An Extended High Step-Up Multi-Input DC-DC Converter

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Abstract

In this paper, an extended structure of a high step-up non-isolated multi-input DC-DC converter (MIC) is presented. The proposed structure, benefits from the both advantages of diode-capacitor and DC-DC boost converters. The main advantages of the suggested topology are possibility of throw continuous current from the input sources with various voltage-current characteristics, high voltage gain can be achieve without high duty cycle, low-voltage stress of power switches, and possibility of switching at high frequencies. Thus the topology is suitable for renewable sources applications like solar farms. In order to evaluate the performance of the proposed converter, simulation results by PSCAD/EMTDC software are presented.

1. Introduction

By increasing the generation of renewable energy sources like photovoltaic (PV) and energy storage, the application of high voltage gain DC-DC converters are increased in clean energy systems. These converters can be used to connect low voltage sources like photovoltaic panels, fuel cells (FC), batteries, etc. to high voltage DC micro-grid system [1-3]. Solar energy, is the main in renewable energy resources. With reduction of photovoltaic panel costs, utilization of PV has spread to feed the grid connected and stand-alone systems. PVs are small energy resources, which can be located near the load points, therefore this feature reduces the costs and losses of transmission. To improve the performance of the system, it is necessary to select an appropriate method for tracking the maximum power point (MPPT). Traditionally, for providing the required power and voltage, the PV modules are connected in parallel and series. Therefore, in this case the MPPT is not possible for each PV module, thus the reliability of the system is reduced. A multi-input converter can be useful in such situations, as a power electronic device to perform the MPPT methods for individual PV modules independently [4].

In past years, the different structures of MICs have been presented for renewable energy applications. In [5], a MIC has been presented for hybridizing different energy resources with capability of bidirectional power flow. The converter, can act as a buck, buck-boost, boost converter, and generating the various output voltage levels without transformer. Although this converter uses a small number of elements, but at any moment, only one input source can deliver its power to the circuit. This issue causes restrictions on transitional power and wide current ripple at the inputs. In [6-9], MICs have been presented to hybridize the PV, FC , and battery. The converters are consist of unidirectional ports for getting power from the PV and FC sources and bi-directional port for charging and discharging the batteries. The proposed converters due to the ability of power management, input current ripple control, integrated control system, and high reliability are suitable for renewable energy applications. In [6], although the battery port is bi-directional but, the battery charge is possible only by FC source and the battery discharge is possible only by PV source. The High number of components, low voltage gain, and the high cost of construction are disadvantages of these converters. In [4, 10], two multi-input DC-DC converters with high voltage gain has been presented. In both converters, the number of inductors, capacitors, diodes, and power switches are equal to the number of inputs. To obtain a high voltage gain, a new group of high voltage gain power electronic DC-DC converters by using the Cockcroft-Walton (CW) voltage multipliers (VM), have been presented in [11, 12]. The advantages and disadvantages of them are mentioned in section 5.

In this paper, an extended structure for high voltage gain multi-input DC-DC converter based on [13] with capability of drawing power from independent input power resources with continuous input current, is proposed. To verify the performance of the proposed converter, simulation results by PSCAD/EMTDC software are presented.

2. Proposed Converter and Operation Modes

The power circuit of the proposed high voltage gain multi-input DC-DC converter is shown in Fig. 1. In this figure, L_j is the inductor of j^{th} input boost cell, V_{in-j} is the voltage of j^{th} input voltage source, S_j is the power switch of j^{th} input boost cell, $D_{i,j}$ is the diode of i^{th} diode-capacitor stage which is forward biased by j^{th} input boost cell, $C_{i,j}$ is the capacitor of i^{th} diode-capacitor stage which is charged by j^{th} input boost cell, R is the output load resistance, and V_{out} is the output voltage the proposed converter. The diode-capacitor stages help the input boost stages to obtain high voltage gain. The voltage gain of the proposed converter depends on the number of the diode-capacitor stages and duty cycle of Power switches.

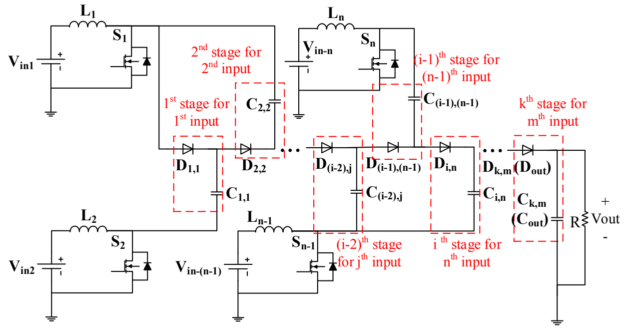

Fig. 1. Power circuit of the proposed MIC DC-DC converter.

