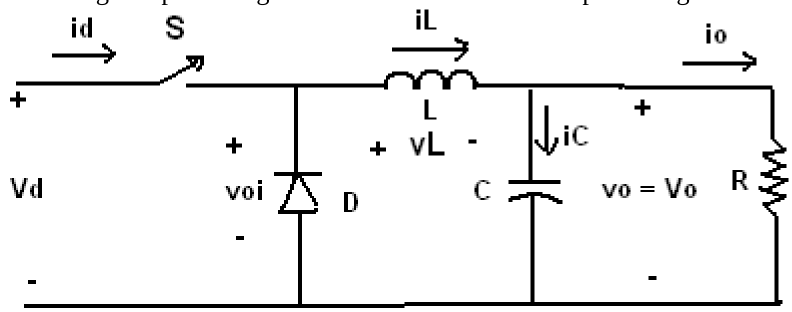

Fig 2.1: Circuit diagram for Buck converter

It is made up of the controlled switch S, the dc input voltage source Vd, the diode (D), the filter inductor(L), the filter capacitor (C), and the load resistance (R). Figure 2.2 displays output voltage.

The average output voltage

$$Vo = \frac{1}{Ts}\int_0^{Ts} vo(t)\,dt = \frac{1}{Ts}\left(\int_0^{ton} Vd\,dt + \int_{ton}^{Ts} 0\,dt\right) = \frac{ton}{Ts}Vd = D\,Vd$$

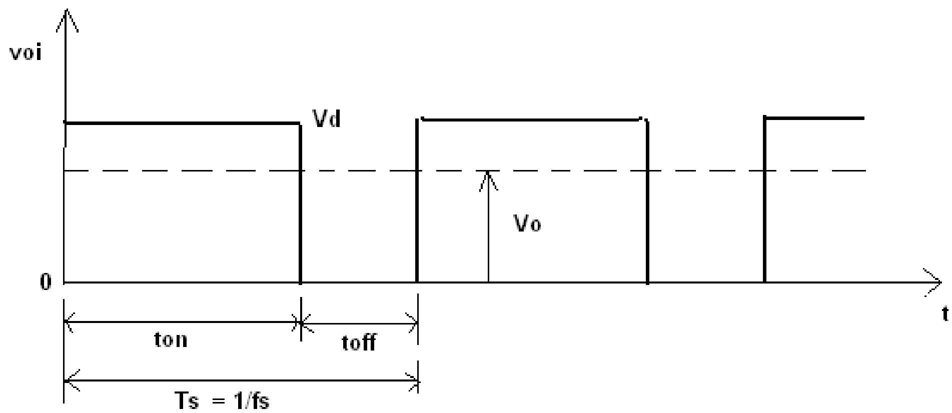

Fig 2.2 Voi voltage waveform

Duty Ratio D = (ton/Ts) of switch,

The average capacitor current in steady state is zero, the average inductor current in this buck converter is equal to the average output current, Io.

Buck converter has two modes of operation:

1. Discontinuous Conduction Mode, where inductor current falls to zero after some time in OFF period.
2. Continuous Conduction Mode, where inductor current flows continuously [iL(t)>0].

2.1.2 Continuous Conduction Mode (CCM):

Switch: ON position:

Switch carries inductor current when it is on, causing the diode to become reverse biased and the input to supply energy to both the load and the inductor. This produces a positive voltage across the inductor, vL = Vd-Vo.

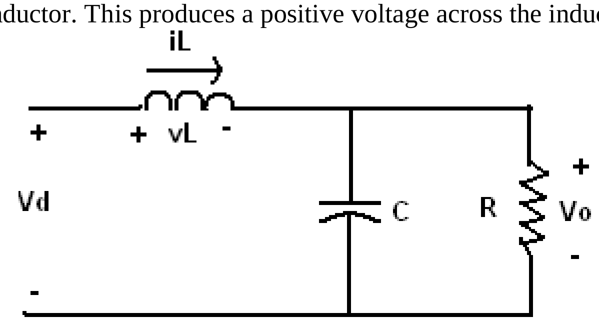

Fig 2.3. Circuit of buck converter when Switch is ON

Switch: OFF position:

During the interval when switch is off, the inductor current flows to through the load and diode, transferring some of its stored energy to the load, and vL = -Vo

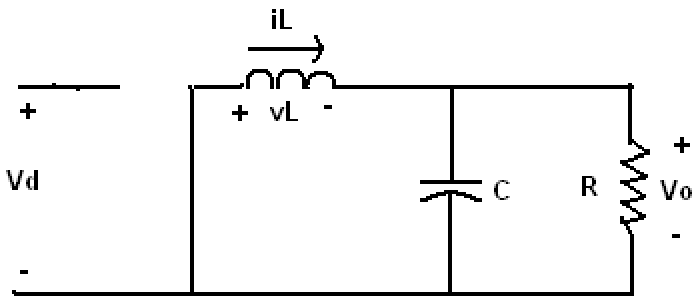

Fig 2.4. Circuit of buck converter when Switch is OFF

Figure 2.5. shows waveforms for continuous conduction mode (CCM) of operation where the inductor current flows continuously [iL(t)>0].

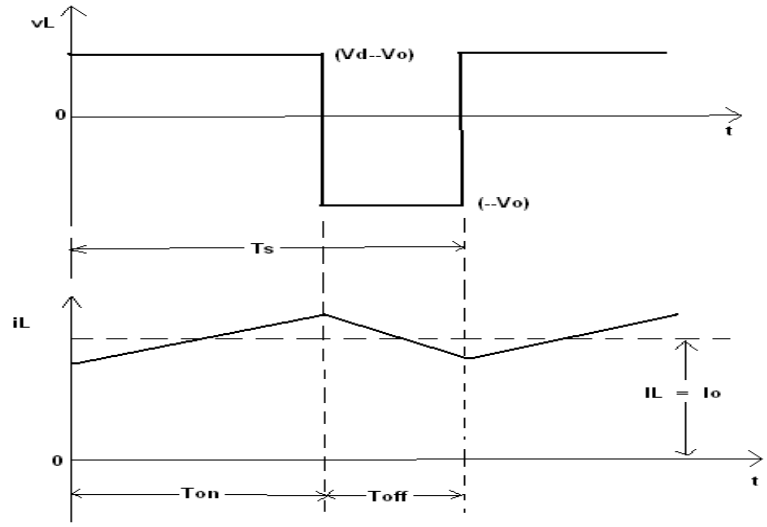

Fig 2.5. Waveforms for continuous conduction mode (CCM) of buck converter

Switch conducts inductor current when it is turned on for a long time, which causes the diode to become reverse biased. As seen in the picture, this causes a positive voltage across the inductor, vL = Vd - Vo.Inductor current (iL) is increased linearly by this voltage.

Due to the inductor storage, iL keeps flowing even after the switch is switched off. This current is now passing through the diode, and in the diagram, vL = -Vo.

