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An Improved Multistage Switched Inductor Boost Converter (Improved M-SIBC) for Renewable Energy Applications: A key to Enhance Conversion Ratio

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Abstract—In this article, an improved Multistage Switched Inductor (M-SI) based power converter or Improved Multistage Switched Inductor Boost Converter (Improved M-SIBC) is proposed for renewable applications which provides a key to enhance voltage conversion ratio. In last decades, Switched Inductor (SI) and M-SI are the popular network/technique employed in DC-DC converter to achieve high voltage conversion ratio. An improved SI and M-SI network/technique is proposed to enhance the existing the voltage conversion capabilities of SI and M-SI by replacing central uncontrolled switches by polarized capacitor. The anticipated power converter configuration combines the feature of conventional boost converter and improved M-SI. The voltage conversion a capability is depends on the number of stages of M-SI and ON time of control switch. The operation modes and characteristics of proposed converter with steady state mathematical analysis for N-stages are discussed in detail. Moreover, the proposed converter compared with existing converter in terms of voltage conversion ratio and the detail of number of components is also provided. Matrix Laboratory R2016a simulation results of 100W proposed improved M-SIBC with considering three stages are provided and the results always shows a good agreement with theoretical analysis and also validates the improved M-SI network concept.

Keywords—Multistage; Switched Inductor; DC-DC; Renewable Energy; Voltage Conversion Ratio, Matrix Laboratory R2016a.

I. INTRODUCTION

Nowadays, renewable energy sources especially wind and photovoltaic technologies are well accepted due to over utilization and depletion of fossil fuels which increases the hotness of earth and also creates several environment issues. In photovoltaic, wind and fuel cells applications, power converters are stipulated and play a vital role for conditioning and conversion of energy [1]–[2]. Furthermore, DC-DC power converter used in renewable energy applications must have efficiency and high voltage capabilities with reduce cost and components. Practically, conventional DC-DC boost converters are not suitable for high voltage conversion due to the effect of inductor internal resistance, voltage stress across controlled switch (MOSFET) and uncontrolled switch (diodes). In addition, very large T_{on}/T (T_{on} is ON time of switch, $T=1/f$, f is switching frequency) of MOSFET result in a severe reverse recovery issue of diodes. Recently, numerous DC-DC power converter configurations are addressed to achieve high voltage conversion ratio without using large T_{on}/T for MOSFET [1]–[7]. Using transformer, a fly-back converter is designed with high voltage conversion and

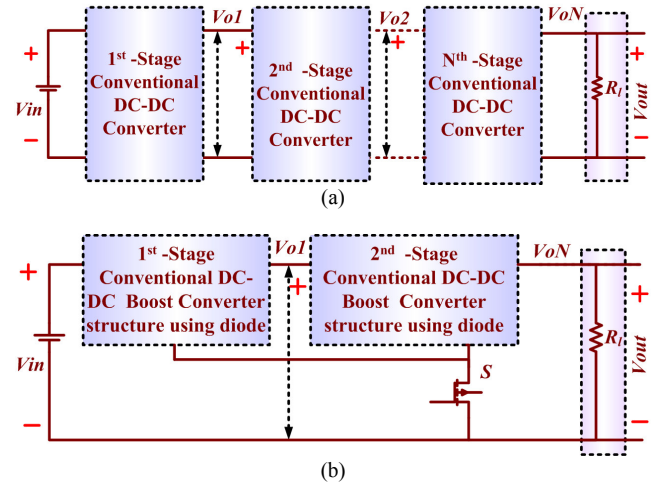


Fig.1 Generalized structure of DC-DC power converter
(a) Cascaded power converter (b) Quadratic power converter

electrical isolation capability but, not suitable for many applications due to transformer leakage inductance and high voltage stress of MOSFET. In, [3], DC-DC converters are addressed with regeneration energy techniques to reduce the voltage stress and recycle the leakage inductance energy. DC-DC converter designed by employing coupled inductor and transformer with or without electric isolation is another solution to attain high voltage conversion ratio, high efficiency, and low voltage stress across switch [4]–[5]. These types of power converters are large in size due to transformer and having more cost and weight.

