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Design and Simulation of High-Step up Converter for Renewable Energy Applications

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Abstract: In present days, the usage of power electronic devices is increasing rapidly specially in switched mode power supply, (SMPS) units which are used in various applications like cell phone chargers, adaptors for laptops and powering to LED circuits etc., The dc – dc converters plays major role in these SMPS for changing the voltages from one level to another level as per the load demand. Thus, the traditional converters, such as boost and fly back converters are not suitable for high step conversion because of the extreme duty cycle (or) high turn's ratio. In this project a high step-up dc-dc converter with high voltage gain is analyzed for renewable energy systems.it has potential advantages of simple structure, high efficiency, low voltage stress, low emi. As the photovoltaic (PV) arrays fuel cells and super capacitors produce low output voltage (12-30) and this voltage is boosted up to (350-400). In this project a single switch high step up converter is analysed. It is simulated in closed loop controller's voltage mode control, current mode control, and fuzzy logic control is used. The output voltage regulation is maintain constant. When source & load is sudden rise or fall the voltage regulation is constant. To decrease switching loss and to increase the efficiency of the converter.

Keywords: High Step-Up, DC-DC, SEPIC, Renewable Energy.

I. INTRODUCTION

Renewable energy sources (RES) have experienced a fast development in recent years. These systems employ with micro sources like PV, fuel cells etc. Though PV cells can be made into array and connected in series to produce high voltage there exist serious problems like shadowing effects, short circuit which drastically reduces its efficiency. In order to overcome such adverse effects this micro source energy is utilized by the high step up converter to produce high voltage and satisfy the demands. Conventional boost converters can't provide such a high DC voltage gain for extreme duty cycle.

Thus high step up dc-dc converters are used as front end converters to step from low voltage to high voltage which are required to have a large conversion ratio, high efficiency and small volume [1]. In some converters active clamp circuit is used to overcome voltage spikes caused by the leakage inductance of the coupled inductor. Though ZVS technique is employed for soft switching it can't sustain light loads [2]. Different switching structures are formed either two capacitor or two inductor with two three diodes. Both the step up and step down operations can be performed in this topology, Performance of hybrid converters are better than classical converters but still its costlier to implement [3]. Low level voltage from the PV, fuel cells is connected to Kilo watt level using step up dc-dc converter and inverter circuits. Voltage spikes and switching losses are eliminated by active clamping. In dc-ac, inverter always tends to draw ac ripple current at twice the output frequency. Resonant inductors cost and circuit volume is high [4]. In some converters high voltage conversion is obtained by changing transformer turns ratio which will increase the overall efficiency but still the operation of main switch involves hard switching and also EMI noise gets raised [5]. Impacts of SiC (silicon carbide) MOSFETS on converter, switching and conduction losses are reduced even though fast switching is done. Si diodes have ideal, but sill SiC devices processes large amount of ringing current at turn OFF relatively to other devices. Package of external diode and the diode itself have more parasitic capacitances that are added to the devices parasitic aggravating the ringing [6].Here, the voltage step is done without a transformer and a high voltage gain s achieved without an extremely high duty ratio but still the circuit becomes more bulky as more number of passive components are used [7]. Though this converter provides a non-pulsating current by using an auto transformer, duty ratio is limited by 0.5 and not suitable for non-linear loads [8].Here voltage stress of the active switch is reduced thereby the conversion efficiency is improved. This converter requires a multi winding transformer which makes the circuit design complex [9]. This converter avoids extremely narrow turn off period, ripples and switching losses are eliminated by ZVS technique. It uses two coupled inductors which makes the circuit complex [10]. In this converter no additional magnetic components used, switching losses are minimized by adopting a regenerative snubber circuit. As the circuit uses more switches controlling is complex [11]. In this converter high voltage gain is obtained but the circuit has more passive components [12]. It employees single ended scheme cost is reduced. Galvanic isolation is needed, but suitable only for low power and frequency applications [13]. In this converter no need of extreme duty ratio but if

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conduction losses or switching losses occurs the efficiency is reduced. It is possible to generate the non-isolated dc-dc converters but the major drawback is that switching frequency must be maintained constant and the turn ratio of the auto transformer must be unity. Some converters operate at very high frequency with fast transient response. The main switch is fabricated from an integrated power process, the layouts can be changed to vary the parasitic, however design of switch layout is complex, fixed frequency and constant duty ratio must be maintained. This converter provides high voltage gain and can be employed for high power applications however the duty ratio is limited to 0.85. In this, the energy of the leakage inductor is recycled to the output load directly, limiting the voltage spike on the main switch. To achieve a high step-up gain, it has been proposed that the secondary side of the coupled inductor can be used as flyback and forward converters. In some converters voltage gain is improved through output voltage stacking.

II. OPERATION PRINCIPLE OF THE PROPOSED CONVERTER

The proposed single-switch high step-up converter is shown in Fig.1, which is derived from a SEPIC converter, while capacitor C1, inductor L2, diodes D1 and D2 combine an extra boost unit, capacitor C3 and diode D3 are used to clamp the voltage of switch S. In order to facilitate the analysis, the following assumptions are given: 1) the proposed converter is operating in the steady state; 2) the components are all ideal; 3) C2 andC3 are equal, C_{out} is large enough to maintain the constant output voltage.

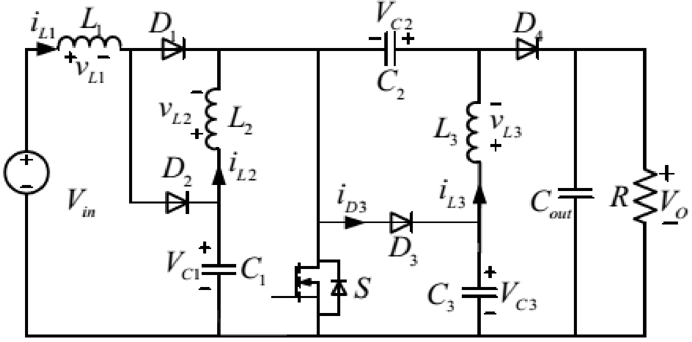

Fig.1. The single-switch high step-up converter

A. Continuous Conduction Mode

When the inductor currents i_{L1}, i_{L2} and i_{L3} are continuous, the proposed converter operates in CCM. The equivalent circuits when switch S is ON and OFF are shown in Fig.2 and Fig.3, respectively. The ideal voltage and current wave forms of the main components in CCM is shown in Fig.4.

Stage I [t_0~t_1]: When $t=t_0$, switch S is turned on. Diode D_1 conducts, while D_2, D_3 and D_4 are blocked. The equivalent circuit and current direction in this stage is shown in Fig.2. During this stage, the input voltage source V_{in} charges inductorL_1 through D_1 and S. Then the inductor voltage V_{L1} across $L_1$is equal to V_{in}. The capacitor C_1 charges inductor L_2 through S, then the inductor voltage V_{L2} across L_2 is equal to V_{C1}. The capacitor C_3 charges L_3 and C_2 through S, then the inductor voltage V_{L3} across L_3 is equal to (V_{C3}-V_{C2}). Therefore, the inductor currents i_{L1}, i_{L2} and i_{L3} increase linearly. The output capacitor C_{out} supplies energy to the load R, and keeps the output voltage V_o constant. When $t=t_1$, S is turned off, stage I ends.

Stage II [t_1~t_2]: When $t=t_1$, S is turned off. D_1 is blocked, while D_2, D_3 and D_4 conduct. The equivalent circuit and current direction in this stage is shown in Fig.4. C_1 is charged by the input voltage source V_{in} and L_1 through D_2 and V_{L1} is equal to (V_{in}-V_{C1}). At the same time, V_{in}, $L_1$and L_2 charge C_3through D_2, then V_{L2} is equal to (V_{C1}-V_{C3}). Moreover, the energy of V_{in}, L_1, L_2 and L_3 transfer to C_{out} and R, and V_{L3} is equal to -V_{C2}. Thus, the inductor currents i_{L1}, $i_{L2}$and i_{L3} decline linearly. When $t=t_2$, S is turned on, the stage II is ended. The proposed converter enters the next switching cycle.