The integral of the inductor voltage vL over one time period must be zero because in steady state operation, the waveform must repeat from one time period to the next.

$$\int_0^{Ts} vLdt = \int_0^{ton} vLdt + \int_{ton}^{Ts} vLdt = 0$$

Where Ts = ton + toff

As volt-seconds balance is there in steady state,(Vd - Vo)ton = Vo(Ts – ton)

Or
$$\frac{V_o}{V_d} = \frac{t_{on}}{T_s} = D$$

In this mode, the duty ratio of the switch for a particular input voltage determines the output voltage linearly. It is independent of every other aspect of the circuit. Input power Pd equals output power Po after accounting for any power losses caused by circuit components.$P_d = P_o$

Therefore,

$$V_d\, I_d = V_o\, I_o$$

And

$$\frac{Io}{Id} = \frac{Vd}{Vo} = \frac{1}{D}$$

2.2 Buck Converter

2.2.1 Principle of operation

DC/DC converter that steps up the DC input voltage to produce a higher average output voltage.

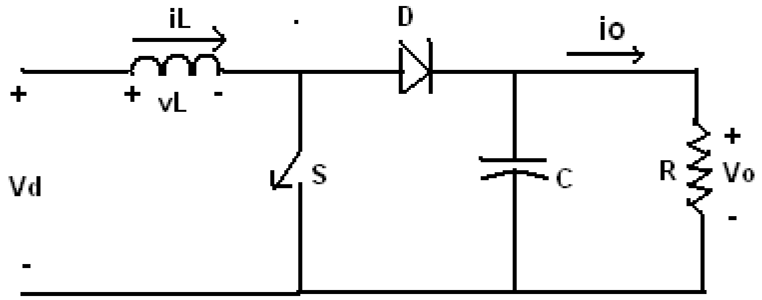

Fig 2.6. Circuit diagram of Boost converter

Switch: ON position:

When the switch(S) is closed, a reverse biased diode isolates the output stage. Inductor receives energy from input. Inductor current increases as a result of a voltage across the inductor, vL = Vd. The capacitor C, which is on at this time, is feeding the load.

Switch: OFF position:

Whenswitch is OFF, energy from the input and the inductor is absorbed by the output stage. The voltage across the inductor, vL = Vd - Vo, lowers inductor current. Additionally, the capacitor receives the energy that was accumulated during the On-state.

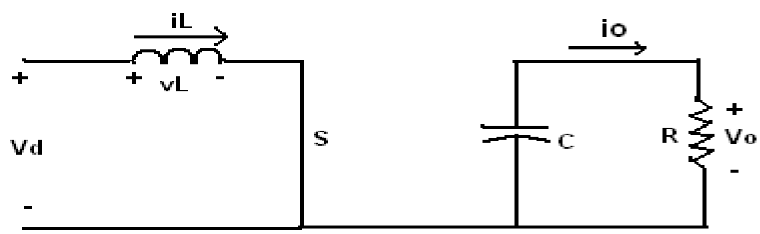

Fig 2.7. Equivalent circuit of boost converter when Switch is ON

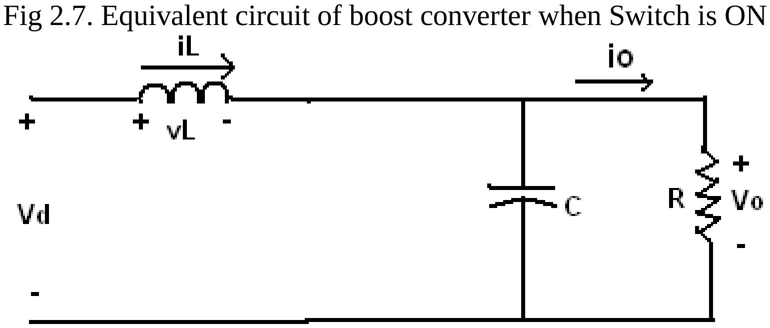

Fig 2.8. Equivalent circuit of boost converter when Switch is OFF

It operates in 2 modes:

1. Discontinuous Conduction Mode, where inductor current falls to zero after some time in OFF period.
2. Continuous Conduction Mode, where inductor current flows continuously [iL(t)>0].

In VR-BESS, only continuous conduction mode of operation is considered.

2.2.2 Continuous conduction mode (CCM)

The current flowing through the inductor (IL) never reaches zero when a boost converter is in continuous operation. The following figure displays the usual current and voltage wave forms in a converter running in this mode.

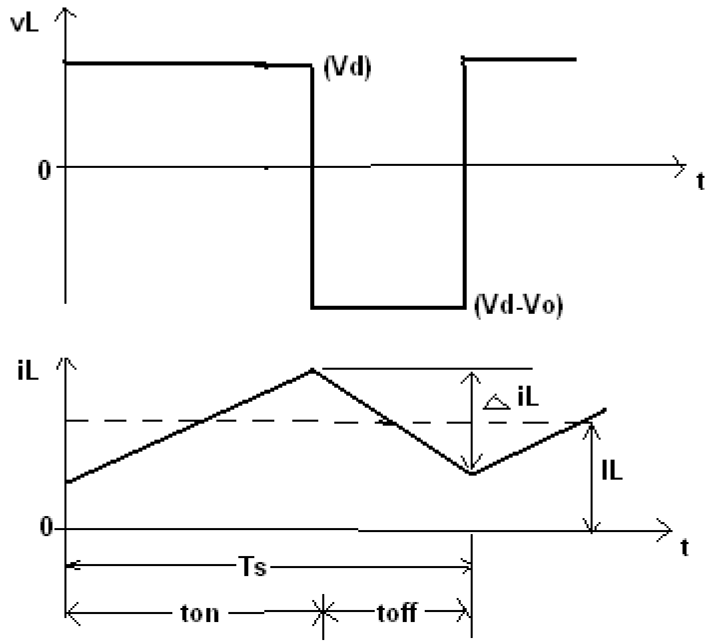

Fig 2.9. Continuous mode of operation

Since the temporal integral of the inductor voltage during one time period must be zero in steady state.

$$V_d t_{on} + (V_d - V_o)\, t_{off} = 0$$

Dividing on both sides by Ts and rearranging terms yield

$$\frac{V_o}{V_d} = \frac{T_s}{t_{off}} = \frac{1}{1-D}$$

The duty cycle is D. It shows the percentage of the commutation period T that the switch is on for. D therefore varies from 0 (S is never on) to 1 (S is always on).
input power, Pd = load power, Po
Therefore, Vd Id = Vo Io

And $$\frac{Io}{Id} = (1-D)$$

3. VOLTAGE REGULATOR - BATTERY ENERGY STORAGE SYSTEM

3.1 General Voltage Regulator

The block diagram of a general system suitable for renewable energy systems is shown in the accompanying figure. DC/DC voltage regulation and energy storage battery are the two power stages [2].