Recently numerous boosting techniques without transformer are proposed to overcome the drawback of transformer in DC-DC converter [6]–[7]. The multiple boosting techniques are employed in a single power converter also called multistage power converter to enhance the voltage conversion ratio capability with reduce T_{on}/T . Multistage DC-DC power converter includes cascaded converter, quadratic converter, switched capacitor based converter, switched inductor based converter, voltage lift converter, voltage multiplier based converter, and XY converter family [8]–[20]. The block diagram of cascaded and quadratic power converter is depicted in Fig. 1(a) and Fig. 1(b) respectively. In cascaded power converter, several conventional boost converters are connected in cascaded manner, where output of $(N-1)^{th}$ stage is feed as input to the N^{th} stage [8]. Large number of inductors, capacitors, and control switches with various current and

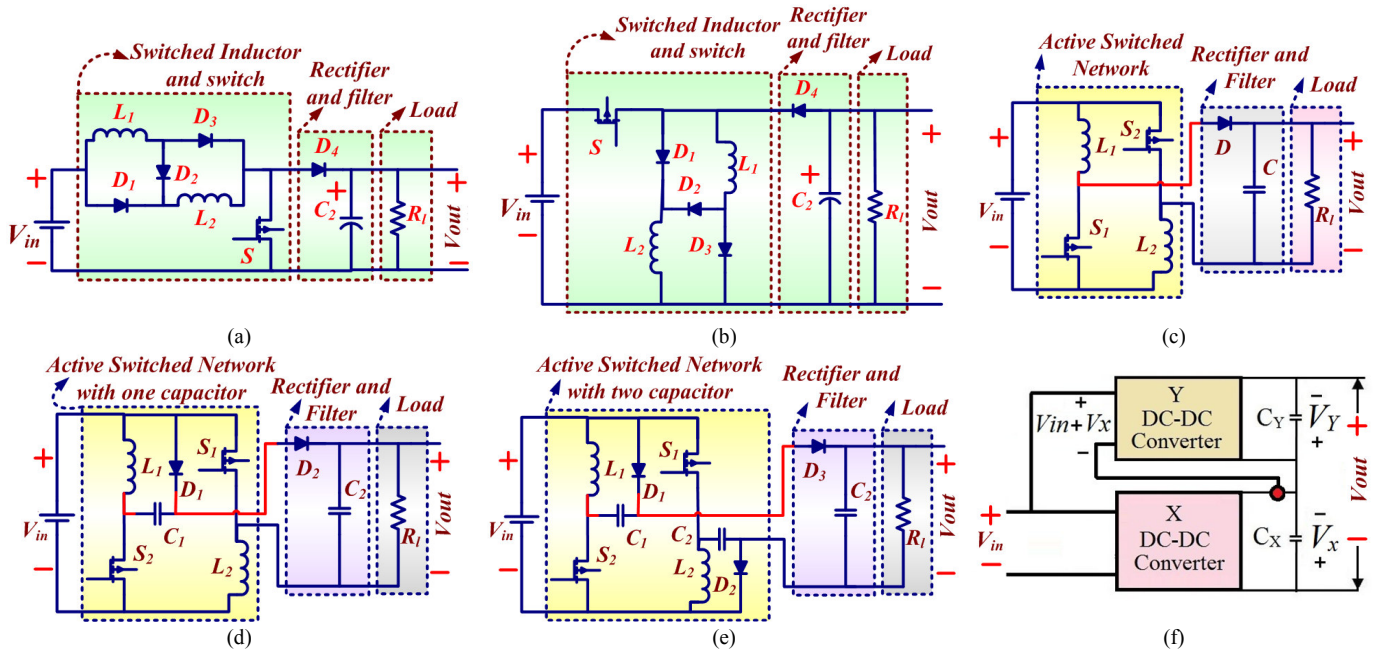


Fig. 2 Recently proposed Switched Inductor based DC-DC power converter (a) Switched Inductor Boost Converter (SI-BC) (b) Switched Inductor Buck Boost Converter (SI-BBC) (c) Converter-I (d) Converter-II (e) Converter-III (f) Generalized structure of XY converter family.

