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Closed Loop Control of Multilevel Dc-Dc Boost Converter

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Abstract: ***This paper presents a multilevel DC-DC boost converter (MBC). It is derived from a conventional boost converter just by adding (2N-1) number of capacitors and same number of diodes in order to obtain N levels of output voltage. Its key feature is to convert low input DC to a high output DC at various levels. This feature makes it a suitable candidate for renewable applications like photovoltaic (PV) system, fuel cell system etc. This paper presents a mathematical model of a N level boost converter. Effect of series resistance (ESR) in inductor is analyzed. A closed loop system for a three level MBC is developed and corresponding simulation results are presented.***

Keywords: ***Multilevel DC-DC boost converter (MBC), PV system, fuel cell system, ESR.***

I. INTRODUCTION

In transmission system the power is transmitted at high voltage to reduce losses [1].Many DC-DC converter topologies are found in literature. Microprocessor and Digital systems requires low voltage DC from 3V to 5V.Buck type converters are necessary for such applications [2].Switching frequency of these converters are kept high to reduce the size of the passive components. But these converters operates at low duty cycles [3][4][5]. Good example of buck converter application on any electronic device which converts 110VAC/220VAC to 3V DC to feed electronic devices are available in literature[1][2].

The applications related to high output voltage with low current are SAI instruments, X-Ray system, ion pumps, electrostatic are reported in[6]. Boost converters applications in renewable like PV system where DC output of PV cells is converted to high voltage DC to feed grid connected inverter is presented in[1]. Light intensity control using LED lamps used in automobile headlamps needs voltage increment from the 12V to 100V DC is presented in [5].Resonant DC-DC converters required high-frequency transformers but this transformer is not suitable for high gain converters due to non-idealistic is claimed in [6].DC-DC converters operates at high frequency in order to reduce the size of inductors and capacitors with less ripple in inductor current and capacitor voltage. Traditional converters change only one level of output voltage but multilevel converters are able to convert small input voltage to various levels of output voltages. It uses high frequency switches like power MOSFET with a minimum effective series resistance (ESR) connected to transformerless utility grid[7].Multilevel converters has some limitations like high power rating switches which is also present in multilevel inverters [8][9]. Multilevel inverters are classified as diode clamped, flying capacitor, cascaded cell all three configurations are excellent for different medium power applications[10]-[15].A significant limitation in the diode clamped converter is balancing DC link voltages [7].

Day by Day conventional energy sources are decreasing due to effect of global warming and chlorofluorocarbons (CFC) effect. In order to meet load demand use of renewable energy sources are recommended. For proper synchronization of renewable energy sources with grid power converter like boost, buck-boost becomes essential. A DC-DC multilevel boost converter designed from the conventional boost converter by adding (2N-1) capacitors and diodes (2N-1) for N*level output is discussed in this paper. Load side capacitors provide self-balanced voltage across every capacitor. MBC is not used in diode-clamped multilevel inverter as the external control circuitry becomes complex. This converter uses only one switch and one inductor required as in conventional boost converter. It has so many advantages unidirectional current flow, continuous input and output currents, high output voltages at low duty cycles. Analysis of the proposed circuit is presented in section. 2. Section .3 deals discusses state space representation of the proposed MBC circuit. Full order modeling of 2 level MBC and reduced order modeling of 2 level MBC is explained in section.4.Section 5 deals with the three level MBC .Section 6 discusses the simulation results done in MATLAB environment. Section 7 concludes this paper.

Basic Types of Dc-Dc Converters: -

DC-DC converters are classified as isolating and non-isolating. Isolating dc-dc converters required high frequency transformers and there is possibility of non-idealities present in outputs and limited to low power applications.

In Non-isolating converters there is no use of transformers and are efficient compare to isolating converters some converters are discussed here.In buck converters output voltage is less than input voltage so generally this converter used in digital circuit applications. In boost converter output voltage is more than input voltage so this converter is used in renewable applications.In buck-boost converter,both buck and boost facility is available.

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II. ANALYSIS OF MBC CIRCUIT: -

MBC topology is shown in below Fig.1 consist of only one switch, one inductor,
(2N-1) capacitors, (2N-1) diodes for N level of output voltages.