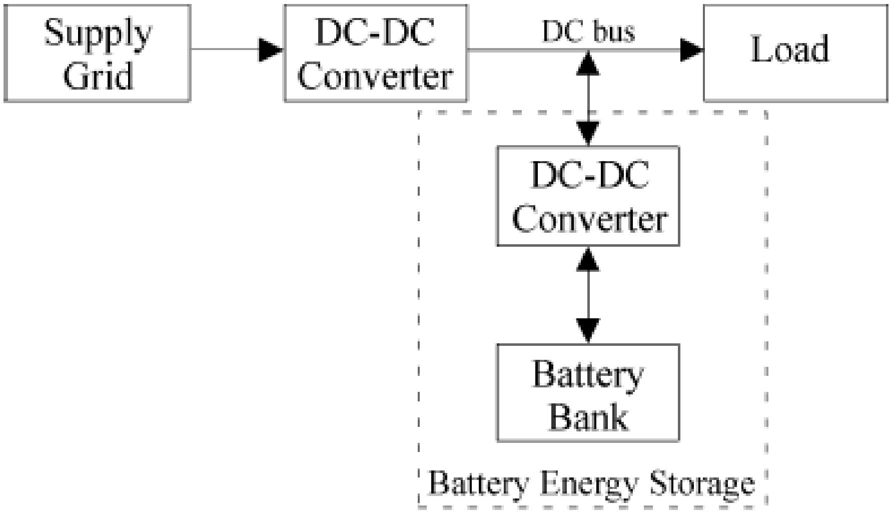

Fig 3.1 Block diagram of a general voltage regulator with battery energy storage.

A DC/DC converter is used to adjust the voltage by raising the supply grid voltage to a regulated output dc bus voltage. In terms of energy storage battery, this power stage injects energy from the battery bank into the output dc bus after storing it in the battery bank using energy from the supply grid. As a result, peak power leveling and power fluctuation compensation are achieved.

3.2Power Circuit of the VR-BESS

DC/DC bi-directional converter-based Voltage Regulator Battery Energy Storage System (VR-BESS), depicted in fig. 2.2, combines the 2 power stages mentioned above. a battery bank, 2 switches, 3 diodes, 2 inductors, 2 capacitors, and make up the VR-BESS. The dc grid (Vs) to which this system is linked is uncontrolled.

The voltage regulator is composed of dc grid voltage Vs, the load, inductor Ls, diode D3, and switches S1 and S2 switching concurrently.

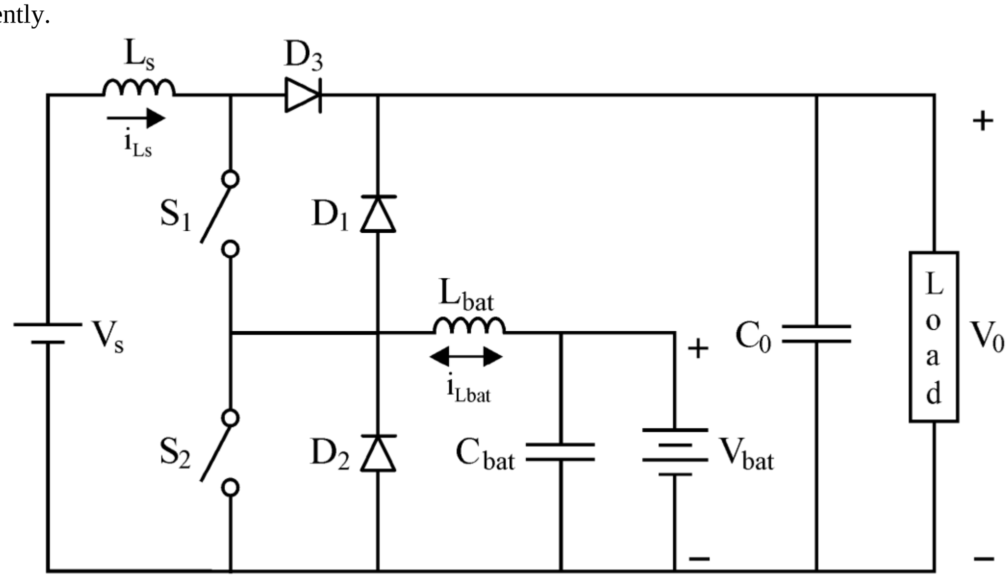

Fig.3.2. Power circuit of the VR-BESS.

The buck converter, which is composed of the battery bank, switch S1, diode D2, and dc grid voltage Vs, is used to charge the batteries.

Energy flows via the VR-BESS in a variety of ways. These can be classified into the following operational modes:

- Mode 1 (Peak power leveling and power fluctuation compensation): The battery bank provides the extra energy needed by the load when the dc grid's energy supply is insufficient.
- Mode 2 (UPS): When a voltage drop or outage is detected, the battery bank provides full load current.

- Mode 3 (Battery charge): The DC grid has the ability to feed the load and charge the battery bank when everything is running normally.

3.3System Analysis

The analytical formulas that describe how the VR-BESS functions are provided here. By analytically analyzing the operating stages depicted in Figs. 3.2.

Definitions:

Switching time period: $T_s = t_3$

Duty cycle 1: $D1 = \frac{t_1}{T_S}$ 3.1

Duty cycle 2: $D2 = \frac{t_2}{T_S}$ ..…3.2

$$\Delta D = \frac{t_2 - t_1}{T_s} \quad .....3.3$$

3.3.1 Mode 1 Operation

The integral of the inductor voltages VLs and VLbat over a single time period must be zero in steady state.

$$\int_0^{T_s} v_{Ls}\,dt = \int_0^{t_1} V_s\,dt + \int_{t_1}^{t_2} (V_s - V_o)dt + \int_{t_2}^{T_s} (V_s - V_o)dt = 0 \quad ......3.4$$

$$\int_0^{T_s} v_{Lbat}\,dt = \int_0^{t_1} -V_{bat}dt + \int_{t_1}^{t_2} (V_o - V_{bat})dt + \int_{t_2}^{T_s} -V_{bat}dt = 0 \quad ......3.5$$

Solving 3.4 and 3.5 gives

$$V_o(T_s - t_1) = V_s T_s \quad ....3.6$$

$$V_{bat}\,T_s = V_o(t_2 - t_1) \quad ....3.7$$

Dividing both sides by $T_s$and rearranging terms…

$$\frac{V_o}{V_s} = \frac{1}{1 - D_1} \quad ....3.8$$

$$\frac{V_{bat}}{V_o} = \Delta D \quad ....3.9$$

As seen from equation 3.8, the system functions in mode 1 like a straightforward boost converter, with input voltage Vs and output voltage V0, and duty cycleD1.

Additionally, the system runs similarly to a straightforward buck converter, with input voltage V0 and output voltage Vbat, both working at duty cycle D.

3.3.2 Mode 2 Operation

The integral of the inductor voltages VLs and VLbat over a single time period must be zero in steady state.

$$\int_0^{T_s} v_{Ls}\,dt = \int_0^{t_1} V_s\,dt + \int_{t_1}^{t_2} (V_s - V_o)dt + \int_{t_2}^{T_s} (V_s - V_o)dt = 0 \quad ....3.10$$

$$\int_0^{T_s} v_{Lbat}dt = \int_0^{t_1} V_{bat}dt + \int_{t_1}^{t_2} V_{bat}dt + \int_{t_2}^{T_s} (V_{bat} - V_o)dt = 0 \quad ....3.11$$

Solving of 3.10 and 3.11 gives

$$V_o(T_s - t_1) = V_s T_s \qquad \text{.....3.12}$$

$$V_o(T_s - t_2) = V_{bat} T_s \qquad \text{......3.13}$$

Dividing both sides by $T_s$and rearranging of terms gives

$$\frac{V_o}{V_s} = \frac{1}{1 - D_1} \qquad \text{.......3.14}$$

$$\frac{V_o}{V_{bat}} = \frac{1}{1 - D_2} \qquad \text{......3.15}$$

Equations 3.14 and 3.15 show that the system behaves like two separate boost converters operating in parallel in mode 2.