voltage rating, high voltage stress across switch, and complex control circuitry are the main drawback of cascaded converter. Quadratic converter is proposed by cascading two boost converters in special manner using single switch to overcome the drawback of large number of control switches in cascaded converter [9]. The high voltage stress across switch (equal to output voltage) and large rating of inductor and capacitor are the main drawback of quadratic converter. Because of numerous attractive features like high efficiency, low weight, magnetic-less structure, switched capacitor structures gaining more popularity in DC-DC power converters [10]-[11]. These DC-DC converters provides a high efficiency with good regulation of output voltage and therefore several DC-DC switched capacitor based power converters are proposed in literature. Pulsating input current, unidirectional power flow, large number of capacitor with various rating and large number of switching devices are the main drawback of switched capacitor based DC-DC converter. To maintain high efficiency the main hurdle for practical design is TDPR (Total Device Power Rating) of converter. Due to these reasons, the switched capacitor converters have limited voltage conversion ratio and mostly employed for low power applications

Hybridization of voltage multiplier with conventional boost converters is another popular solution to achieve high voltage conversion ratio with low voltage across switch. In [4], voltage multiplier circuitry is employed with conventional (Boost, Buck-Boost) and derived (Cuk, SEPIC) DC-DC converter. In [12], Nx multilevel power converter is proposed with inverting output voltage capability which provides N times voltage conversion ratio compared to conventional boost converter. In [13], Nx interleaved multilevel power converter is proposed with reduce current and voltage ripples which also provides high voltage conversion ratio. To enhance the voltage conversion ratio, 2Nx and 4Nx interleaved multilevel power

converter are proposed which provides 2N and 4N times voltage conversion ratio compared to conventional boost converter [14]-[16]. In [15], inverting Nx and 2Nx multilevel power converter is addressed to achieve inverting voltage with high voltage conversion ratio. These voltage multiplier based power converter provides a high voltage conversion ratio but the main drawbacks are capacitor voltage balancing, difficult in selection of capacitor with proper time constant (RC), large number of capacitor and diodes, the energies is flowing through many multiple stages which reduces the efficiency and the energy conversion is completely depends on charging and discharging of capacitors.

Switched Inductor (SI) based DC-DC converters also provide a viable solution to achieve high voltage conversion ratio [16]-[17]. In SI, two inductors are charged in parallel and discharge in series. Fig. 2(a) and 2(b) depicts the power circuit of Switched Inductor Boost Converter (SI-BC) and Switched Inductor Buck Boost Converter (SI-BBC) respectively. The power circuit SI-BC is designed by replacing inductor of conventional boost converter with SI. The main benefit of SI-BC is voltage conversion ratio is augmented by $(1+D)$ times compared to conventional boost converter. The power circuit SI-BBC is designed by replacing inductor of conventional buck-boost converter with SI. The main benefit of SI-BBC is voltage conversion ratio is augmented by two times compared to conventional buck-boost converter. The power circuitry of SI-BC and SI-BBC converter is simple and single switch is required. Large voltage stress across switch is the main drawback of the SI-BC and SI-BBC configurations. In [17], three new power converters (Converter I, II and III) are addressed to overcome the drawback of SI-BC. All the three converters have low voltage stress across switch, high voltage conversion ratio and the minimum numbers of power devices are present in the path of current flow. The power

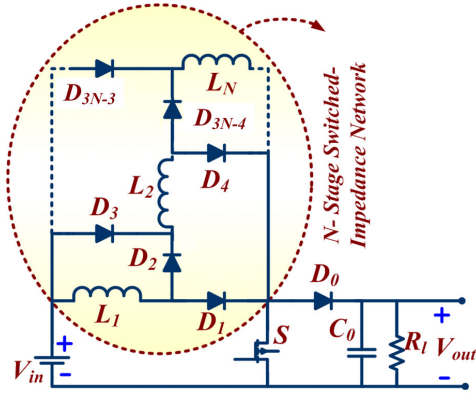


Fig. 3 Power circuit of existing N-stages Switched Inductor Boost Converter (M-SIBC for N stages)

circuit of converter I, II and III is depicted in Fig. 2(c), Fig. 2(d) and Fig. 2(e) respectively. Converter-I is designed with the help of Active Switched Inductor (A-SI) network and filter. Additionally, Converter-II required one capacitor-diode circuitry and Converter-III required two capacitor-diode circuitries. These converters are not suitable for high voltage with high power application and also required two control switch and additional capacitors-diodes circuitry.