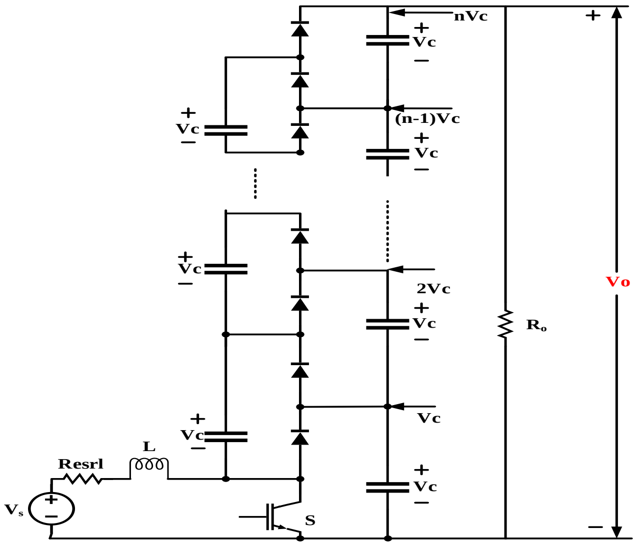

Fig.1. N level DC-DC MBC

2.1 Principle of Operation: -

Four level DC-DC boost converter shown in Fig.2 is selected for analysis. This circuit consists of 7 capacitors, 7 diodes. In conventional boost converter output voltage is equals to capacitor voltage, but in multilevel boost, converter output voltage is equals to the N times of the capacitor voltage i.e. $V_o = N \times V_c$, from Fig.1.

There are total two modesof operation.Mode1 is during switch on condition ($T_1 = DT_s$), other mode during switch off condition ($T_2 = (1-D)T_s$) both modes operations are explained in sections 2.1.1, 2.1.2.

2.1.1 Switch on Condition ($T_1 = DT_s$):-

Four level DC-DC boost converter is shown in Fig.2.During switch on condition inductor connected to the source voltage. If voltage across C6 is less than C7 then C7 clamps voltage across C6 through D6 and switch. In similar manner C5, C7 clamps the voltage of C4, C6 through D4 and switch, C3,C5,C7 clamps the voltage of C2,C4,C6 through D2 and S.

2.1.2 Switch off Condition:-

During switch off condition inductor, source voltage charges C7 through D7 for one level output voltage. Source voltage, inductor, C6 charges both capacitor C5 and C7 for second level output voltage. Source voltage, inductor, C6, C4 charges both capacitor C5, C7, C3 for third level output voltage. In similar manner all levels output voltages generates and maintain constant output voltage across the load.It is clear that during on state D2, D4, D6 and switch(S) and During off state D1, D3, D5 and D7 conducts.

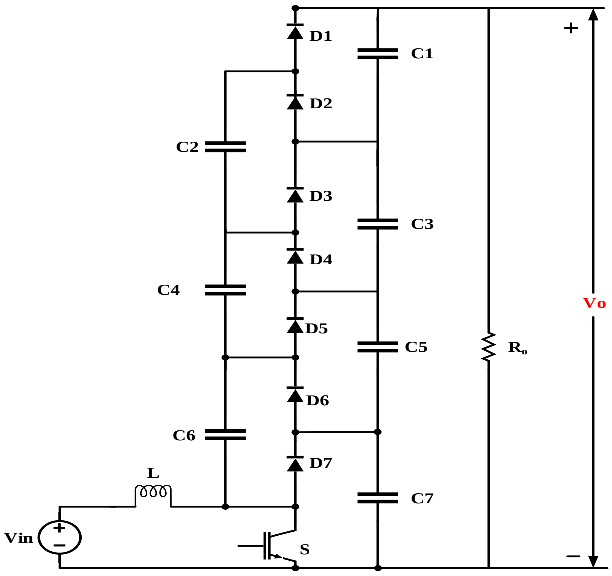

Fig.2. 4 level DC-DC MBC

2.2. Effect of Series Resistance (Resrl): -

Multilevel boost converter at ideal case has maximum boost ratio. In practical applications it is not maximum as it is limited by the parasitic resistance (Resrl) present in inductor, the reason is input current is N times of output. Output voltage of converter in both cases is presented below for ease of understanding.