4. MODELLING & SIMULATION

The circuit is simulated using MATLAB software. Various modes of operation are presented below.As 'battery' block is not present in MATLAB 7.2, it is indirectly represented in each mode.
Parameters used: Ls: 600 uF , Lb: 1500 uF, Cb: 3.3 uF, Co: 22 uF and Maximum DC grid power, Ps = 50 W.

4.1 Mode 1 Operation:

4.1.1 Parameters and definitions

Parameters:

DC grid voltage: 30 V
Load resistance, RL = 40 ohms
Load power, Po = 40W
Equivalent battery resistance, Rb = 25.6 ohms
D1 = 0.25 (for switch S2)
D2 = 0.65 (for switch S1)

Definitions:

Load voltage = Vo volts
Average dc source current = ILs amperes
Input power to converter, P_{source} = Vs * ILs watts
Load power, $P_{load} = Vo^2/RL$ watts
Power drawn by battery, $P_{bat} = Vcb^2 / Rb$ watts

4.1.2 Simulation Diagram

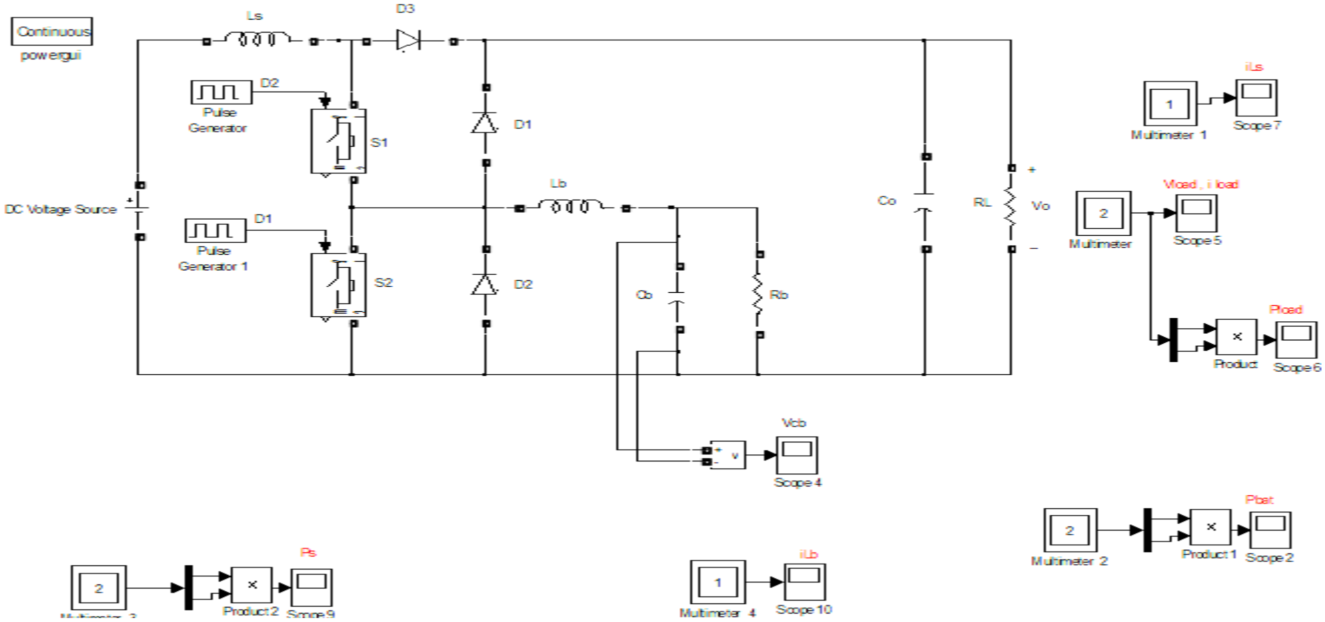

Fig. 4.1 Simulation diagram of Mode-1

4.1.3 Waveforms:

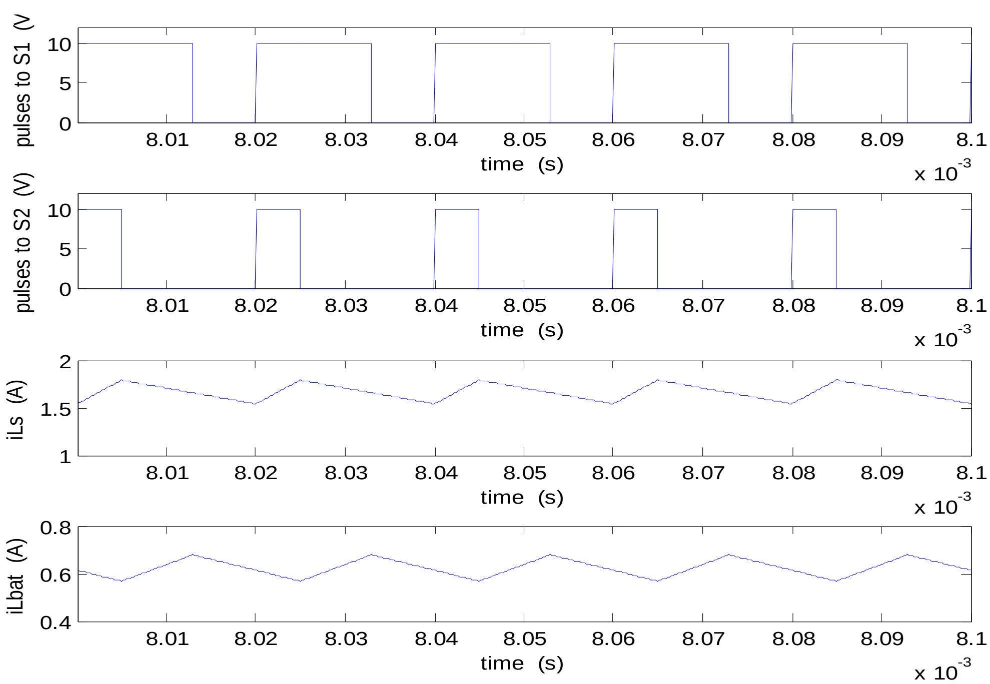