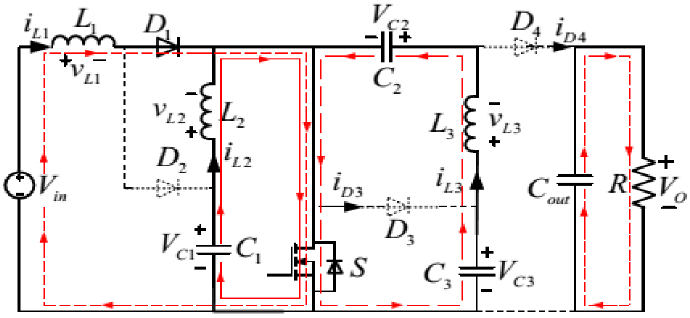

Fig.2. The equivalent circuit of stage I in CCM

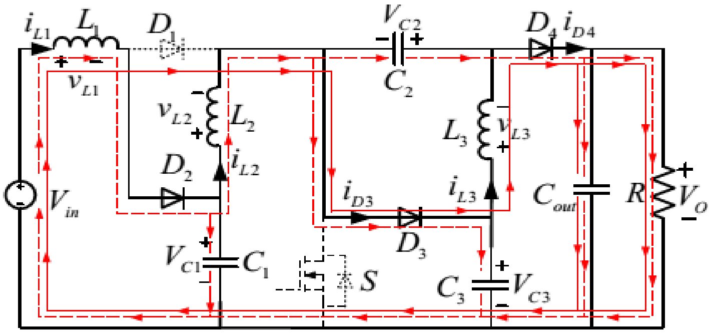

Fig.3.The equivalent circuit of stage II in CCM

Based on the voltage-second balance principle of inductor, we have

$$\begin{cases} DV_{in} = (1-D)(V_{C1}-V_{in}) \\ DV_{C1} = (1-D)(V_{C3}-V_{C1}) \\ D(V_{C3}-V_{C2}) = (1-D)V_{C2} \end{cases} \quad --- (1)$$

Where D is the duty cycle of the switch S.

Assumed that the capacitor voltage is constant in the steady state, based on Eqn. (1), the relationships of capacitor voltages are

$$\begin{cases} V_{in} = (1-D)V_{C1} \\ V_{C1} = (1-D)V_{C3} \\ V_{C2} = DV_{C3} \end{cases} \quad --- \quad (2)$$

As V_o is equal to the sum of V_{C2} and V_{C3} during Stage II, the voltage gain of the proposed converter under CCM can be expressed by

$$M_{CCM} = \frac{V_0}{V_{in}} = \frac{(1+D)}{(1-D)^2} \quad --- (3)$$

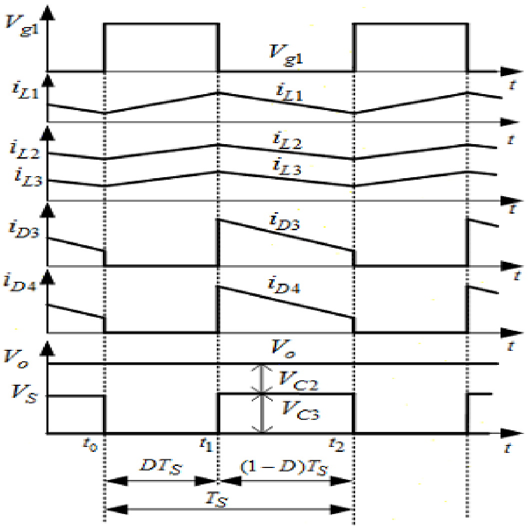

Fig.4. The theoretical waveforms in CCM

B. Discontinuous Conduction Mode

When switch S is turned off, if the inductor currents i_{L1} is continuous, but both i_{L2} and i_{L3} are pseudo-continuous, the diode currents i_{D3} and i_{D4} decrease gradually until they are locked, then the proposed converter will operate in DCM. During the switching period, the proposed converter has three modes, the equivalent circuits of the first two stages in DCM correspond to those in CCM, i.e. Fig.2 and Fig.3, the equivalent circuit of the stage III is shown in Fig.4. The ideal voltage and current waveforms of the main components in DCM are shown in Fig.6

Stage I [t_0~t_1]: the equivalent circuit is shown in Fig.2. Almost all statuses are same as Stage I in CCM except of the inductor current i_{L3} begins to increase from its negative initial value.

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Stage II [t_1~t_2]: the equivalent circuit is shown in Fig.3. Most of the statuses are same as Stage II in CCM, but the inductor current i_{L3} decline linearly until it is equal to the inductor current i_{L2}. When t=t_2, the diode D_3 and D_4 are blocked, and the stage II is ended.

Stage III [t_2~t_3]: The switch S remains turned off and the diode D_2 keeps conductive, at the same time, the diode D_1, $D_3$and D_4 are blocked. The equivalent circuit in this stage is shown in Fig.5. The input voltage source V_{in} and the inductor L_1 charge capacitor C_1 through the diode D_2. V_{L1} is equal to (V_{in}-V_{C1}), so i_{L1} declines linearly. But the inductor current i_{L2} and i_{L3} keep constant, thus V_{L2} and V_{L2} equal to zero. And the drain-source voltage V_{DS} is equal to (V_{C3}–V_{C2}). Moreover, the energy of the output capacitor C_{out} is transferred to the load Rand keeps the output voltage Vo constant. When t=t_3, S is turned on, the stage III is ended. The proposed converter enters the next switching cycle.

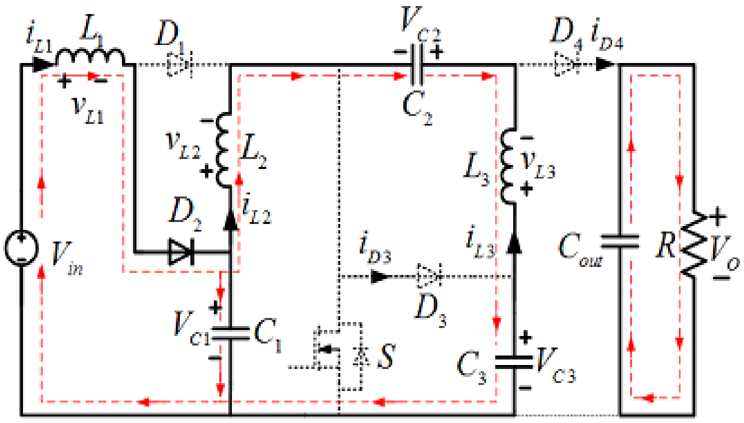

Fig.5. The equivalent circuits of stage III in DCM

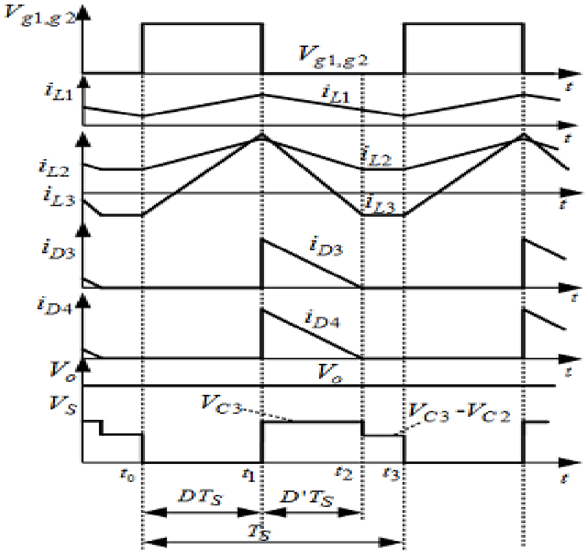

Fig.6. The theoretical waveforms in DCM

Assumed D ' is the conduction duty cycle of diode D_3 andD_4, based on the voltage-second balance principle of inductor, we have

$$\begin{cases} DV_{in} = (1-D)(V_{C1}-V_{in}) \\ DV_{C1} = D(V_{C3}-V_{C1}) \\ D(V_{C3}-V_{C2}) = D'V_{C2} \end{cases} \quad ---(4)$$

Assumed that the capacitor voltage is constant in the steady state, based on Eqn. (4), the relationships of capacitor voltages are

$$\begin{cases} V_{in} = (1-D)V_{C1} \\ V_{C1} = \dfrac{D'}{(D+D')}V_{C3} \\ V_{C2} = \dfrac{D}{(D+D')}V_{C3} \end{cases} \quad ---(5)$$

As Vo is equal to the sum of V_{C2} and V_{C3} during Stage II, the voltage gain of the proposed converter under DCM can be expressed by

$$M_{CCM} = \frac{V_0}{V_{in}} = \frac{2D + D'}{D'(1-D)} \quad ---(6)$$

C. Boundary Condition

When the converter operates in the boundary conduction mode (BCM), the relationships of D ' and D are

$$D' = 1 = D \quad ---(7)$$

According to the Fig.3 and Fig.4, we have

$$\begin{cases} i_{C2} + i_{C3} = 0 \\ i_{D3} = i_{L2} + i_{C2} \\ i_{D4} = i_{L3} - i_{C2} \end{cases} \quad ---(8)$$

Based on Eqn. (8), the diode peak current i_{D3_pk} and i_{D4_pkcan} be expressed by

$$iD4_{PK} = iD3_{PK} = \frac{iL2_{PK} + iL3_{PK}}{2}$$
$$= \frac{1}{2}\left[\frac{VC1DTS}{L_2} + \frac{VC1DTS}{L_3}\right] = \frac{VC1DTS}{2L_{eq}} \quad ---(9)$$