2.3. Output Voltage of MBC: -

2.3.1 Output Voltage MBC (Resrl =0): -

From Fig.1 $V_0 = N \times V_c, I_L = I_s$ (1)

During on condition inductor voltage

$$V_L = V_s \quad (2)$$

During off condition inductor voltage

$$V_L = (V_s - V_c) \quad (3)$$

Applying volt-second balance, average voltage across inductor during on and off condition is equals to zero.

$$V_L|_{on} + V_L|_{off} = 0 \quad (4)$$

Using equations (2), (3) and(4)

$$DV_s|_{on} + (1-D)(V_s - V_c)|_{off} = 0 \quad (5)$$

From (5)

$$V_s = V_c(1-D) \quad (6)$$

From equation (6) and (1)

$$V_0 = \frac{N \times V_s}{(1-D)} \quad (7)$$

Equation (7) represents t output voltage equation of N level MBC. For lossless converter input power equal to the output power.

$$V_s \times I_s = V_0 \times I_0 \quad (8)$$

From equation (7),

$$V_s \times I_s = \frac{N \times V_s}{(1-D)} \times I_0$$

After modifying equation (9)

$$I_s = \frac{N \times I_0}{(1-D)} \qquad (10)$$

Equation (10) represents source current of N level MBC.

2.3.2 Output Voltage MBC (Resrl): -

From above Fig1.when switch is on condition inductor voltage,

$$V_L = (V_s - I_L \times R_{esrl}) \qquad (11)$$

During off condition inductor voltage

$$V_L = (V_s - V_c - I_L \times R_{esrl}) \qquad (12)$$

$$V_L\big|_{on} + V_L\big|_{off} = 0$$

$$D(V_s - I_L \times R_{esrl}) + (1-D)(V_s - V_c - I_L \times R_{esrl}) = 0 \qquad (13)$$

After solving equation (13)

$$V_s = V_c \times (1-D) + I_L \times R_{esrl} \qquad (14)$$

Equations (1), (10) and (14) one has

$$V_s = \frac{V_0 \times (1-D)}{N} + \frac{V_0 \times N \times R_{esrl}}{(1-D) \times R_0} \qquad (15)$$

Equation (15) represents the output voltage of N level MBC with ESR i.e. Resrl.

2.4. Voltage gain (vs.) duty cycle for different values of resrl/rofor n level MBC:

Fig.3. depicts the gain and duty cycle with different values of Resrl/Ro.It is observed that MBC can't operate at D =1 because it is highly non-linear, but best operating duty cycle is D = 0.5 for high-level strategy. If MBC operates at high duty cycle, inductor may get saturate and non-linearity increases in converter output increasing its size which is not acceptable.

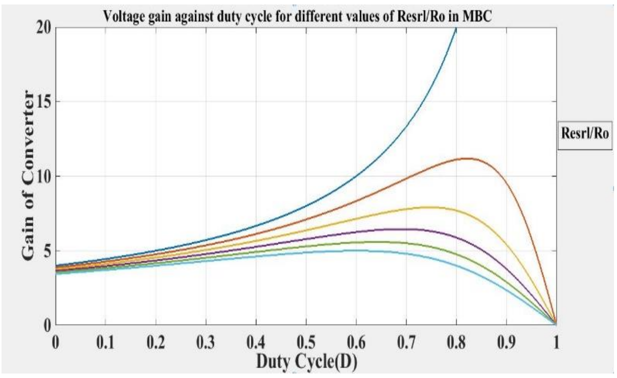

Fig.3. gain vs duty cycle for different values of Resrl/Ro

2.5. Switche and Diodes Voltage Drops: -

In Practical implementations, the drop present in the switches and diodes during conduction becomes important to analyse the efficiency.