XY converter family is another solution to achieve high voltage conversion ratio and to overcome the drawback of voltage multiplier based power converter [18]-[19]. XY converter family consists of sixteen configurations which are designed with the help of Switched Inductor (SI), Voltage Lift Switched Inductor (VLSI) and modified Voltage Lift Switched Inductor (mVLSI). In XY converter, two derived buck-boost converters called X and Y converters are connected in special arrangement. The generalized structure of XY converter family is shown in Fig. 2(f). Discontinuous input current is the main drawback of XY converter family, thus less utilization of input source. In [20], Multistage Switched Inductor Boost Converter (M-SIBC) is proposed for renewable energy application. The M-SIBC power circuit is depicted in Fig.3. To design N-Stage M-SIBC, N number of inductor, $3N-2$ uncontrolled switches, single capacitor and single switch is required. In this work, a key solution is provided to enhance

the voltage conversion ratio of M-SIBC for renewable applications. An improved M-SI network or technique is proposed by replacing central uncontrolled switches of N-stage SI network by polarized capacitor. The mode of operation with mathematical analysis is explained in the following section. Matrix Laboratory R2016a simulation results are provided to validates the performance and functionality of Improved M-SIBC.

II. IMPROVED M-SIBC: POWER CIRCUITRY AND WORKING MODES

An improved M-SI network is proposed to enhance the voltage conversion ratio of boost converter. The power circuit of conventional boost converter Improved Two-stage SIBC is shown in Fig. 4(a). Its noticed that the circuitry of conventional boost converter and improved single-stage SIBC is same and having same performance. Two diodes, two inductor and single capacitor are required to design improved two-stage SI network. In two-stage SIBC, input supply is directly connected to improved two-stage SI network and remaining circuitry is similar to conventional boost converter. In improved two-stage SIBC, two inductor (L_1 and L_2) and single capacitor (C_1) are charged in parallel when control switch S is turned ON and discharge in series with input voltage V_{in} when control switch S is turned OFF. Diode D_1 and D_2 are forward biased and diode D_0 is reversed biased when switch S is turned ON. Diode D_1 and D_2 are reversed biased and diode D_0 is forward biased when switch S is turned OFF. The power circuit of improved three-stage SI network based boost converter (Improved three-stage SIBC) is shown in Fig. 4(b). Four diodes, three inductors and two capacitors are required to design improved three-stage SI network. In three-stage SIBC, input supply is directly connected to improved three-stage SI network and remaining circuitry is similar to conventional boost converter. In improved three-stage SIBC, three inductor (L_1 , L_2 and L_3) and two capacitors (C_1 and C_2) are charged in parallel when control switch S is turned ON and discharge in series with input voltage V_{in} when control switch S is turned OFF. Diode D_1 , D_2 , D_3 and D_4 are forward biased and diode D_0 is reversed biased when switch S is turned ON. Diode D_1 , D_2 , D_3 and D_4 are reversed biased and diode D_0 is forward biased when switch S is turned OFF.