Where i_{L2_pk} and i_{L3_pk} are the peak inductor currents and L_{eq} is the equivalent inductance

$$L_{eq} = \frac{L_2 L_3}{L_2 + L_3} \quad ---(10)$$

The average value of output current I_O is equal to the average current of diode D_4, then we have

$$I0 = \frac{iD4\_PKD'}{2} = \frac{VC1DD'TS}{4Leq} \quad ---(11)$$

Assumed that the time parameter τ_{Leq} is defined by

$$\alpha + \beta = x^{\tau Leq} = \frac{Leq}{RTS(1)} = \frac{LeqI0}{V0TS(1)} \quad ---(12)$$

Based on Eqns. (5) and (11), (12) turns to be

$$\tau Leq = \frac{DD'^2}{4(2D + D')} \quad ---(13)$$

When the converter operates in BCM, based on Eqns. (3.7) and (13), the boundary time parameter τ_{LeqB} is

$$\tau LeqB = \frac{D(1-D)^2}{4(1+D)} \quad ---(14)$$

Fig.7 shows the curve of τ_{LeqB} vs duty ratio D. When τ_{Leq} is greater than τ_{LeqB}, the converter will operate in CCM; when τ_{Leq} is less than τ_{LeqB}, the converter will operate in DCM; when τ_{Leq} is equal to τ_{LeqB}, the converter will operate in BCM.

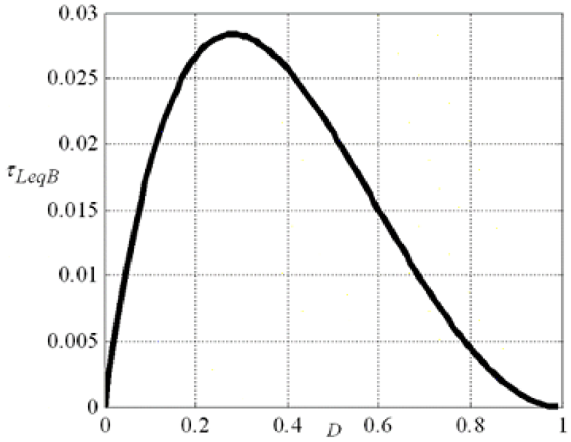

Fig.7. The curve of τLeqBvs D

III. PARAMETER DESIGN

A. Inductance

From Fig.3, the current ripple of inductor L_1 under CCM can be expressed by

$$\Delta i_{L1} = \frac{V_{in} D}{f_s L_1} \qquad --- (15)$$

Then, the inductance L_1 can be determined by

$$L_1 = \frac{V_{in}\, D}{\Delta i_{L1}} = \frac{V_{in}\, D}{\Delta i\% I_{L1} f_s} \qquad --- (16)$$

Where Δi% is the ripple tolerance of inductor current.
Similarly, the inductances of L_2 and L_3 can be defined by

$$L_2 = \frac{V_{C1}\, D}{\Delta i_{L2}} = \frac{V_{C1}\, D}{\Delta i\% I_{L2} f_s} \qquad --- (17)$$

$$L_3 = \frac{(V_{C3} - V_{C2})D}{\Delta i_{L3}} = \frac{V_{C1}\, D}{\Delta i\% I_{L3} f_s} \qquad --- (18)$$

From Fig.3, the following current relationships can be obtained,

$$\begin{cases} I_{C1} = I_{L2} \\ I_{C2} = -I_{C3} = I_{L3} \end{cases} \quad for\ stage \quad I \qquad --- (19)$$

$$\begin{cases} i_{C1} = i_{L1} - i_{L2} \\ i_{C2} = -i_{C3} = i_{L3} - i_0 \end{cases} \quad for\ stage \quad II \quad --- (20)$$

Based on the ampler-second balance principle of capacitor, we have

$$I_{L2} = (1 - D)I_{L1} \qquad And \quad I_{L3} = (1 - D)I_0 \quad - (21)$$

If the output power Po, efficiency of the converter η and road resistance R are known, as $I_{L1} = I_{in} = \frac{p_0}{\eta V_{in}}$ and $I_0 = \sqrt{\frac{P_0}{R}}$, the inductances of the proposed converter can be obtained.

B. Capacitance

As the current of capacitor C_2 is the same as that of C_3during Stage I, the voltage difference of C_2 or C_3 is defined by

$$\Delta V_{C2} = \frac{I_{L3} D}{C_2 f_S}\ , \qquad \Delta V_{C3} = \frac{I_{L3} D}{C_3 f_S} \quad --- (22)$$

Then

$$C_2 = C_3 = \frac{I_{L3}\, D}{\Delta v\% V_{C3} f_s} \qquad --- (23)$$

Where Δv% is the ripple tolerance of capacitor voltage. In addition, the capacitances of C_1 and C_{out} should be large enough to keep the capacitor voltage constant.

C. Switching components

From Fig.3 and Fig.4, the drain-source voltage V_{DS} of the switch S in stage II is equal to V_{C3}, the voltage on D_1 equals toV_{L2} in stage II or V_{C3} - V_{C1}, that on D_2 equals to V_{L2} or V_{C1} in stage I, that on D_3 equals to V_{C3}, and that on D_4 equals to the difference between V_o and V_{C2}. Then based on Eqns. (2) and (3), we have

$$V_{DS} = V_{C3} = \frac{V_{in}}{(1 - D)^2} = \frac{V_0}{1 + D} \qquad --- (24)$$

$$V_{D1} = V_{C3} - V_{C1} = \frac{D}{(1 - D)^2} V_{in} = \frac{D}{1 + D} V_0 \ --- (25)$$

$$V_{D2} = V_{L2} = V_{C1} = \frac{V_{in}}{1 - D} = \frac{1 - D}{1 + D} V_0 \qquad --- (26)$$

$$V_{D3} = V_{C3} = \frac{V_0}{1 + D} \qquad --- (27)$$

$$V_{D4} = V_0 - V_{C2} = \frac{V_0}{1+D} \qquad --- (28)$$

As the current passing switch S during stag I is the sum of inductor currents i_{L1}, i_{L2} and i_{L3}, then the maximum switch current will be

$$I_{s-max} = \left(1 + \frac{\Delta i\%}{2}\right)(I_{L1} + I_{L2} + I_{L3}) \qquad --- (29)$$

Both i_{D1} and i_{D2} are part of i_{L1}, and then the maximum value of i_{D1} and i_{D2} will be

$$I_{D1-max} = I_{D2-max} = \left(1 + \frac{\Delta i\%}{2}\right) .\ I_{L1} \quad --- (30)$$

It is known that $i_{D3} = i_{L2} + i_{C2} = i_{L3} + i_{C3}$ and $i_{C2} = - i_{C3}$ in stage II, then the maximum value of I_{D3} will be

$$I_{D2-max} = \left(\frac{1}{2} + \frac{\Delta i\%}{4}\right) .(I_{L2} + I_{L3}) \quad --- (31)$$

Finally, the current passing diode D4 can be considered as the output current Io.

Table:1: Parameters Of The high step-up Converter

PARAMETER	SIMBOL	VALUVE
Output power	P_0	120 W
Input voltage	V_{in}	28 V
Output voltage	V_o	134 V
Switching frequency	F_s	100 KHZ
Inductance	L_1	127 µH
Inductor	L_2	550 µH
Inductor	L_3	295 µH
Capacitance	C_2,C_3	2 µF
Capacitance	C_1 , C_{out}	470 µF

IV. MATLAB/SIMULINK RESULTS

1 Simulation of high step up converter with PI controller.

The simulink model of High step-up converter with PI controler citcuit is used to increase the universal input dc voltage 28V dc to 134V at 120W is shown in fig 8