For ease of understanding the operation of the converter, a sample of the proposed converter with five diode-capacitor stages and three input boost cells has been selected to explain. Fig. 2 shows the proposed converter structure with five Diode-capacitor stages (one stage for the first input cell, two stages for the second input cell, and other two stages for the third input cell).

For normal operation of the converter, there should be some overlapping time between ON state of the power switches. As shown in Fig. 3, the switching signals of the input cell switches which are charging the even-numbered capacitors are interleaved with 180° phase shift with the switching signals of the input cell switches, which are charging the odd-numbered capacitors. Thus according to the Fig. 2, since first and third inputs are charging the odd numbered capacitors, their switches have the same switching signal phase and also just the second input is charging the even numbered capacitors, the second input switching signal is applied with 180° phase shift. For displaying the operating modes of the proposed converter, the duty cycles of the switches are considered equal. Fig. 4 shows the operating modes of the proposed converter. The proposed converter can operate in low duty cycles and there is no overlap time through the ON states of the switches. This operating mode, because of the low voltage gain, is not so attractive to be done.

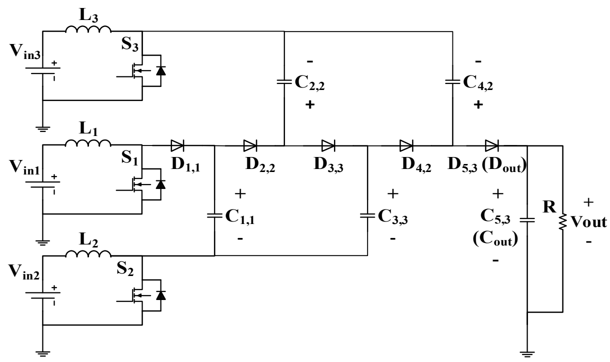

Fig. 2. The proposed converter with three input cells and five diode-capacitor stages.

Mode 1: In this mode, all the power switches S_1, S_2, and S_3 are in ON state (shown in Fig. 4a). The three inductors L_1, L_2, and L_3 are charged with their input voltages and their currents are rise linearly. All the diodes are biased reversely and also they are not conducting; therefore, the voltage of all the capacitors except the output capacitor remain constant. The output load is supplied by the output capacitor $C_{5,3}$.

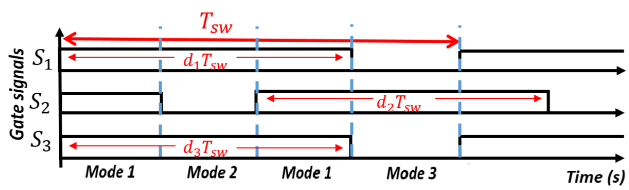

Fig. 3. Switching signals of the proposed three-input converter.

Mode 2: In this mode, the first and third switches (S_1 and S_3) are ON and the second switch S_2 is OFF (shown in Fig. 4b). All the even numbered diodes $(D_{2,2}, D_{4,2}, \ldots)$ are forward biased and the odd numbered diodes $(D_{1,1}, D_{3,3}, D_{5,3}, \ldots)$ are reverse biased. Current of the second inductor L_2 is charging the even numbered capacitors $(C_{2,2}, C_{4,2}, \ldots)$ and discharging the odd numbered capacitors $(C_{1,1}, C_{3,3}, C_{5,3}, \ldots)$. Since here the number of diode-capacitor stages is odd, the output capacitor $C_{5,3}$ supplies the load.