Fig 4.2 Triggering Pulses to switches and inductors currents

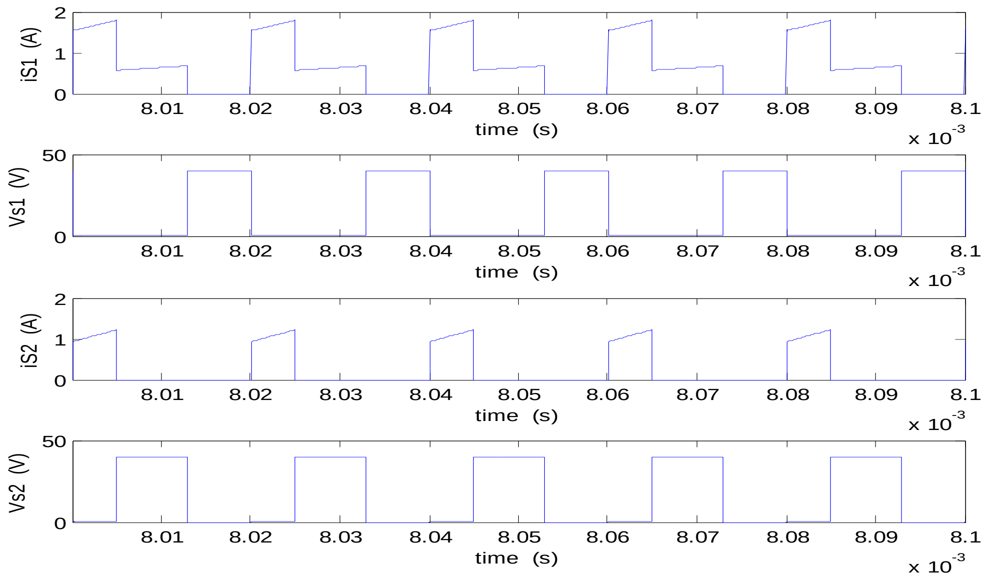

Fig 4.3 Switch voltages and currents

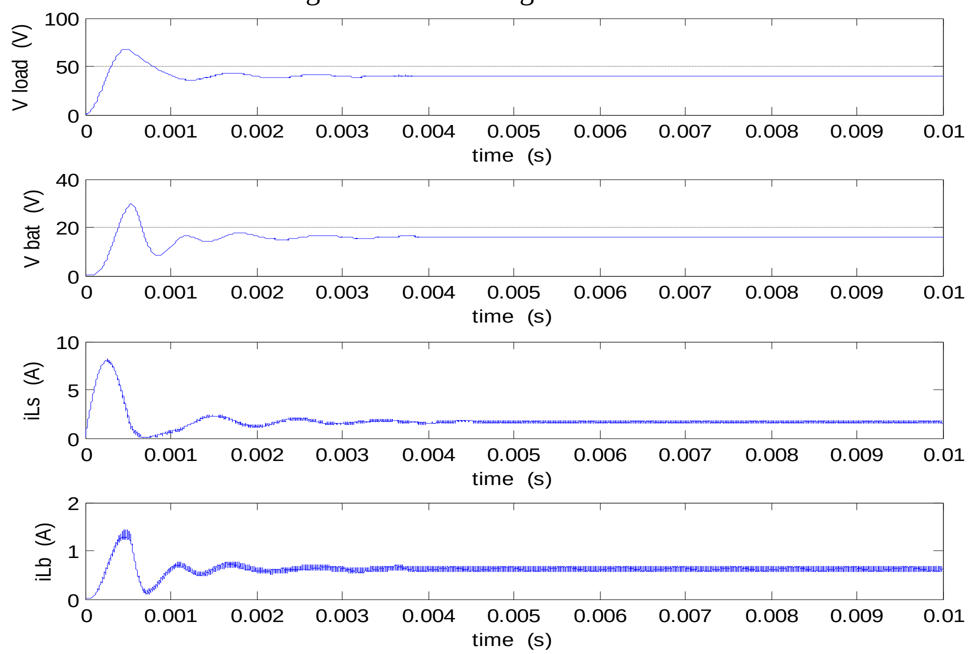

Fig 4.4 Voltages across load & battery and inductor currents

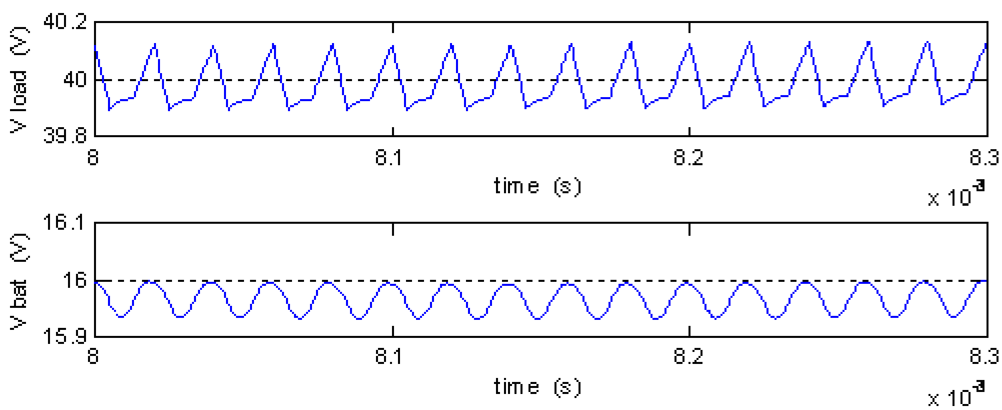

Fig 4.5 Ripples in Vload, Vbat.

4.2 Mode 2 Operation:

4.2.1 Parameters and definitions

Parameters:

DC grid voltage, Vs = 30 V
Load power, Po = 60 W
Battery power (discharging), Pbat = 10 W
Battery terminal voltage (rated), Vbat = 16 V
Load resistance, RL = 26.67 ohms
Open circuit voltage of battery (considered), Voc = 15.5 V
Internal resistance of battery, Rb = 0.75 ohms
D1 = 0.25 (for switch S1)
D2 = 0.625 (for switch S2)

Definitions:

Load voltage = Vo volts
Average dc source current = ILs amperes
Input power to converter, P_{source} = Vs * ILs watts
Load power, P_{load} = Vo^2/RL watts
Power supplied by battery, P_{bat} = Vcb * iLb watts