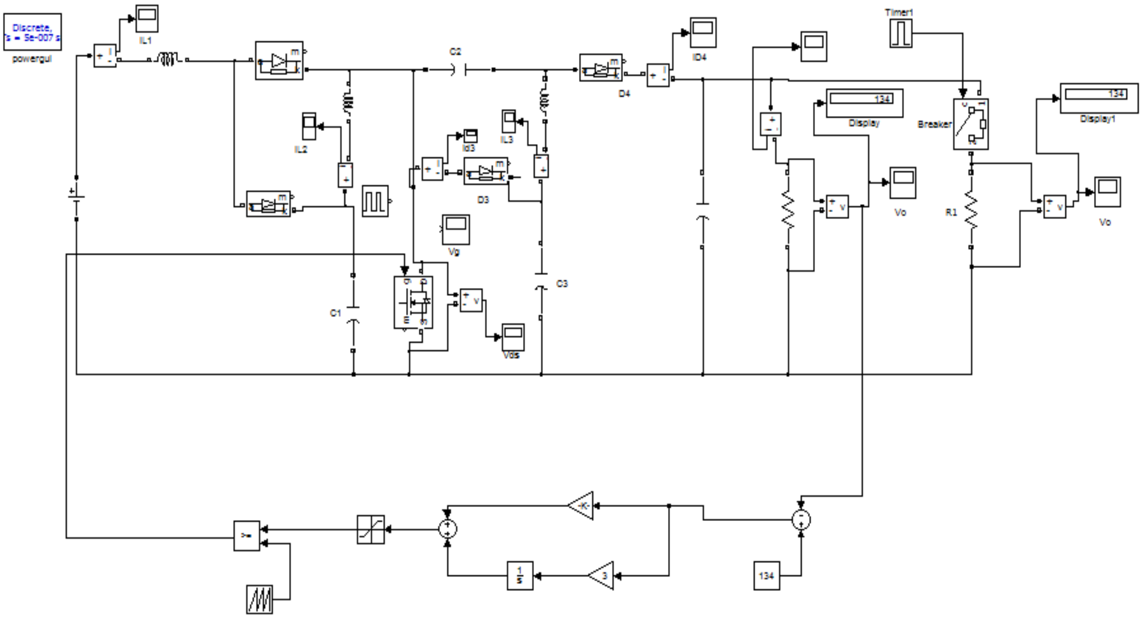

Fig.8 MATLAB/SIMULINK circuit for the single-switch high step-up converter for PI

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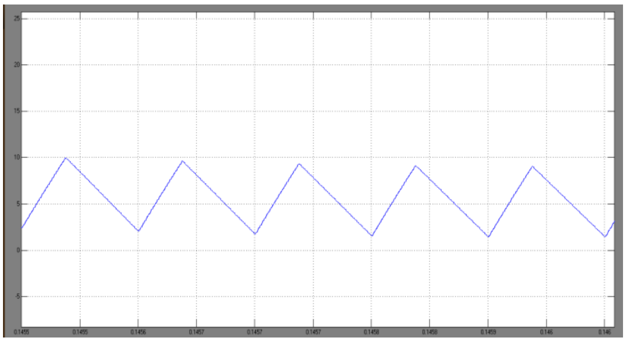

Fig.9 Inductor current-1

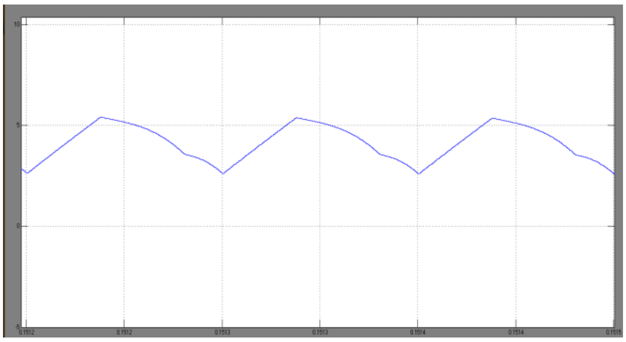

Fig.10 Inductor current-2

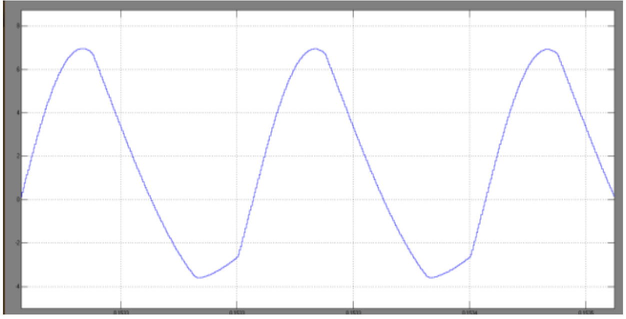

Fig.11 Inductor current-3

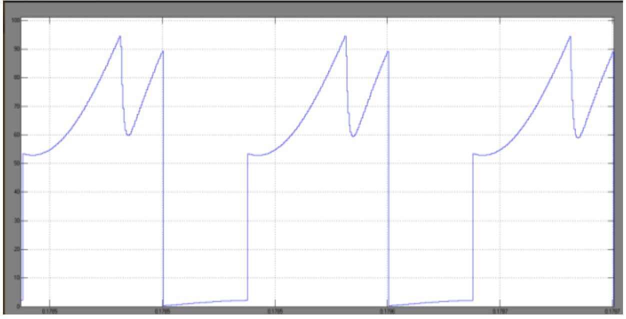

Fig.12 Source drain voltage-2

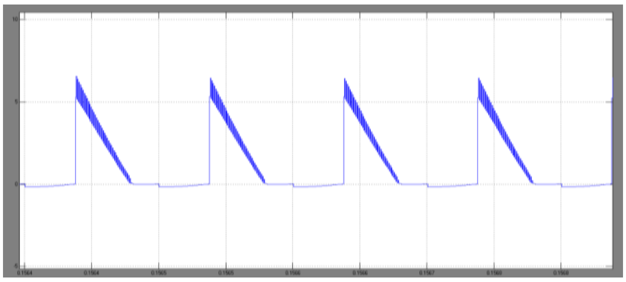

Fig.13 Diode current 3

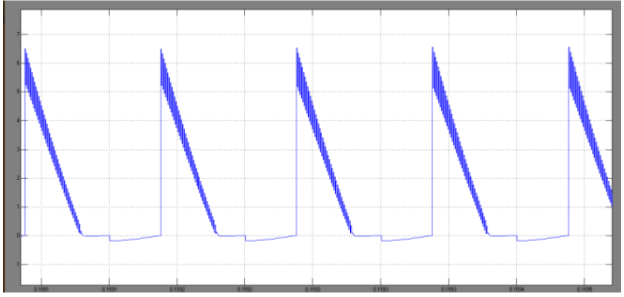

Fig.14 Diode current -4

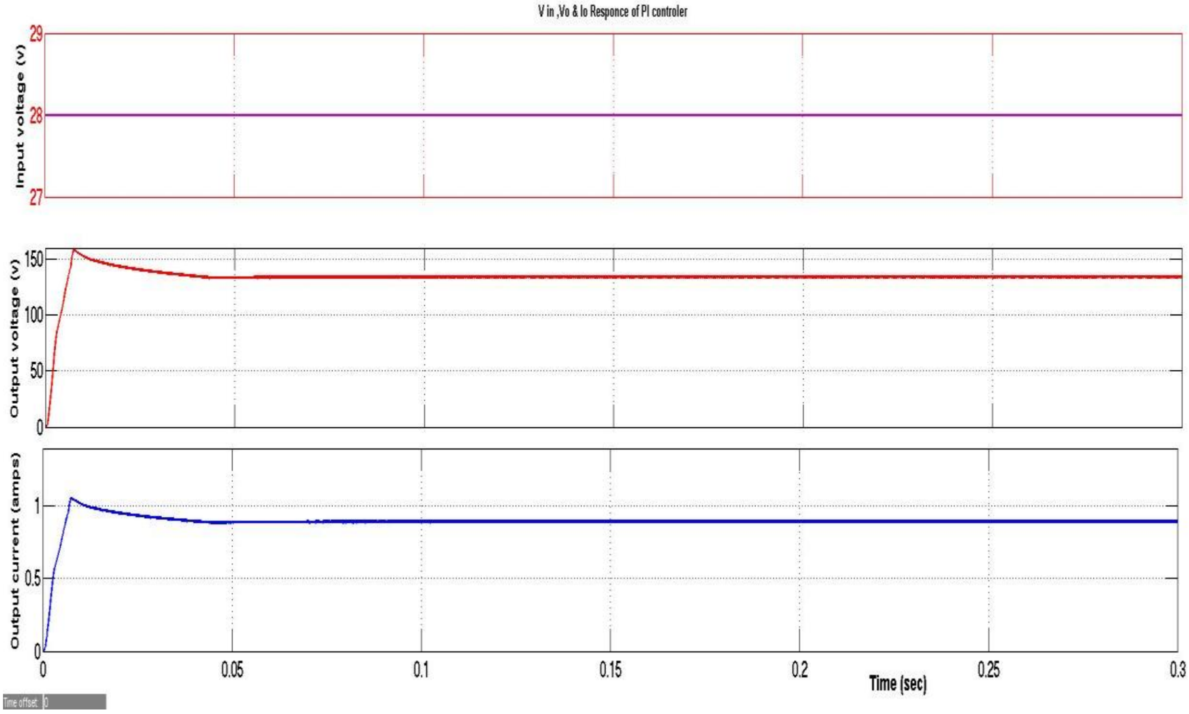

Fig.15 input voltage, Output voltage& current for pi controller.

Fig.15 shows the input voltage of 28V, output voltage of 134V and load current of 0.895 amps.with PI controller.