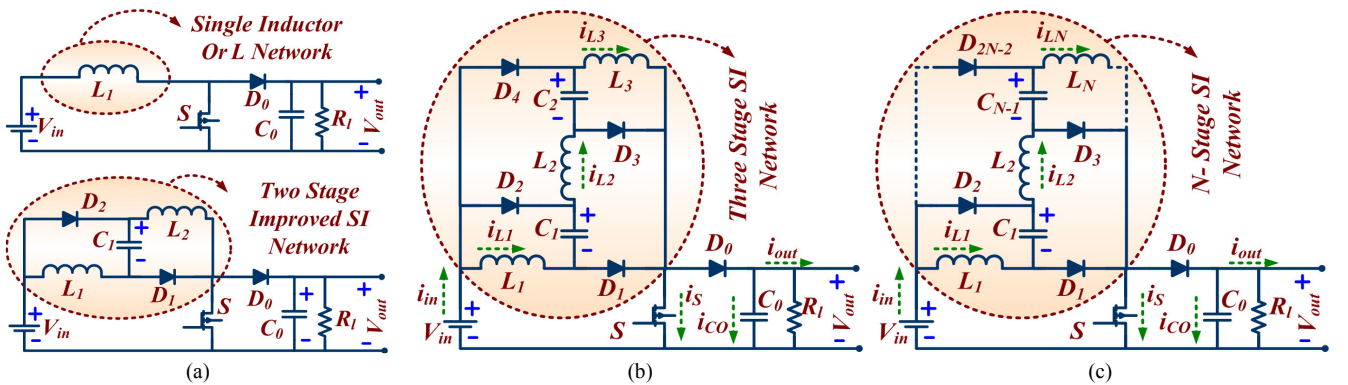


Fig. 4 Power circuit of proposed Improved M-SIBC and its stages
(a) Conventional boost converter (b) Improved Two-stage SIBC (c) Improved Three-stage SIBC (d) Improved N-stage SIBC.

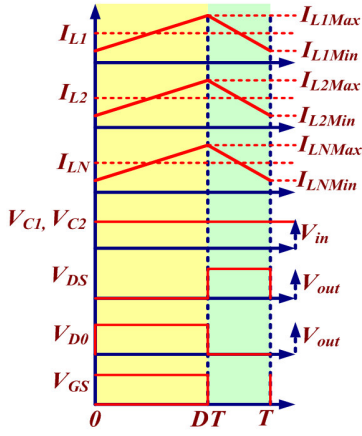


Fig. 5 Characteristics waveform of Improved N-stage SIBC

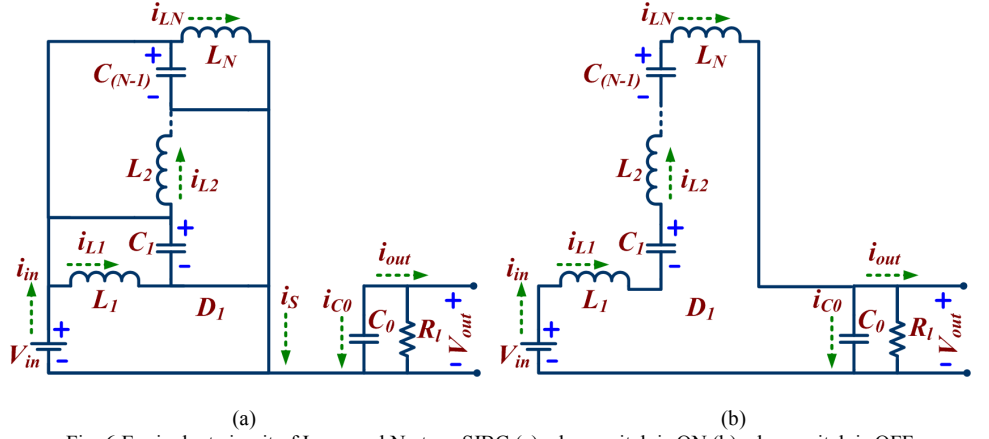


Fig. 6 Equivalent circuit of Improved N-stage SIBC (a) when switch is ON (b) when switch is OFF

The power circuit of improved N-stage SI network based boost converter (Improved N-stage SIBC) is shown in Fig. 4(c). $2(N-1)$ diodes, N inductors and $N-1$ capacitors are required to design improved N-stage SI network. In N-stage SIBC, input supply V_{in} is directly connected to improved three-stage SI network and the remaining circuitry is similar to conventional boost converter. In improved N-stage SIBC, N inductors ($L_1, L_2, L_3, \dots, L_N$) and $N-1$ capacitors (C_1, C_2, \dots, C_{N-1}) are charged in parallel when control switch S is turned ON and discharge in series with input voltage V_{in} when control switch S is turned OFF. Diode $D_1, D_2, D_3, \dots, D_{2(N-1)}$ are forward biased and diode D_0 is reversed biased when switch S is turned ON. Diode $D_1, D_2, D_3, \dots, D_{2(N-1)}$ are in reversed biased and diode D_0 is forward biased when switch S is turned OFF. Fig. 5 depicts the characteristics waveform of Improved N-stage SIBC. ON state and OFF state equivalent circuitry of N-stage SIBC is shown in Fig. 6(a) and Fig. 6(b). Table-I provides the information regarding requirement of components and semiconductor devices to design proposed Improved M-SIBC. For better understanding, the graphical 3-dimensional view of the relation between number of stages (N), capacitors (N_C) and diodes (N_D) is shown in Fig. 7. In the next section voltage gain analysis of proposed Improved M-SIBC converter is discussed in detail.