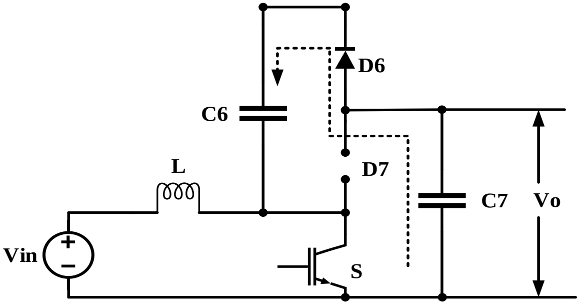

Fig.4.Charging C6 through diode D6

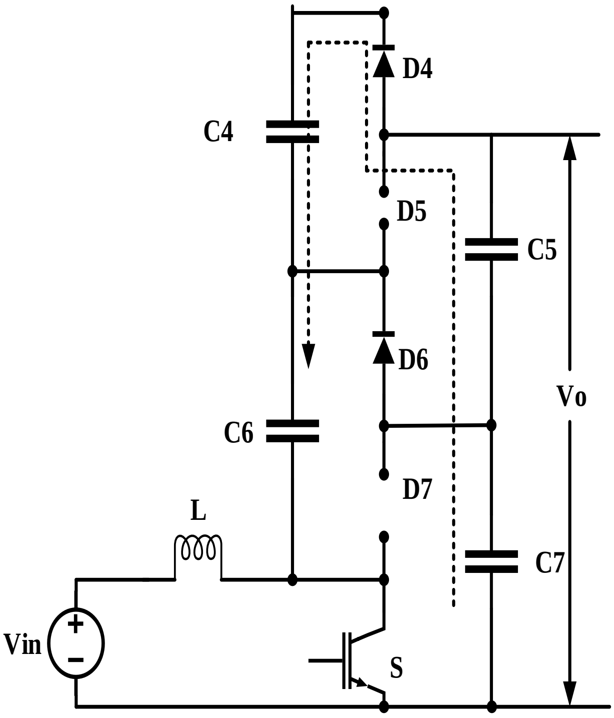

Fig. 5. Charging C4 through diode D4

From Fig4, Voltage across C6 is $V_{C6} = V_{C7} - 2V_d$, $2V_d$ is the voltage drops due to switch(S) and diode D6.

Voltage across C5, $V_{C5} = 2V_{C7} - 2V_d$, $2V_{C7}$ is the output voltage for 2 level inverter, $2V_d$ is the voltage drops due to switch and diode D4.

In similar manner same drop present during switch off condition is found as follows.

FromFig1, at ideal condition $V_o = NV_c$, but during on and off condition switch drop is represented as

$\text{Total drop} = \text{During switch}\big|_{on} + \text{During switch}\big|_{off}$ for N level MBC.

$$V_o = NV_c - (N-1)4V_d \qquad (16)$$

Equation (16) is the actual output voltage of converter.

III. STATE SPACE REPRESENTATION OF MBC

Conventional boost converter consist of one inductor and one capacitor and state space order of matrix is 2.For N level MBC, order of state space matrix is 2N.Analysis of bode, root locus for exact model is very difficult. A simplistic approach for that is reduced order model for the analysis of MBC. Here state space represents for the 2* MBC shown in Fig6. For easy understanding 2 level boost converter is presented which consist of 3 capacitors and 1 inductor and the order is 4. For 3 level boost converter consisting of 5capacitors and one inductor, order is 6. For N* MBC consist of (2N-1) capacitors and one inductor, order is 2*N.

IV. FULL ORDER MODELLING 2 LEVEL MBC

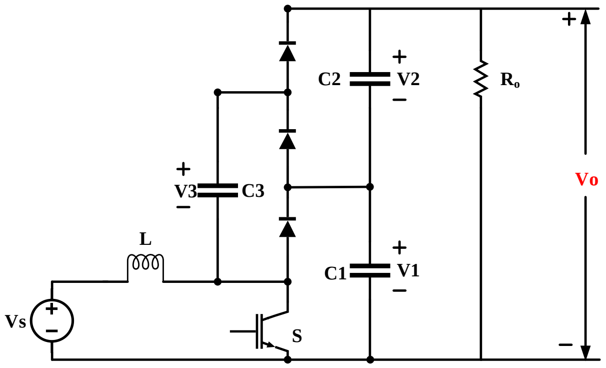

Fig. 6 Three level DC-DC boost converter

For full order state space model represent for a 2 level MBC shown in Fig.6 is discussed below.

During ON condition ($T_1 = DT_s$): -

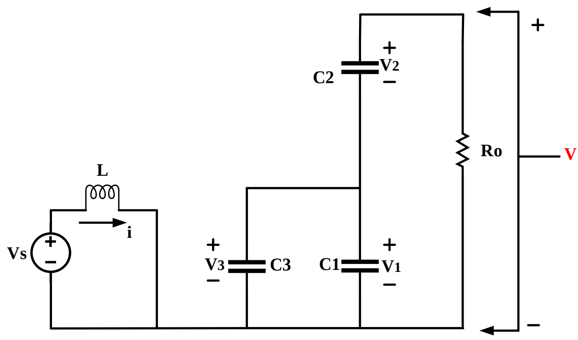

Fig7.MBC during switch on condition.