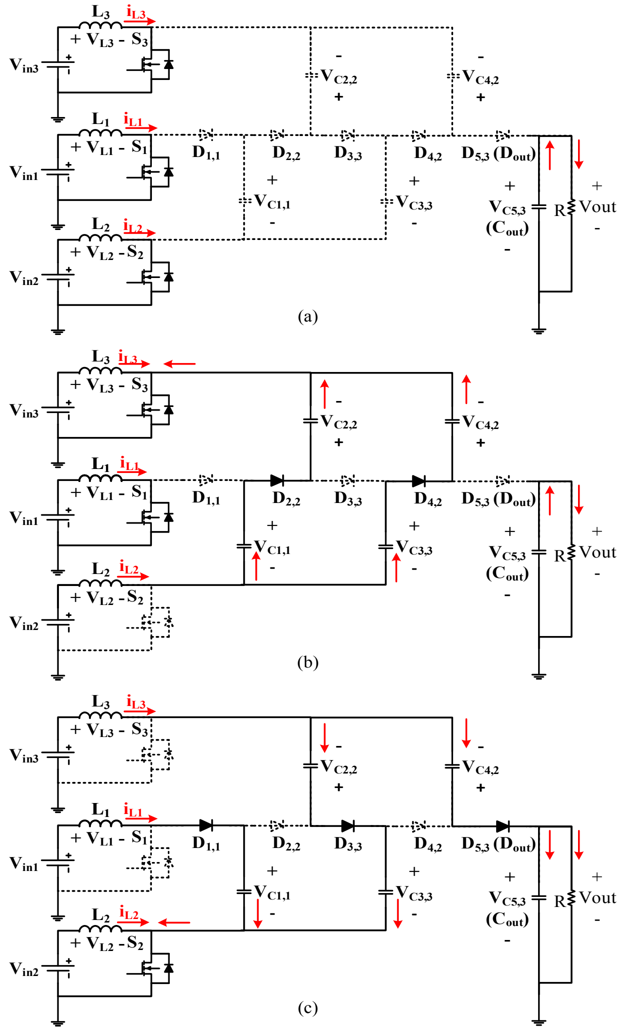

Fig. 4. Operating modes of the proposed converter. a) *Mode 1*, b) *Mode 2*, c) *Mode 3*.

Mode 3: In this mode, the first and third switches (S_1 and S_3) are OFF and the second switch S_2 is ON (shown in Fig. 4c). All the even numbered diodes $(D_{2,2}, D_{4,2}, \ldots)$ are reverse biased and the odd numbered diodes $(D_{1,1}, D_{3,3}, D_{5,3}, \ldots)$ are forward biased. Current of the first and the third inductors (L_1 and L_3) are charging the odd numbered capacitors $(C_{1,1}, C_{3,3}, C_{5,3}, \ldots)$ and discharging the even numbered capacitors $(C_{2,2}, C_{4,2}, \ldots)$. Also, in this operation mode, because of odd number of diode-capacitor stages, the last input inductor L_3 supplies the load and output capacitor.

3. Voltage Gain of the Converter

Gradually, by charging and discharging the capacitors, the power is transferred through the inputs to the output. Applying the voltage-second balance requirement on input inductors $(L_1,$

L_2, and L_3), voltage of the capacitors can be calculated as follows

$$\begin{aligned} V_{C1,1} &= \frac{1}{1-d_1}V_{in1} \\ V_{C2,2} &= \frac{1}{1-d_1}V_{in1} + \frac{1}{1-d_2}V_{in2} \\ V_{C3,3} &= \frac{1}{1-d_1}V_{in1} + \frac{1}{1-d_2}V_{in2} + \frac{1}{1-d_3}V_{in3} \\ V_{C4,2} &= \frac{1}{1-d_1}V_{in1} + \frac{2}{1-d_2}V_{in2} + \frac{1}{1-d_3}V_{in3} \end{aligned} \quad (1)$$

$$V_{out} = V_{C5,3} = \frac{1}{1-d_1}V_{in1} + \frac{2}{1-d_2}V_{in2} + \frac{2}{1-d_3}V_{in3} \quad (2)$$

The above calculations can be expanded to a converter with M number of diode-capacitor stages for first input cell, N number of diode-capacitor stages for second input cell, P number of diode-capacitor stages for third input cell, and etc. thus the output voltage can be expressed as

$$V_{out} = \frac{M}{1-d_1}V_{in1} + \frac{N}{1-d_2}V_{in2} + \frac{P}{1-d_3}V_{in3} + \dots \quad (3)$$

4. Component Design

4.1. Inductor Design

Current of the each boost cell inductor depends on the number of the corresponding diode-capacitor stages. The average current of the inductors can be expressed as

$$\begin{cases} i_{L1,avg} = \frac{M}{1-d_1}I_{out} \\ i_{L2,avg} = \frac{N}{1-d_2}I_{out} \\ i_{L3,avg} = \frac{P}{1-d_3}I_{out} \\ \dots \end{cases} \quad (4)$$

Where I_{out} is the avrage output current.