III. STEADY STATE ANALYSIS OF IMPROVED M-SIBC AND COMPARISON WITH EXISTING POWER CONVERTERS

Following assumption is considered to analyze the steady state characteristic of proposed improved M-SIBC. 1) All the devices having zero ON-state resistance, 2) Internal resistance of inductor is zero, 3) Always maintain a constant voltage across capacitor and 4) All the capacitors are sufficiently charging and discharging.

When switch S is ON,

TABLE I. NUMBER OF DEVICES/ COMPONENTS FOR IMPROVED M-SIBC

Number of				
Stages	Inductors	Capacitors	Switches	Diodes
1	1	1	1	1
2	2	2	1	3
3	3	3	1	5
N	N	N	1	2N-1

$$\left. \begin{aligned} V_L &= V_{L1} = V_{L2} \dots = V_{LN} = V_{in} \\ V_{C1} &= V_{C2} = \dots = V_{CN-1} = V_{in} \\ V_{C0} &= V_{out}, V_{DS} = 0 \end{aligned} \right\} \quad (1)$$

When switch S is OFF,

$$\left. \begin{aligned} V_{in} - V_{L1} + V_{C1} - V_{L2} + V_{C2} \dots - V_{LN} &= V_{out} \\ V_L &= V_{L1} = V_{L2} \dots = V_{LN}, V_{C1} = V_{C2} \dots = V_{CN-1} = V_{in} \\ V_{in} + (N-1)V_{in} - NV_L &= V_{out} \\ V_L &= V_{in} - (V_{out} / N), V_{C0} = V_{out}, V_{DS} = V_{out} \end{aligned} \right\} \quad (2)$$

Using volt second balance method on inductor and following conversion ratio can be obtained where N is number

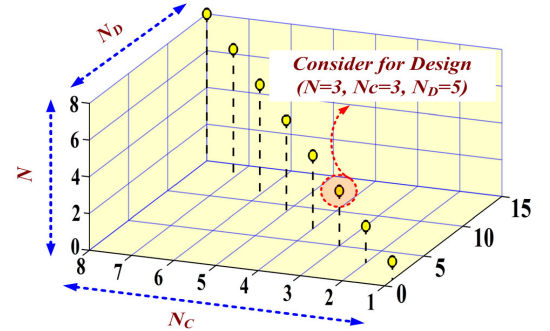


Fig. 7 Graphical view of the relation between number of stages (N), capacitors (N_C) and diodes (N_D)

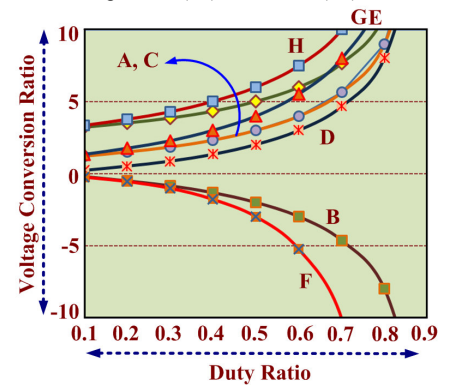


Fig. 8 Comparison of improved M-SIBC with existing converter (A: SI-BC, B: SI-BBC, C: Converter-I, D: Converter-II, E: Converter-III, F: L-L Converter, G: existing M-SIBC, H: Improved M-SIBC)

of stages and D is duty cycle,

$$V_{out} / V_{in} = N / (1 - D) \text{ and } I_{out} / I_{in} = (1 - D) / N \quad (3)$$