During on condition,the rate of change of inductor current and rate of change of capacitors voltages are as follows.

$$\frac{di_L}{dt} = \frac{V_s}{L} \tag{17}$$

$$\frac{dV_1}{dt} = -\frac{V_1}{R(C_1+C_3)} - \frac{V_2}{R(C_1+C_3)} \tag{18}$$

$$\frac{dV_1}{dt} = -\frac{V_1}{RC_2} - \frac{V_2}{RC_2} \tag{19}$$

$$\frac{dV_3}{dt} = -\frac{V_1}{R(C_1+C_3)} - \frac{V_2}{R(C_1+C_3)} \tag{20}$$

During OFF condition (1-D)Ts: -

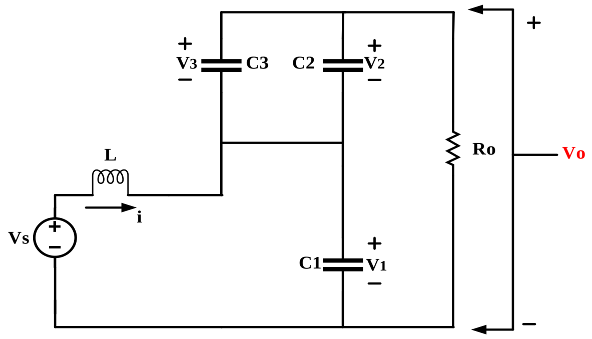

Fig 8 .MBC during switch off condition

The rate of change of inductor current and capacitors voltage written below

$$\frac{di_L}{dt} = -\frac{V_1}{L} + \frac{V_s}{L} \tag{21}$$

$$\frac{dV_1}{dt} = \frac{i}{C_1} - \frac{V_1}{RC_1} - \frac{V_2}{RC_1} \tag{22}$$

$$\frac{dV_2}{dt} = -\frac{V_1}{R(C_1+C_2)} - \frac{V_2}{R(C_1+C_2)} \tag{23}$$

$$\frac{dV_3}{dt} = -\frac{V_1}{R(C_2+C_3)} - \frac{V_2}{R(C_2+C_3)} \tag{24}$$

As full order modelling difficult to analysis of system of order system for that reduction of order by second order by reducing number of capacitors during on and off condition.

DURING SWITCH ON CONDITION: -

2 level MBC reduced circuit configuration during switch on condition is shown in Fig.9

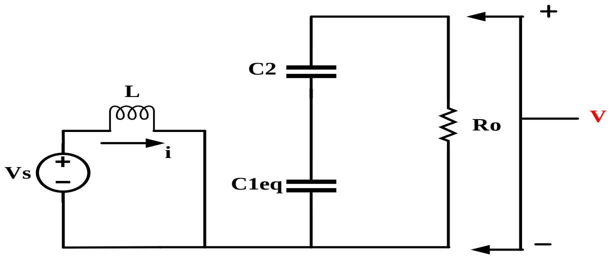

Fig9. Reduced order model of 3 level MBC during ON condition

During on conditions voltage and current equations written below.

$$L\frac{di_L}{dt} = -E \tag{25}$$

$$C_{1eq}\frac{dv}{dt} = -\frac{N}{R} \times V \tag{26}$$

DURING SWITCH OFF CONDITION: -

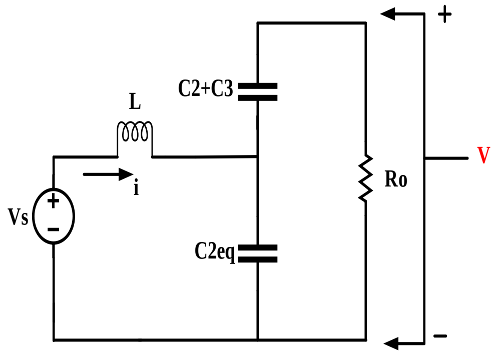

Fig10. Reduced order model of 3 level MBC during OFF condition

2 level MBC Reduced another circuit configuration during switch off condition is shown inFig.10.

$$L\frac{di_L}{dt} = -\frac{V}{N} + E \qquad (27)$$

$$C_{2eq}\frac{dv}{dt} = i - \frac{N}{R} \times V \qquad (28)$$

By combining both on and off conditions equations of reduced order model, one has

$$L\frac{di_L}{dt} = -(1-D)\frac{V}{N} + E \qquad (29)$$

$$C_{eq}\frac{dv}{dt} = (1-D)i - \frac{N}{R} \times V \; \{ C_{eq} = C_{1eq} + C_{2eq} \} \qquad (30)$$

Output equations: -

$$V_0 = V_c \qquad (31)$$

$$I_g = i_L \qquad (32)$$

From (27) to (32) , the state space matrix formed is given below.