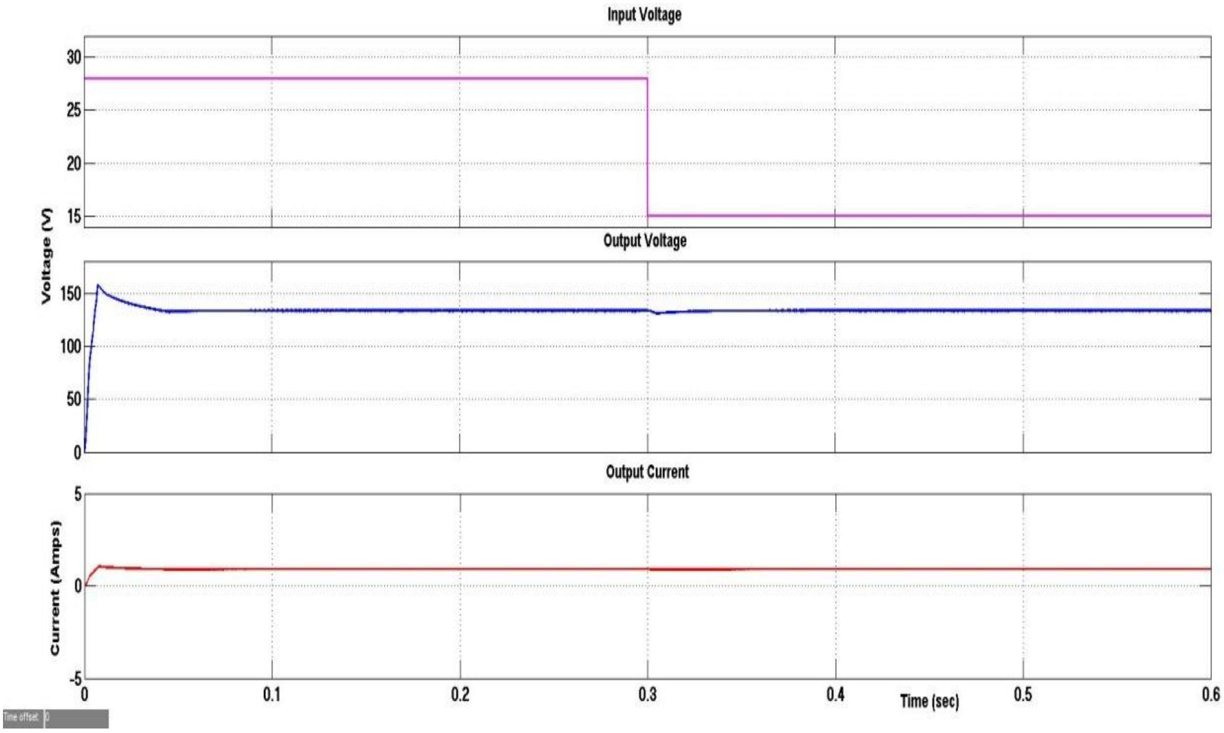

Fig.16 Input voltage ,output voltage & current response of high step up converter with PI controller.

Fig 16 shows the input voltage 28V , output voltage of 134V, and load current of 0.895 amp With PI controller. For a step change in input from (28V to 15V).

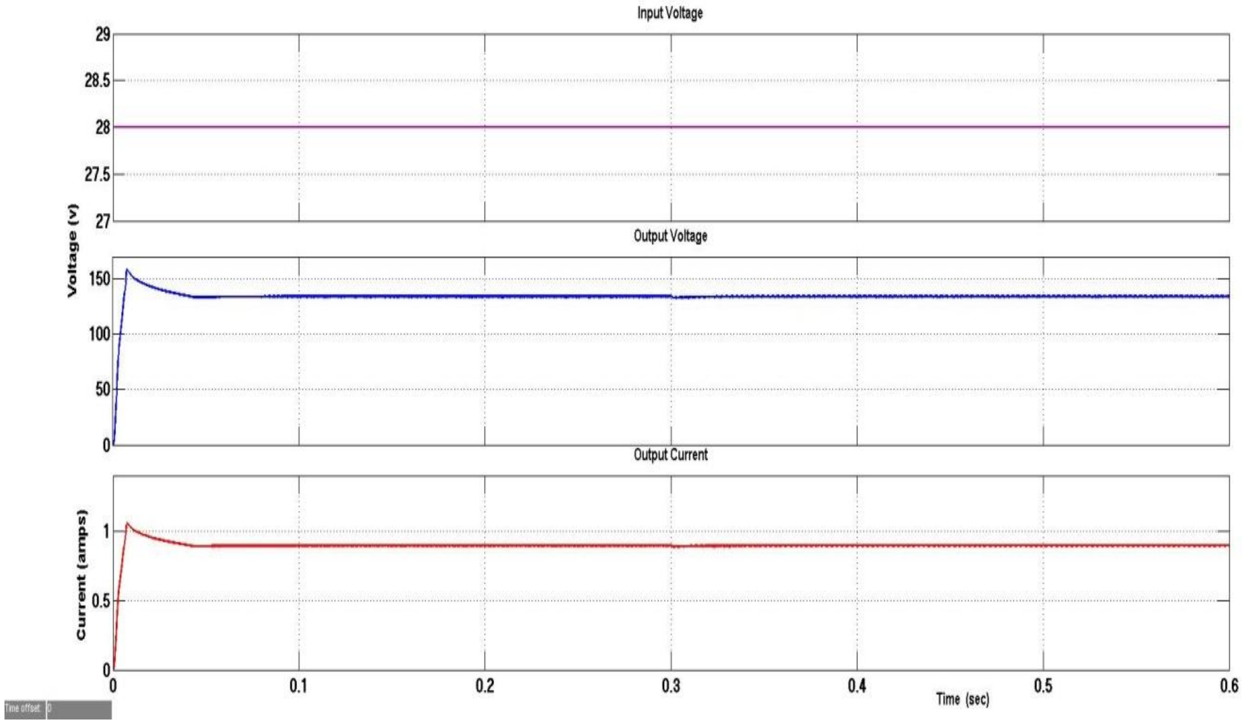

Fig 17.Input voltage,output voltage & current response of high step up converter load change with PI Controller.

Fig 17. shows the input voltage 28V, output voltage of 134V, and load current of 0.895 amp With PI controller. For a load change. As most of the applications require a tight voltage with a better regulation, there is a need of voltage control for changes in the loads.

2.Simulation of high step up converter with ACM controller.

The simulink model of High step-up converter with ACM controler citcuit is used to increase the universal input dc voltage 28V dc to 134V at 120W is shown in fig 17.

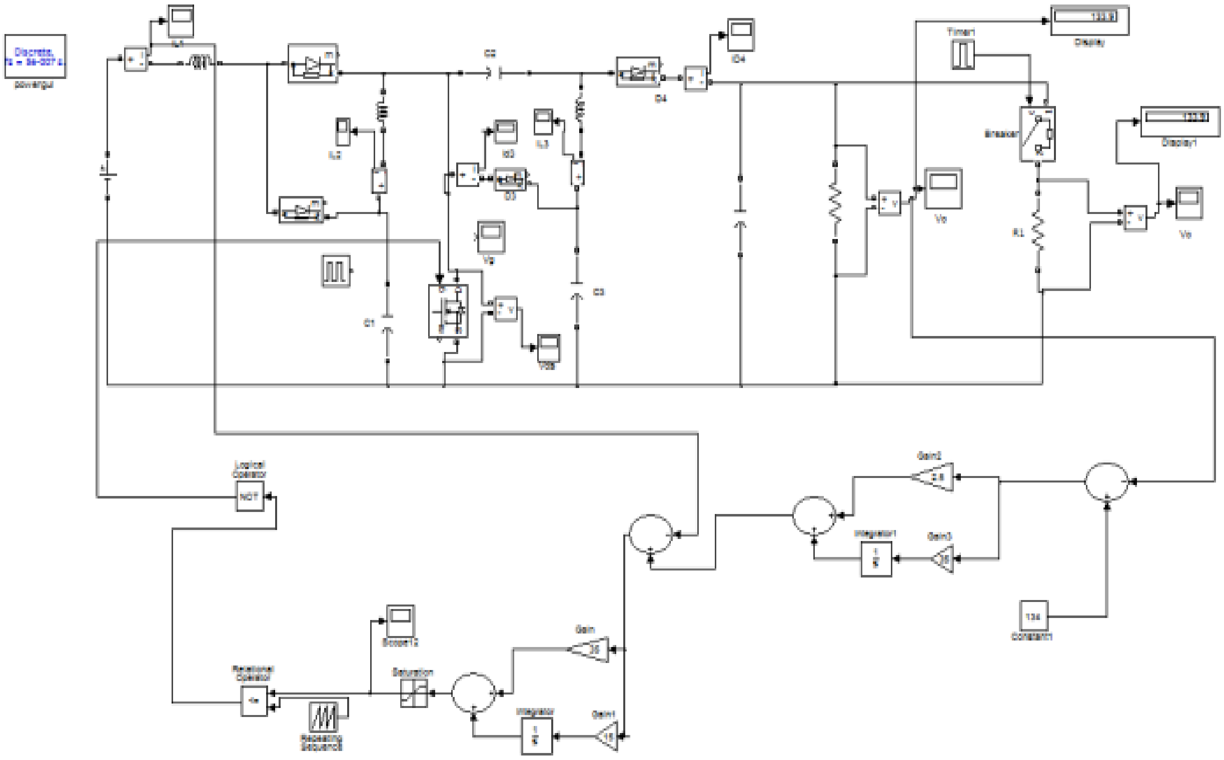

Fig.18 MATLAB/SIMULINK circuit for the single-switch high step-up converter with current mode controller