Thus, Improved M-SIBC provides N times higher voltage conversion ratio compared to conventional boost converter. In Fig. 8, Improved M-SIBC compared with recently proposed SI based DC-DC converter in terms of voltage conversion ratio and it is observed that proposed converter attain higher voltage conversion ratio at low duty cycle. 3-dimensional view of relations between voltage conversion ratio, duty cycle and number of stages is shown in Fig. 9(a). 3-dimensional view of relations between current conversion ratio, duty cycle and number of stages is shown in Fig. 9(b). For the better understanding, the left and right view of Fig. 9(a) is shown in Fig. 9(c) and 9(d) respectively. From the plot it is observed that voltage conversion ratio is increased with number of stages and duty cycle. Right and left view of Fig. 9(b) is shown in Fig. 9(e) and 9(f) respectively. From the plot it is

observed that current conversion ratio is decreased with the number of stages and duty cycle.

IV. NUMERICAL SIMULATION RESULTS AND DISCUSSION

Matrix Laboratory R2016a Simulink is used to verify the performance and functionality of improved M-SIBC. Improved M-SIBC is simulated for three-stage with 10V input supply, 100W power, 70% T_{on}/T and 100kHz switching frequency. High switching frequency is used to reduce rating of inductor and semiconductor devices. L_1 , L_2 and $L_3 = 100\mu\text{H}$, $C_0 = 5\mu\text{F}$, C_1 and $C_2 = 220\mu\text{F}$ are used to design three-stage proposed improved M-SIBC. Obtained output voltage waveform and its ripple content are shown in Fig. 10(a). It is investigated that nearly 100V with 1V ripple is achieved. Hence, voltage conversion ratio at 70% duty cycle is nearly 10. Obtained output current waveform and its ripple content are shown in Fig. 10(b). It is investigated that nearly 1A with 0.01A ripple is achieved. Obtained drain to source voltage of

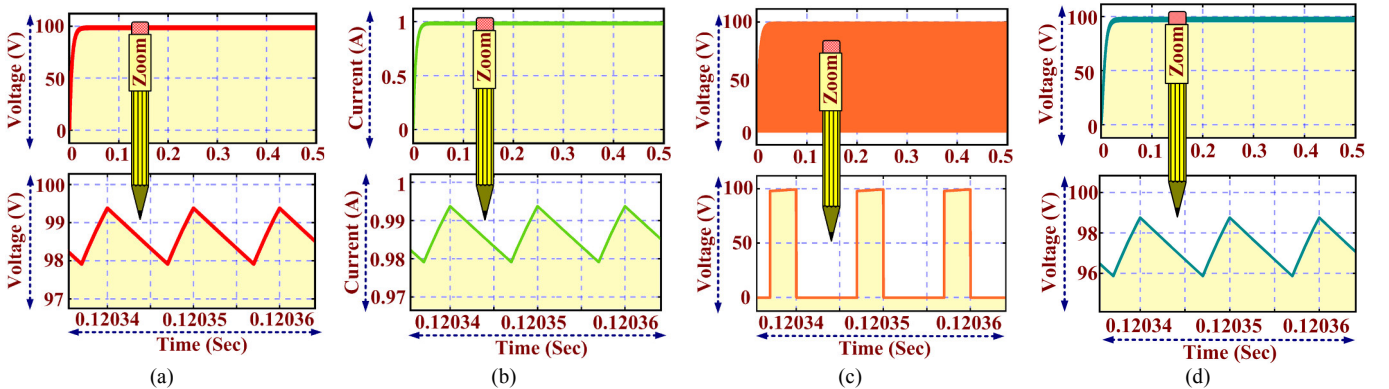


Fig. 10 Simulation Result Improved M-SI based power converter or Improved M-SIBC (a) Output Voltage (b) Output Current (c) Output Current (d) Drain to Source voltage of control switch