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-D)}{N \times L} \\ \frac{(1-D)}{C_{eq}} & -\frac{N}{R \times C_{eq}} \end{bmatrix} \begin{bmatrix} i_L \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_s \qquad (33)$$

$$\begin{bmatrix} V_0 \\ I_g \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} \qquad (34)$$

At steady state condition above matrices $\frac{di_L}{dt} = 0 \, , \frac{dv_c}{dt} = 0$ both become zero matrices (33) and (34).In steady state gain of the converter is found out.

$$\frac{dX}{dt} = 0 = AX + BU \Longrightarrow \qquad X = -A^{-1}BU \qquad (35)$$

$$Y = CX \Longrightarrow \qquad Y = -CA^{-1}BU \Longrightarrow \frac{Y}{U} = -CA^{-1}B \; (36)$$

$$V_0 = -CA^{-1} \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_s \qquad (37)$$

From (33) to (37) gain of converter is

$$V_0 = \frac{N \times V_s}{(1-D)} \qquad (38)$$

The equation (38) justifies the mathematical modeling of N level boost converter.

V. CIRCUIT MODEL FOR 3* MBC: -

5.1. Three levelMBC OPEN LOOP CIRCUIT MODEL: -

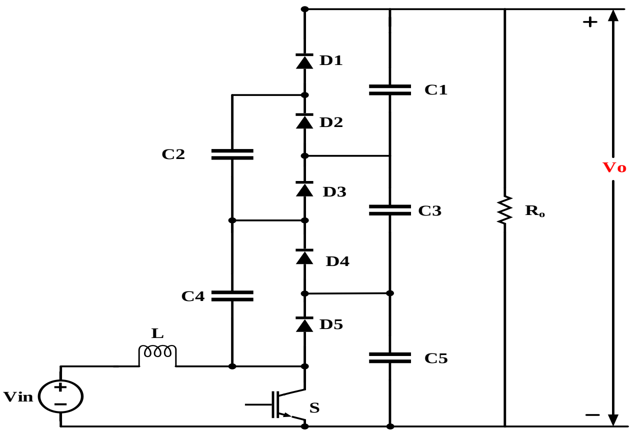

Fig11. Open Loop Circuit for 3 level MBC

Fig1 indicates that for N* MBC for the N level we can design any level of MBC open loop model, but this open loop model exists for particular values of frequency(kHz), load resistance , inductance and Capacitor. For ease of understanding a3* MBC circuit model is shown in Fig. 11.

5.2. Closed Loop Circuit Model: -

To keep the output voltage constant during load variation , a closed loop system is developed. Fig.12 represents the 3* MBC closed loop system.A PI controller is used to control the duty cycle of switch.

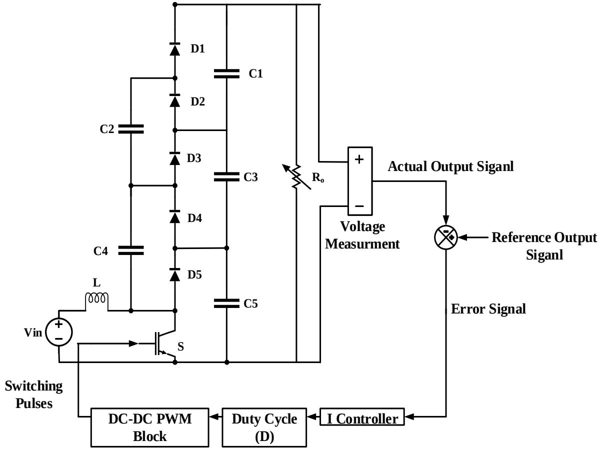

Fig12. Closed Loop Circuit Model

Results carried out for closed loop system is discussed in section 6.