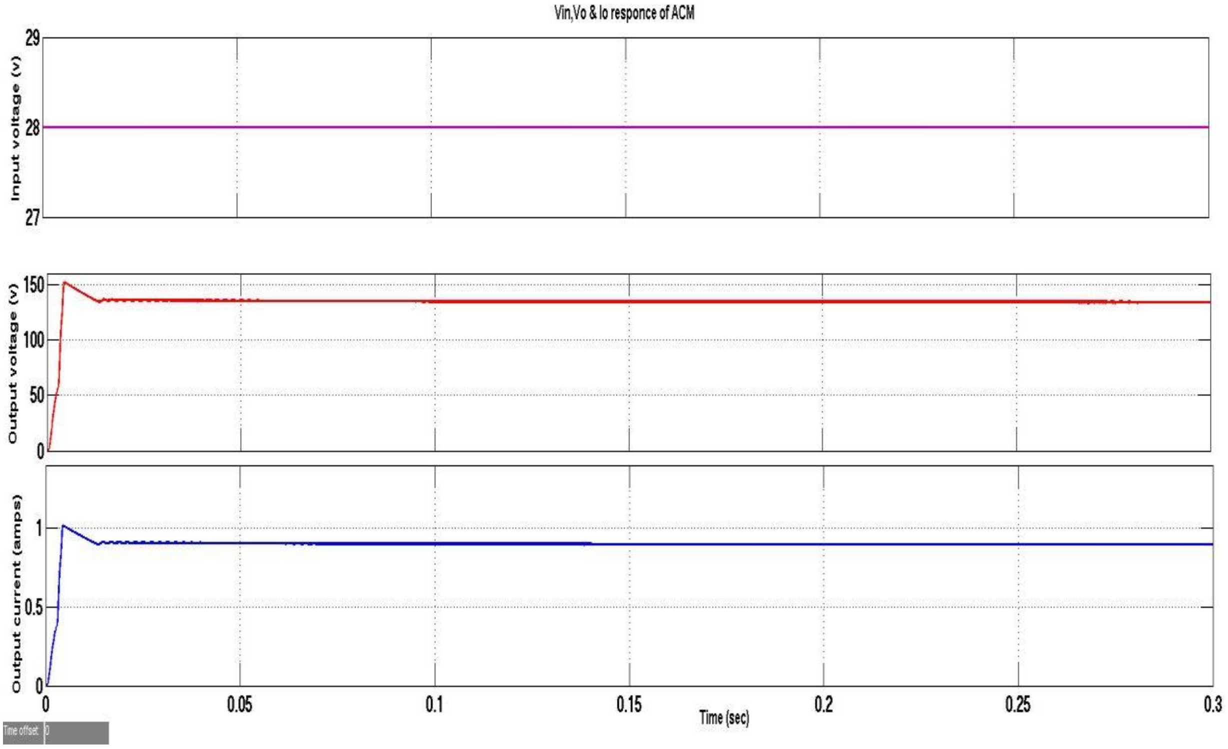

Fig.18 Vin,Vo&Io. resistor 150 ohms for acm controller

Fig19.shows the input voltage 28V, output voltage of 134V, and load current of 0.895amps with ACM controller.

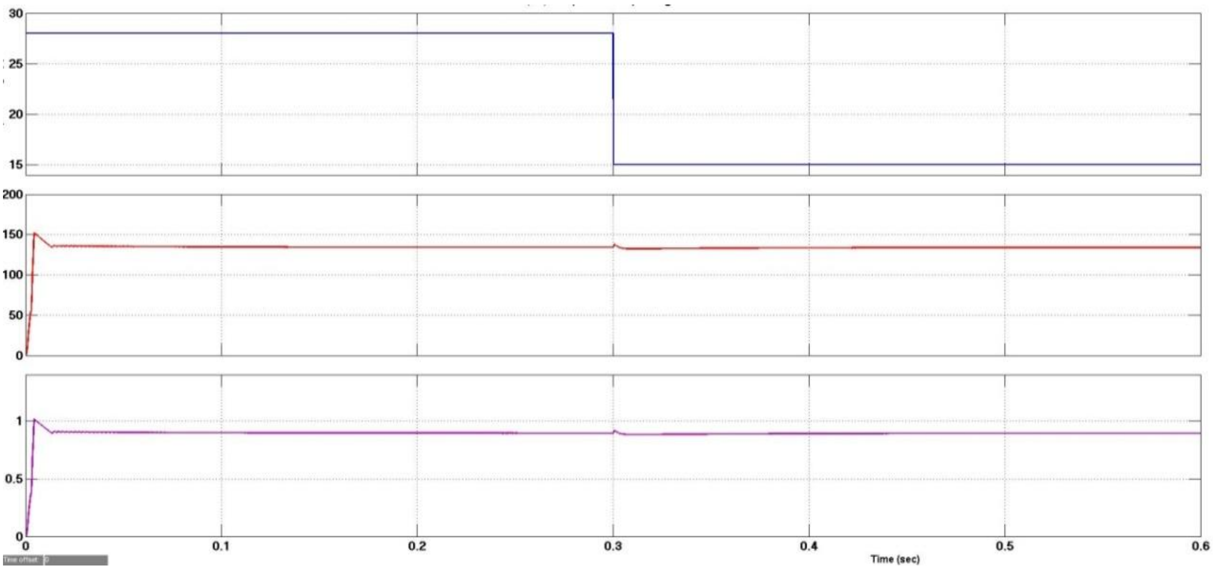

Fig 20. output voltage & current response of high step up converter step change with ACM controller

Fig 20. shows the input voltage 28V , output voltage of 134V, and load current of 0.895 amp With ACM controller. For a step change in input from (28V to 15V).

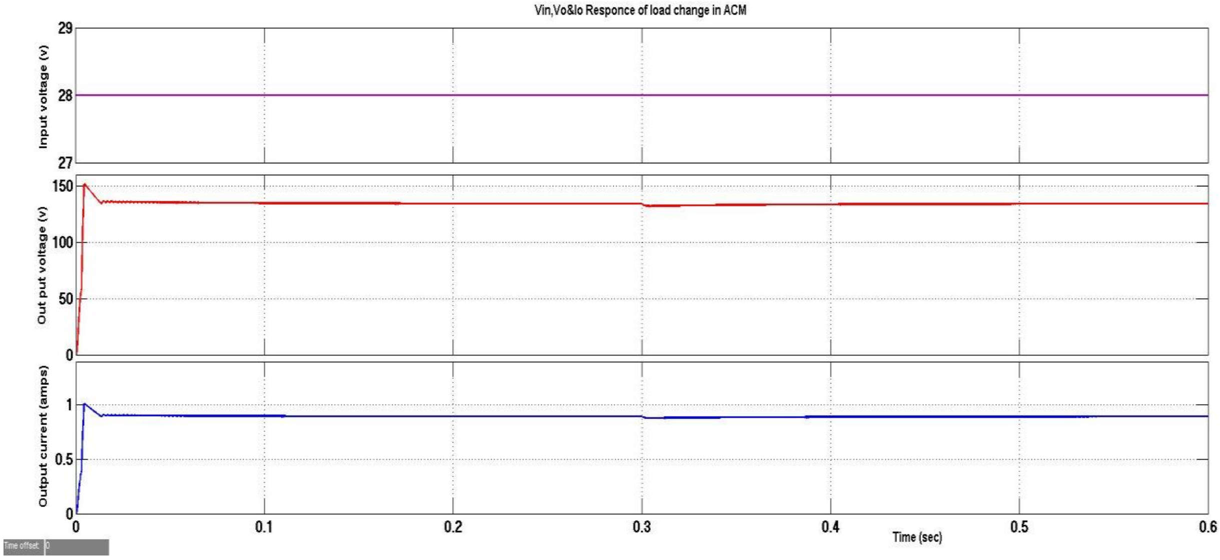

Fig 21. output voltage & current response of high step up converter load change with average current mode controller.

Fig 21. shows the input voltage 28V, output voltage of 134V, and load current of 0.895 amp With ACM controller. For a load chang As most of the applications require a tight voltage with a better regulation, there is a need of voltage control for changes in the loads.