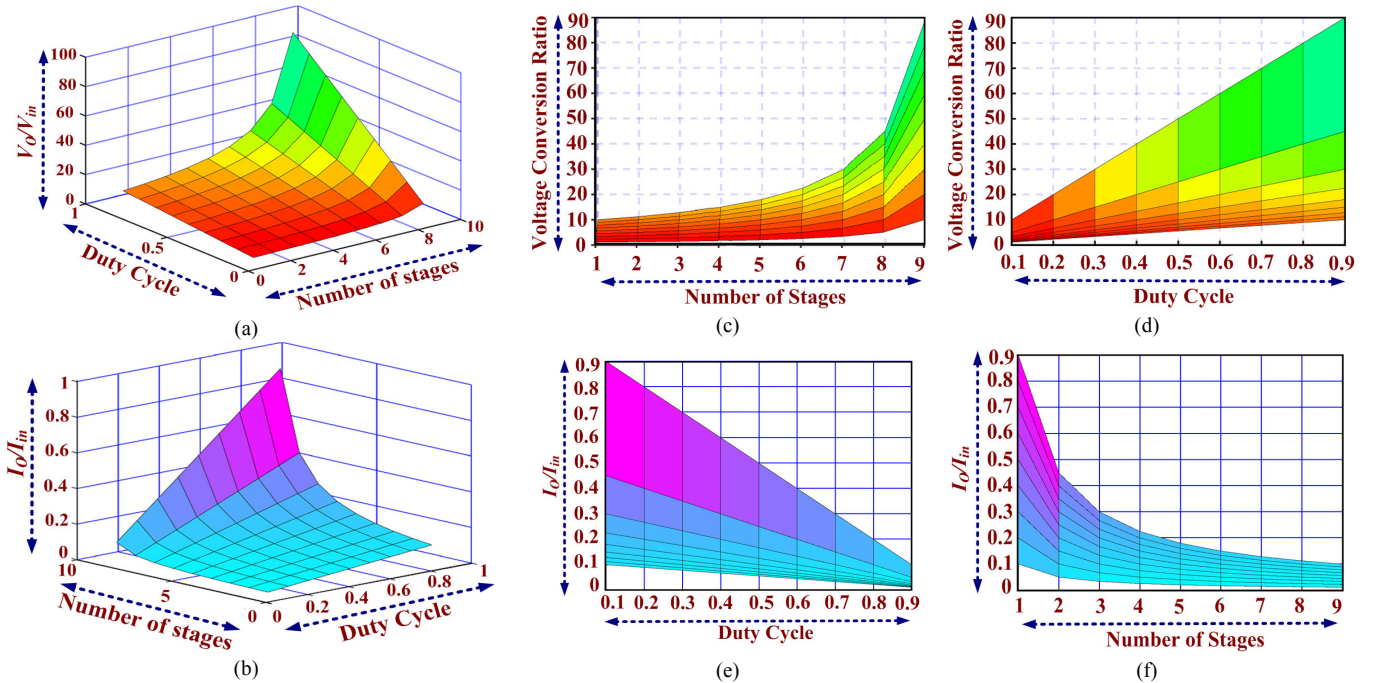


Fig. 9 Plot of Improved M-SIBC (a) Relation between number of stages (N), voltage conversion ratio and duty cycle (b) Relation between number of stages (N), current conversion ratio and duty cycle (c) Left view of Fig. 9(a), (d) Right view of Fig. 9(a), (e) Right view of Fig. 9(b), (f) Left view of Fig. 9(b).

switch S is shown in Fig. 10(c). It is investigated that the voltage across switch in OFF state is 100V and it is equal to output voltage. The obtained power waveform with ripples is shown in Fig. 10(d) and 98W power is observed (2W is drop due to small on-state resistance of diode and switch).

V. CONCLUSIONS

An Improved Multistage Switched Inductor Boost Converter (Improved M-SIBC) is proposed for Renewable energy applications. A key is provided to improve the voltage conversion ratio of existing M-SIBC. The striking feature of Improved M-SIBC are 1) Required single switch and single gate driver, 2) High voltage conversion ratio without using high T_{on}/T , 3) Configuration is derived from conventional boost converter and 4) Easy to increase number of stages without disturbing the output end of the converter. The converter operation modes are simple and converter circuitry is easy in control due to only single switch. Simulation results are provided which validates the proposed concept and converter functionality. The experimental setup is under investigation at Aalborg University, Denmark.

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