4.2.2 Simulation Diagram

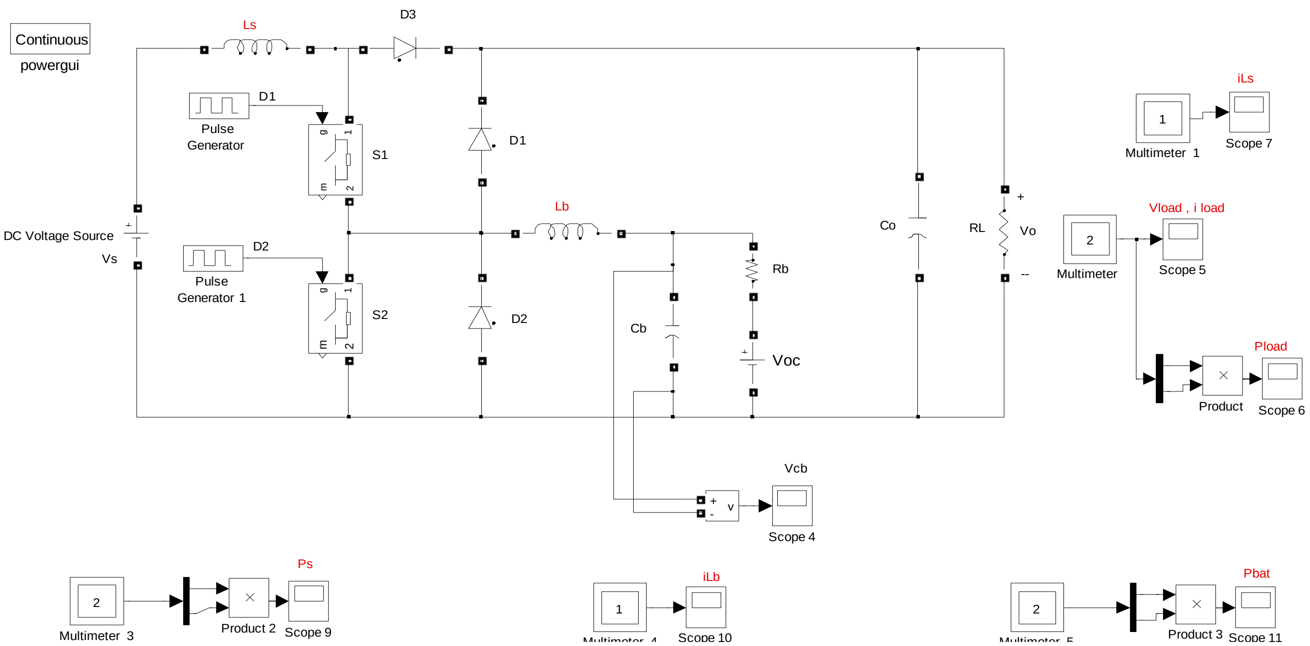

Fig.4.6 Simulation diagram of mode-2

4.2.3 Waveforms:

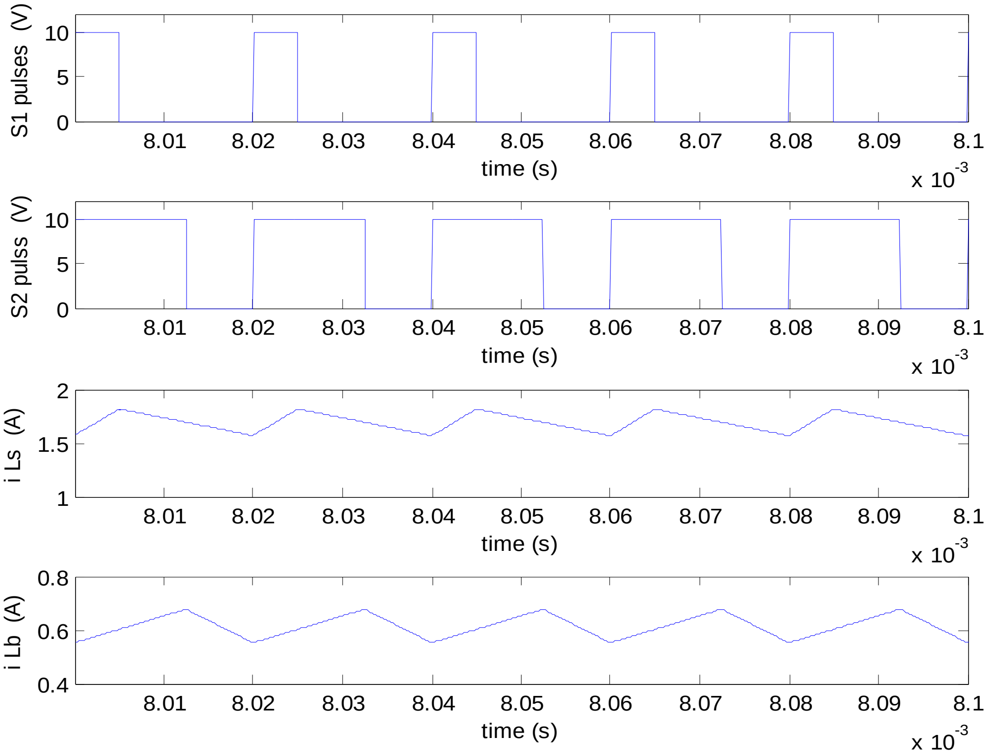

Fig 4.7 Triggering pulses to switches and inductors currents

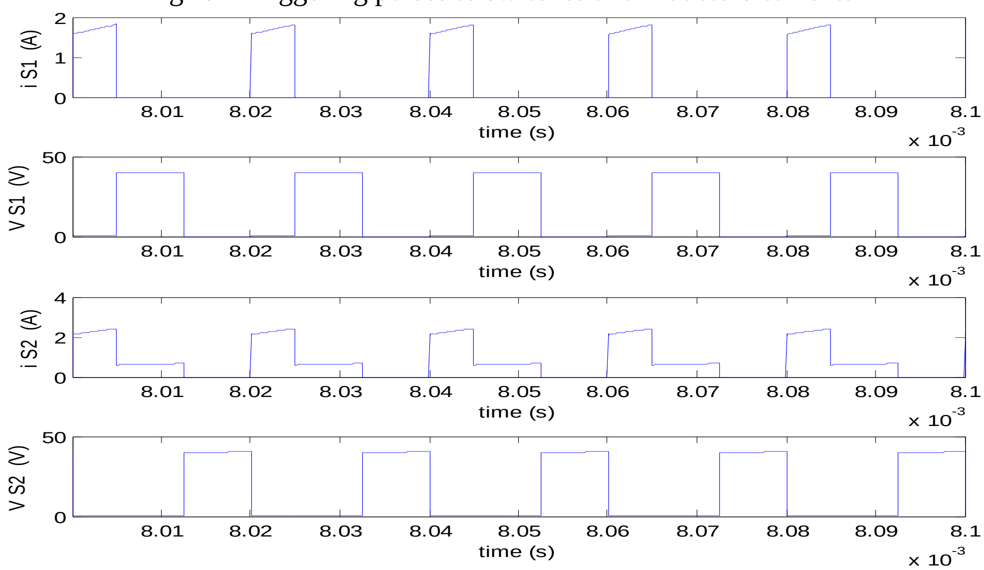

Fig 4.8 Switch voltages and currents

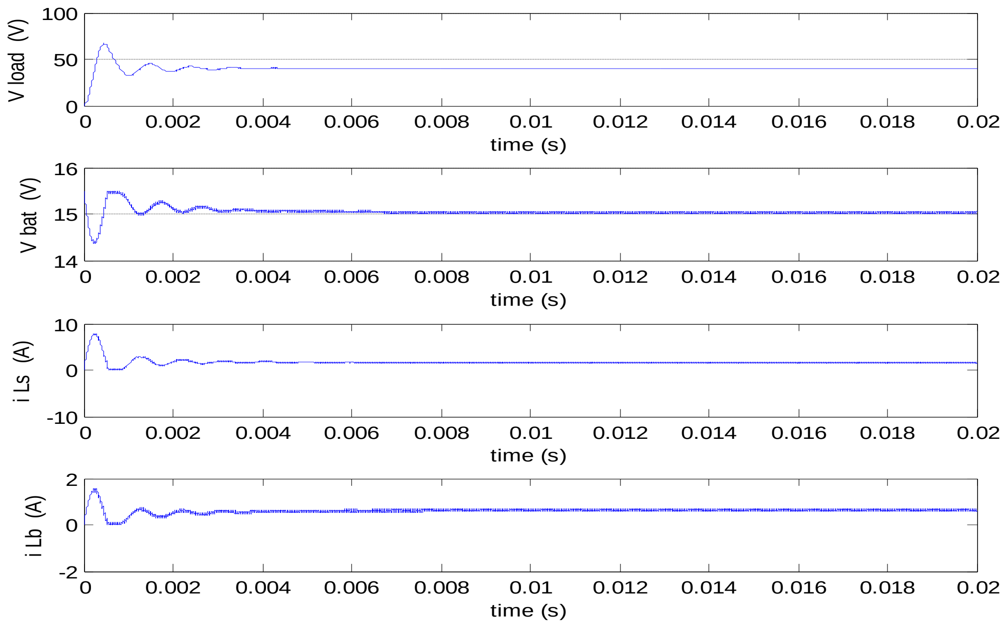

Fig 4.9Voltages across load, battery and inductor currents

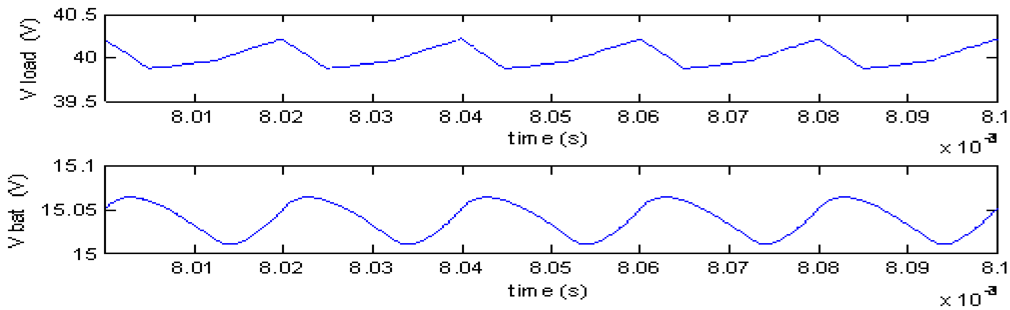

Fig 4.10 Ripples in Vload, Vbat

4.3 Mode 3 Operation:

4.3.1 Parameters and definitions

Parameters:

DC grid voltage: 24 V
Load resistance, RL = 40 ohms
Load power, Po = 40W
Equivalent battery resistance, Rb = 25.6 ohms
D1 = 0.40 (for switch S2), D2 = 0.80 (for switch S1)

Definitions:

Load voltage = Vo volts, Average dc source current = ILs amperes
Input power to converter, P_{source} = Vs * ILs watts
Load power, $P_{load} = Vo^2/RL$ watts,
Power drawn by battery, $P_{bat} = Vcb^2 / Rb$ watts