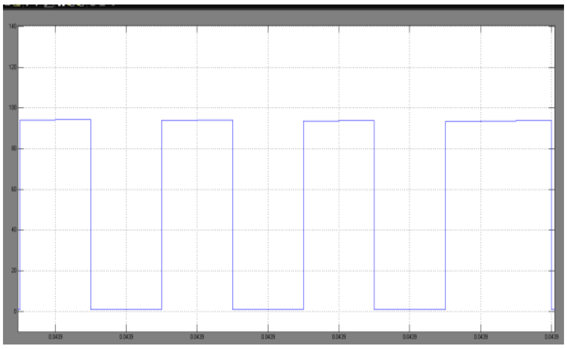

Fig.22 Source drain voltage

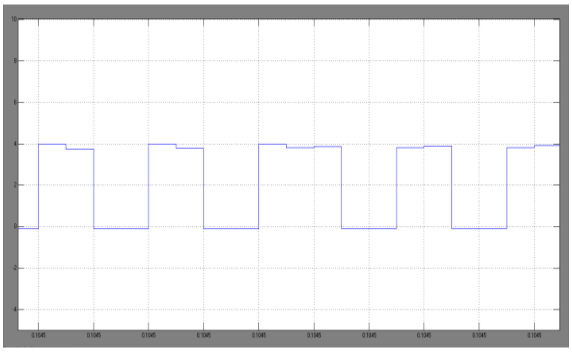

Fig.23 I_{D3}

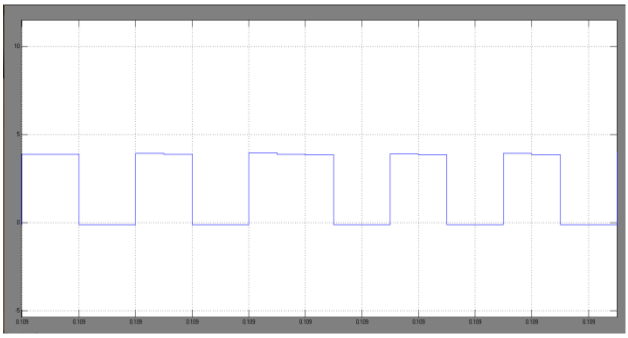

Fig.24 I_{D4}

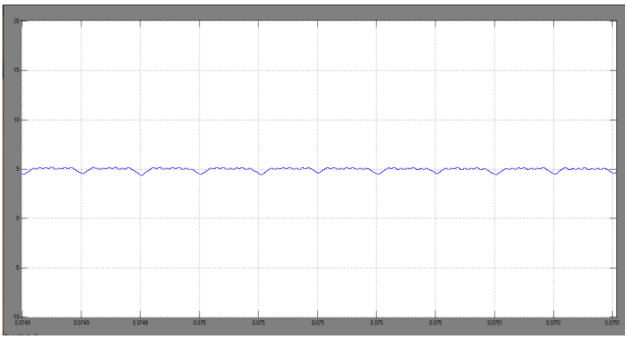

Fig.25 I_{L1}

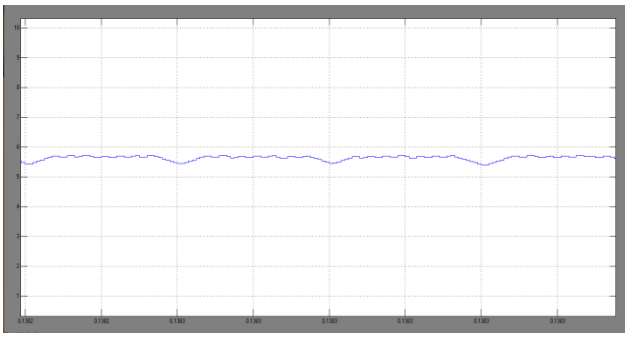

Fig.26 I_{L2}

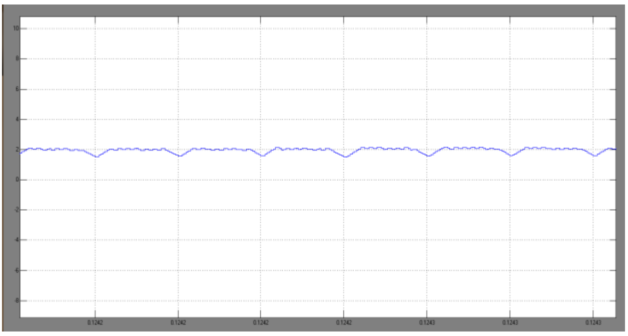

Fig. 27 I_{L3}

3. Simulation of high step up converter with FUZZY Controller.

The simulink model of High step-up converter with FUZZY controler citcuit is used to increase the universal input dc voltage 28V dc to 134V at 120W is shown in fig 4.5

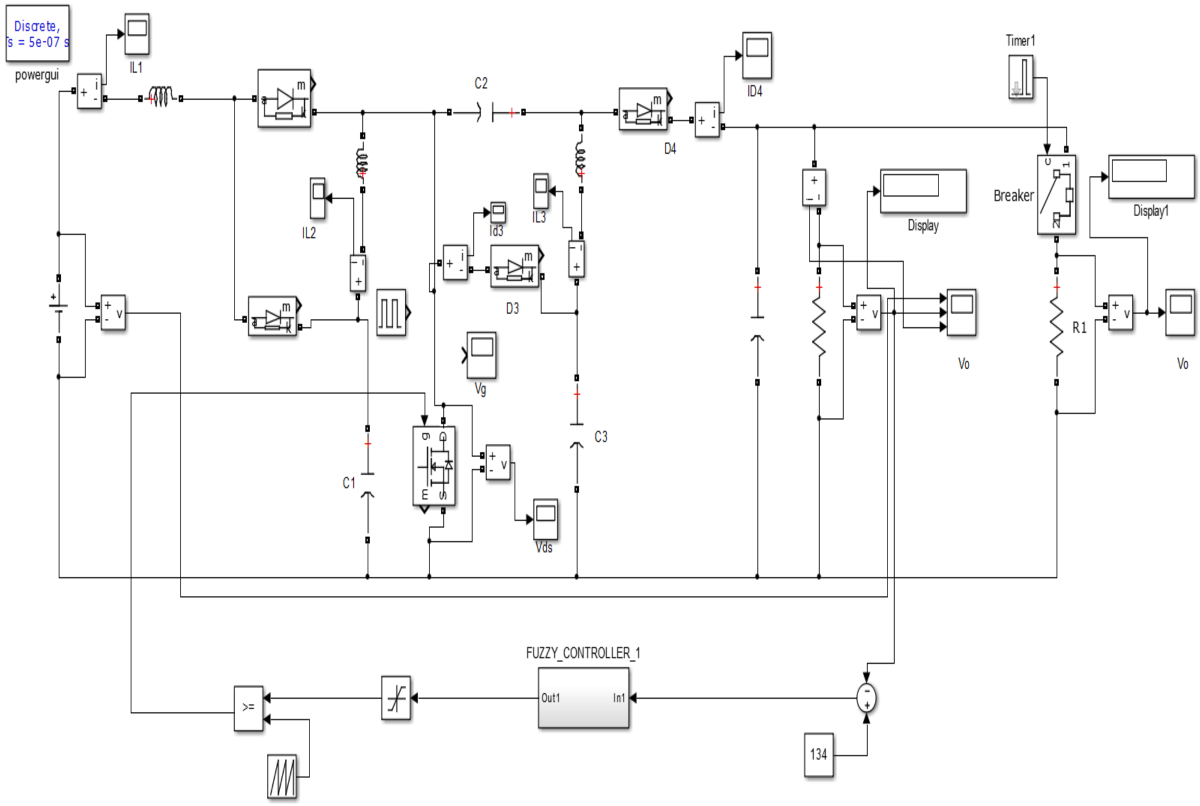

Fig.28 MATLAB/SIMULINK circuit for the single-switch high step-up converter with fuzzy logick controller