VI. SIMULATION RESULT AND ANALYSIS: -

Simulations are carried out in Matlab environment. The parameters for simulations are : Vin = 50(V), L = 1.33(mH), C = 100(μF),Duty Cycle(D) = 0.5.To check the operation of closed loop system, a change in resistance is introduced after 50 ms. Initially the resistance was 10Ω and at 50ms the resistance is increased to 20Ω.As resistance changes oscillations present in the duty cycle(D), output voltage(V), input current(A) after settling time again duty cycle, output voltage(V), input current(A) maintain constant as shown in simulation results, Figs.

(16, 17 and 18).As the load resistance increases the settling time increases in all the responses. For different values of load resistances , settling times are measured as tabulated in Table1.Simulation of 3*MBC closed loop system is carried out at variable resistive load.As load resistance increases settling time of converter responses like input current, output current and output voltage graphs are shown in Figs. (19) and (20).

Table. 1

R-Load(ohm)	Input Current settling time(ms)	output Current settling time(ms)	Output voltage settling time (ms)
20	2	2	2
50	6.5	4.5	4.5
70	8	6	6
100	10	9.5	9.5

6.1 RESULTS OF 3*MBC OPEN LOOP SYSTEM: -

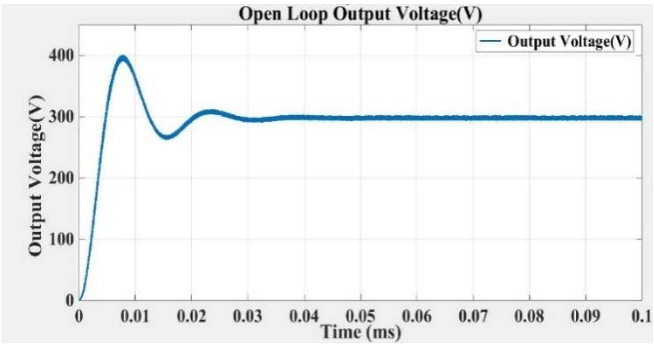

Fig.13. Open loop output voltage of 3* MBC

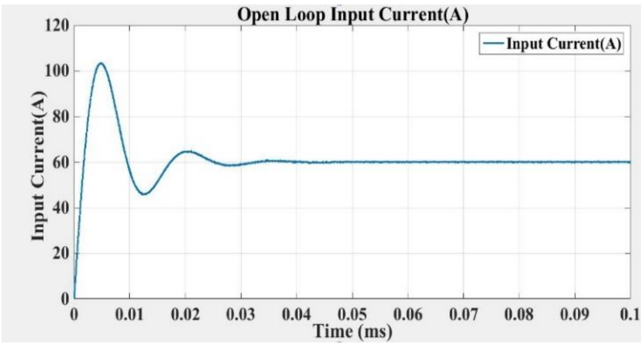

Fig.14. Open loop input current of 3* MBC

6.2 RESULTS OF 3*MBC CLOSEDLOOP SYSTEM: -

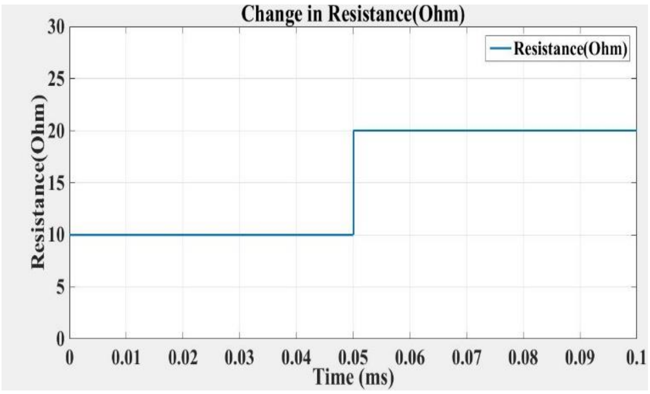

Fig.15. Change in Resistance(Ohm)

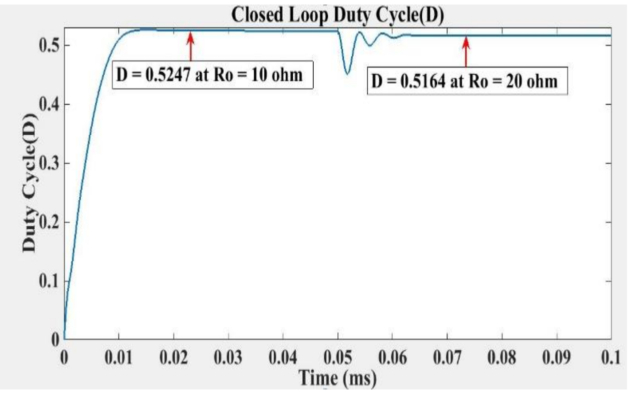

Fig.16. Closed loop Duty cycle(D)