4.3.2 Simulation Diagram

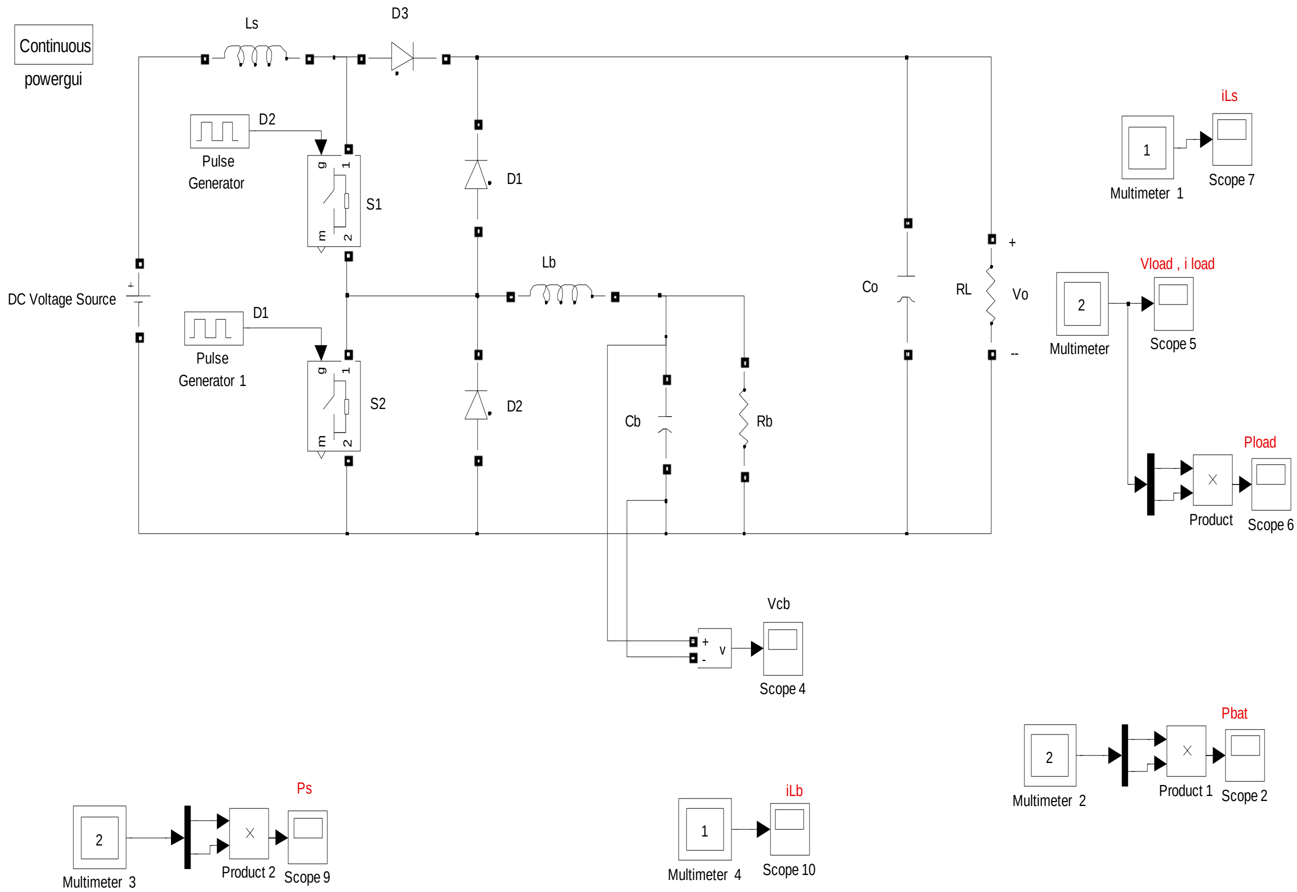

Fig. 4.11 Simulation diagram of mode-3

4.3.3 Waveforms

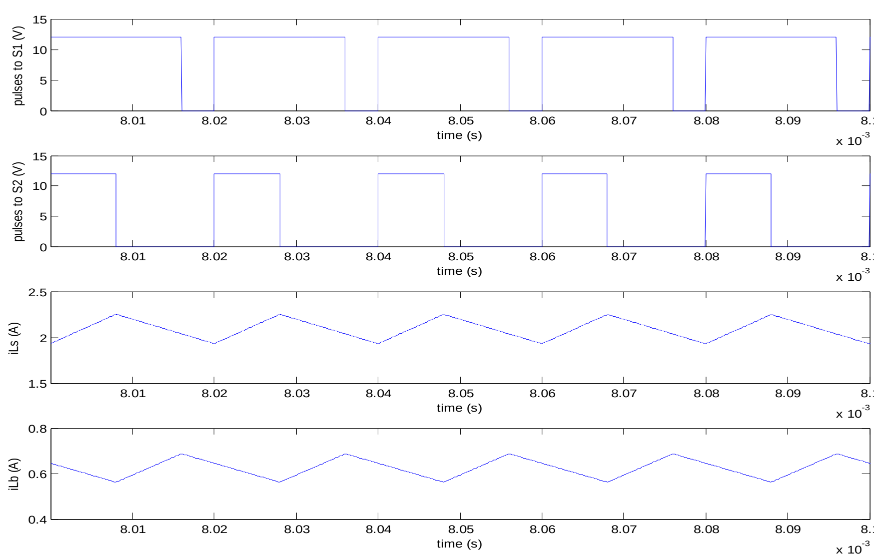

Fig 4.12 Triggering pulses to switches and inductors currents

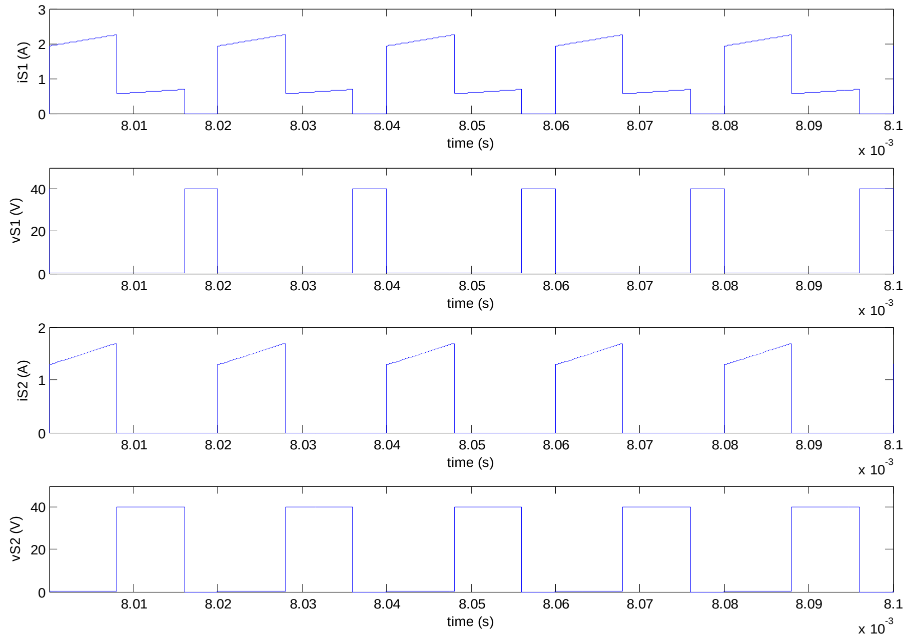

Fig 4.13 Switch voltages and currents

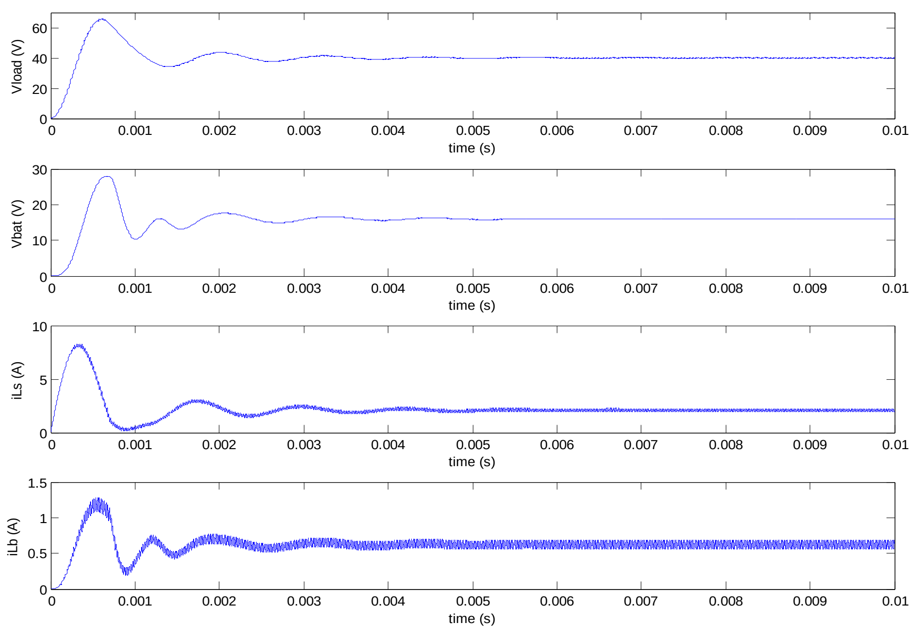

Fig 4.14 Voltages across load, battery and inductor currents

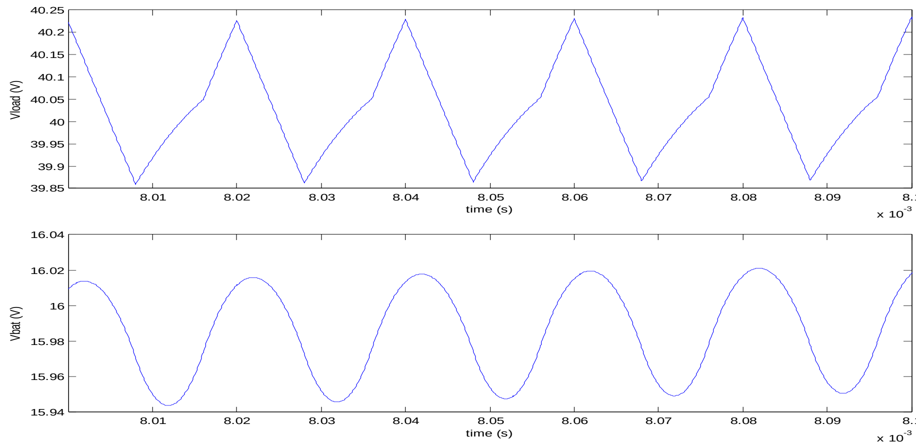

Fig 4.15 Ripples in Vload, Vbat

CONCLUSION

The paper presented an analysis of system composed of voltage regulator and battery energy storage. A straightforward structure was used to achieve voltage regulation, peak power leveling, and correction for power variations. The suggested solution is now suitable for use with renewable energy sources like wind and solar electricity. Voltage Regulator Battery Energy Storage System performs voltage regulation and steps up the battery bank voltage to output dc bus like a typical boost converter. The VR-BESS functions like a typical buck converter to charge batteries. Different operating modes were examined in open circuit. To characterize the operation of the VR-BESS, mathematical equations, computer simulations, and experimental findings for several modes of operation were established. The operational concept is supported by the findings.

Future scope:

This proposed strategy can be extended to closed loop operation so that

- It detect itself the changes in power requirement from load side and accordingly change into different mode of operation to supply power accordingly, i.e. peak power leveling and power fluctuation compensation.
- It detect the voltage sag in input DC source voltage and change duty cycles of switches accordingly to operate load and battery charging at rated parameters
- It detect voltage outage and supply the load current from battery, i .e. Uninterruptible Power Supply operation or protection against outage.

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