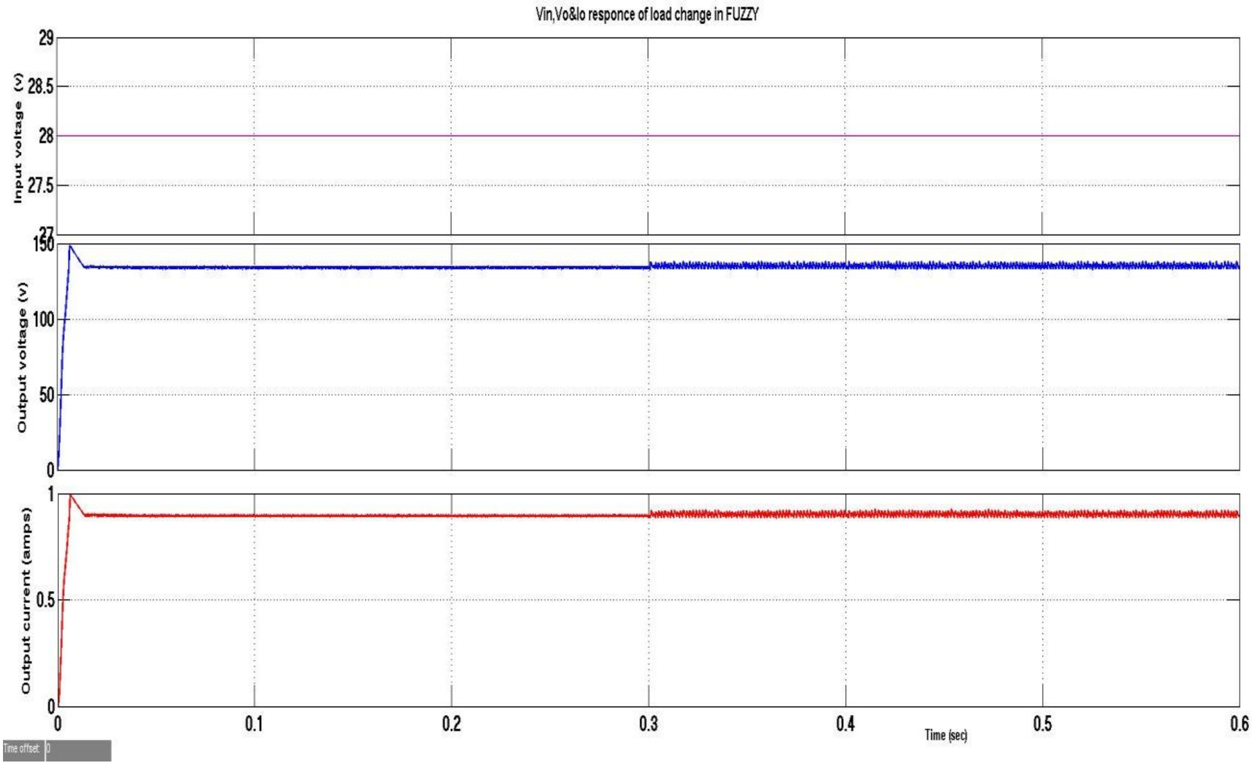

Fig 29 shows the input voltage 28V ,output voltage of 134V, and load current of 0.895 amp With FUZZY controller.

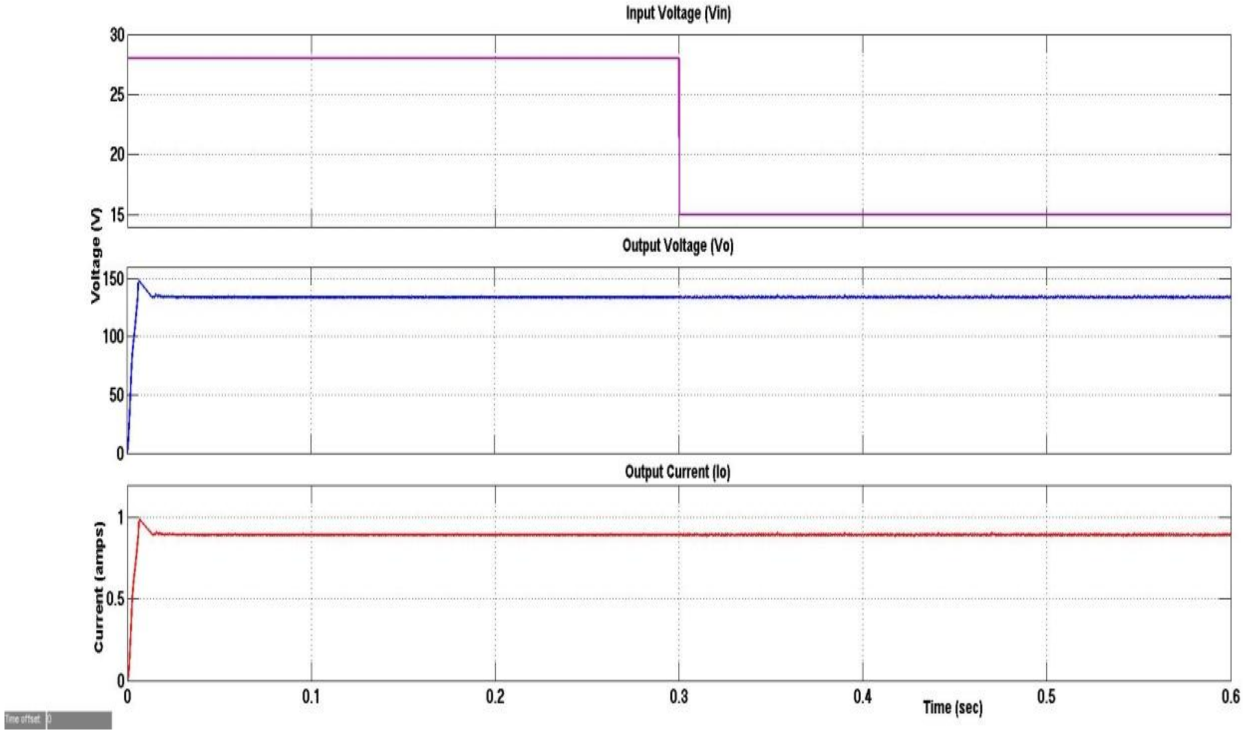

Fig.30 output voltage & current response of high step up converter step change with fuzzy logic controller.

Fig 30 shows the input voltage 28V, output voltage of 134V, and load current of 0.895 amp With FUZZY controller. For a step change in Input from (28V to 15V).

Fig 31 shows the input voltage 28V , output voltage of 134V, and load current of 0.895 amp With FUZZY controller. For a load change.As most of the applications require a tight voltage with a better regulation, there is a need of voltage control for changes in the loads.

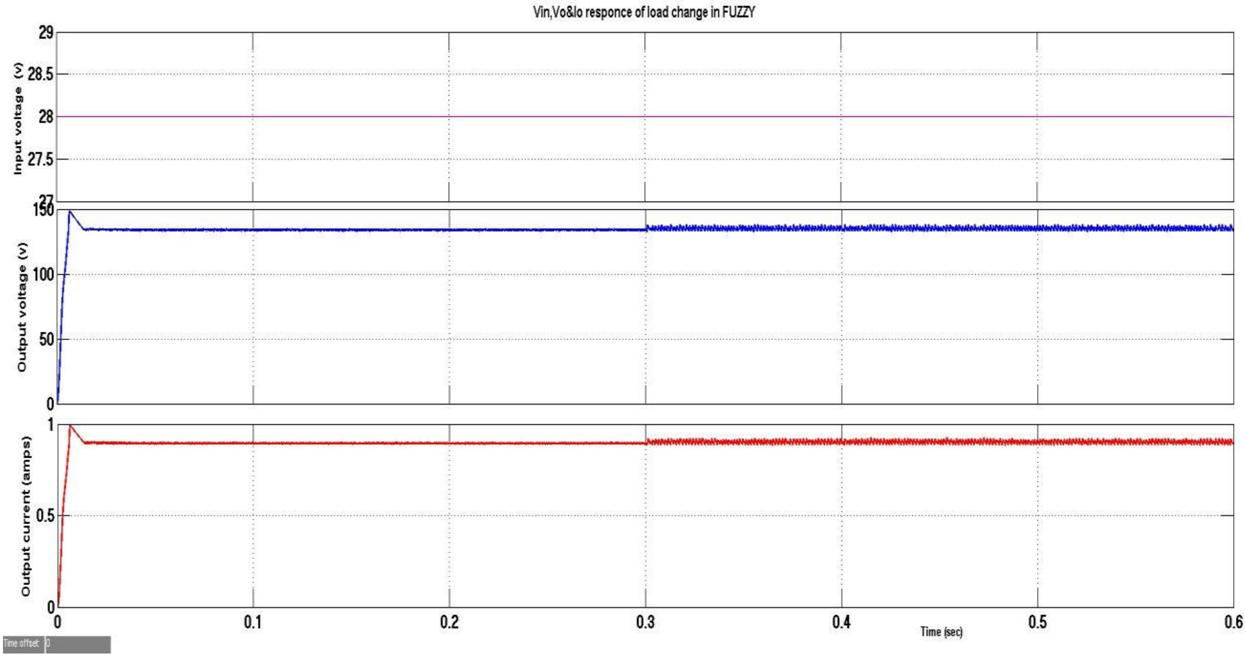

Fig 31 Output voltage & current response of high step up converter load change with fuzzy controller.

VI. CONCLUSION

In this paper, single switch high gain without coupled inductor boost converter has been proposed. In the proposed converter high voltage gain is achieved without using extreme duty cycle values, which is a big advantage over conventional step up converters and also obtained low voltage across the switch. Finally closed loop operation of high step up converter; line and reference regulations, principle of operation, theoretical analysis, and waveforms are discussed.

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