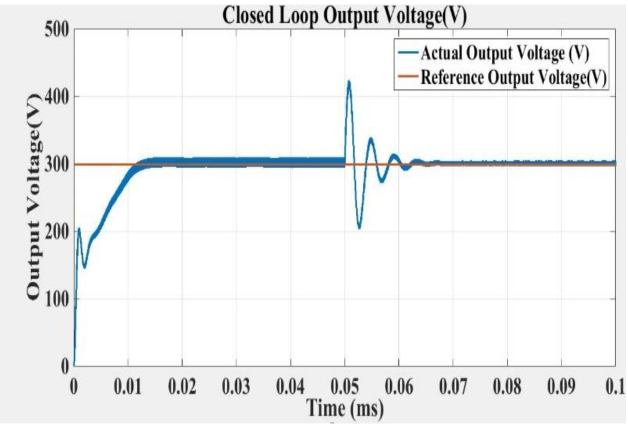

Fig.17. Closed Loop Output Voltage of 3* MBC

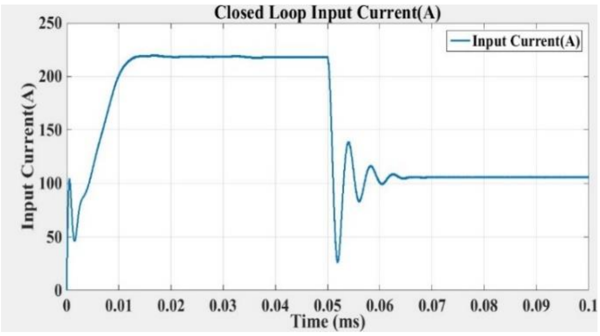

Fig.18.Closed Loop input current of 3* MBC

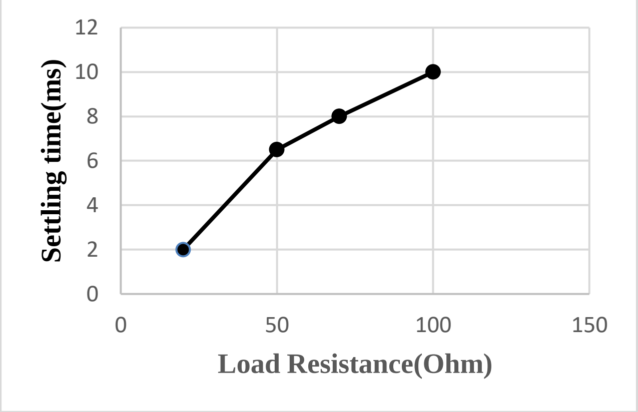

Fig.19.settling time of input current

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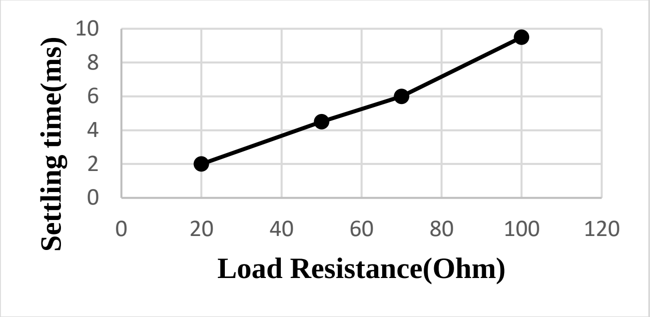

Fig.20.settling time of output current and voltage

VII. CONCLUSIONS: -

This paper discussed the multilevel DC-DC boost converter. Mathematical modeling of N Level MBC is presented. Simulation results for open loop and closed loop system are presented. A three level MBC is selected for simulation results.To verify the suitability of closed loop system a change in load is considered.The results justifies that the controller used take cares the change in duty cycle to give steady output voltage. High frequency switch is used to reduce the size of the passive components. The converter is suitable for renewable energy applications like solar energy.

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