Design of the boost cell inductors are similar to the conventional boost converter. The inductors are designed to the operation of the converter in continuous conduction mode (CCM). The minimum value of the inductors for CCM operation of the converter can be calculated as follows

$$\begin{cases} L_{1,min} = \frac{(1-d_1)d_1\ V_{in1}}{2MI_{out}\ f_{sw}} \\ L_{2,min} = \frac{(1-d_2)d_2\ V_{in2}}{2NI_{out}\ f_{sw}} \\ L_{3,min} = \frac{(1-d_3)d_3\ V_{in3}}{2PI_{out}\ f_{sw}} \\ \dots \end{cases} \quad (5)$$

In (5), f_{sw} is the switching frequency of the converter.

The maximum value of the inductor currents is calculated as

$$\begin{cases} I_{L1,peak} = \frac{M}{(1-d_1)}I_{out} + \frac{d_1}{2L_1 f_{sw}}V_{in1} \\ I_{L2,peak} = \frac{N}{(1-d_2)}I_{out} + \frac{d_2}{2L_2 f_{sw}}V_{in2} \\ I_{L3,peak} = \frac{P}{(1-d_3)}I_{out} + \frac{d_3}{2L_3 f_{sw}}V_{in3} \\ \dots \end{cases} \quad (6)$$

4.2. Switch Design

Voltage and current stress calculation for all the Power switches is essential to select appropriate switches. The maximum blocking voltage of all the power switches is similar to the conventional boost converter which is expressed as

$$V_{stress\text{-}Si} = \frac{1}{1-d_i}V_{in_i} \quad , i=\{1, 2, 3, \dots\} \quad (7)$$

The current stresses of all the power switches depend on the number of corresponding diode-capacitor stages. The average current of the power switches can be expressed as

$$\begin{cases} I_{s1,avg} = \frac{(M-1)+d_1}{(1-d_1)}I_{out} \\ I_{s2,avg} = \frac{N}{(1-d_2)}I_{out} \\ I_{s3,avg} = \frac{P}{(1-d_3)}I_{out} \\ \dots \end{cases} \quad (8)$$

According to (8), the average current of the first power switch is lower than the average of the first input current and the average current of the other power switches is equal to the average of corresponding input current.

4.3. Diode Design

The voltage stresses of the diodes depend on the voltages of those two capacitors which the diode is connected between them. If $D_{i,j}$ and $D_{(i+1),K}$ are the two consecutive diodes, the voltage stress of all the stage diodes can be expressed as

$$V_{D_{i,j}} = \frac{1}{1-d_j}V_{inj} + \frac{1}{1-d_k}V_{ink} \quad (9)$$

Thus the Voltage stress of the output diode can be expressed as

$$V_{D_{i,j}} = \frac{1}{1-d_j}V_{inj} \quad (10)$$

In (9) and (10), V_{inj} and V_{ink} are the voltages of the j^{th} and k^{th} inputs respectively and, d_j and d_k are the duty cycles of the j^{th} and k^{th} power switches respectively.

As previously mentioned, the even numbered diodes conduct during operation mode 2 and the odd numbered diodes conduct during operation mode 3. The average currents of all the diodes are equal together which can be expressed as

$$I_{D_{1,1,avg}} = I_{D_{2,2,avg}} = \ldots = I_{D_{5,3,avg}} = \ldots = I_{out} \quad (11)$$

5. Comparison Results

The proposed converter aims to throw continuous current from the renewable input sources with various voltage-current characteristics and transfer the power to the output load with high reliability and voltage gain.

The advantages of the presented converter in [10] are high voltage gain, MPPT capability, low voltage stress of power switches and diodes, and high reliability. But for the *N* number of inputs, the driving signals of the power switches are interleaved with *360°/N* phase shift and the duty cycles of the power switches must be larger than *(1-1/N)*; therefore, increasing the number of inputs, decreases the power control at the inputs. The advantages of the presented converter in [4] are high voltage gain, MPPT capability and high reliability with extra diode. The voltage stress of the last power switch, and output diode is higher than the output voltage and increasing the number of inputs causes increase the voltage gain of the converter and the voltage stress of the last power switch and output diode. The converters are presented in [11, 13] has the advantages of high voltage gain, MPPT capability, low voltage stress of power switches and diodes, and increasing the voltage gain by increasing the number of voltage multiplier stages. The maximum number of inputs are only two and in [11] by increasing the voltage multiplier stages, the output impedance increases rapidly and this is the limitation of the converters based on CW voltage multipliers; therefore, in high voltage gains, the output voltage regulation and the efficiency of these converters. Because of being dependent on the output impedance would be affected. The proposed converter has all the advantages of the presented converters in [4, 10, 11, 13] such as high voltage gain, minimum voltage stress of power switches and diodes, high reliability, MPPT capability for all the inputs, and increasing the voltage gain by increasing the number of voltage multiplier stages, without the mentioned disadvantages.

Table 1. Simulation parameters of the proposed converter.

Parameter	value
Input Voltages	32 V
Inductors	100 μH, 1.5 mΩ
Duty Cycles of the Switches	0.6
Power Switches	$R_{DS(ON)}$=7.5 mΩ, V_{fw}=1.5 V
Diodes	V_D=0.97 V, 2.5 mΩ
Capacitors	20 μF, 2. 5 mΩ
Switching Frequency (f_{sw})	80kHz
Output Power	500W

5. Simulation Results

In this section, to verify the correctness of the proposed converter operation, the three-input of the converter with five diode-capacitor stages as it shown in fig. 2 is simulated in PSCAD/EMTDC software and the simulation results are presented. The simulation parameters of the converter are given in table 1.

Fig. 5 shows the output voltage of the converter from simulation results. The output voltage is obtained 400V from (2) or (3), but because of the conduction and switching losses the output voltage of the simulated converter is obtained 377.58V.

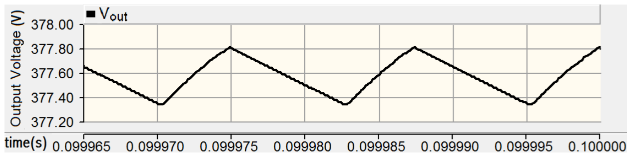

Fig. 5. Output voltage of the proposed converter.

Wave forms of the inductor current at 500W output power is shown in Fig. 6. The average inductor currents at 500W output power are calculated 3.125A for I_{L1} and 6.25A for I_{L2} and I_{L3} from (4). As shown in the figure, the average current values of the inductors are obtained 3.3A for I_{L1} and 6.6A for I_{L2} and I_{L3} from the simulation results.

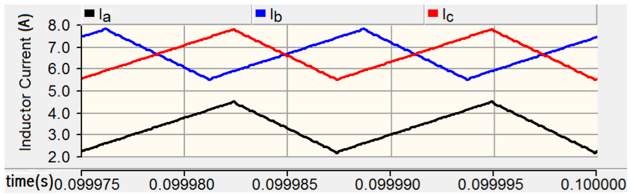

Fig. 6. Wave forms of inductor current at 500W output power.

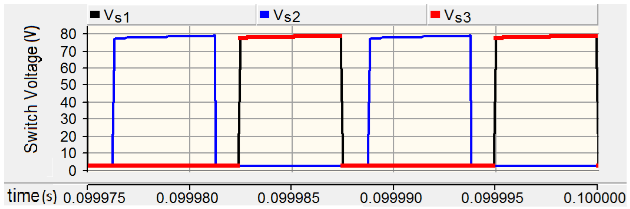

Fig. 7. Boost power switch voltages.

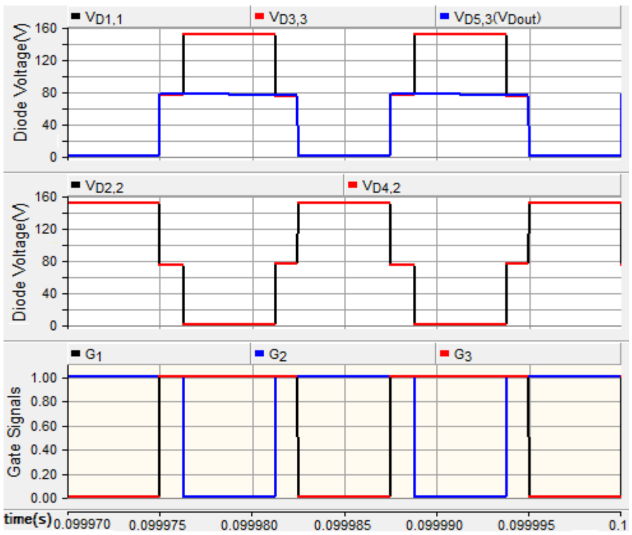

Fig. 8. Gate signals and diode voltages.

The maximum blocking voltage of the power switches is shown in Fig. 7, which is calculated from (7). The peak blocking voltage of the switches is obtained lower than 80V from the simulation results. Fig. 8 shows the gate signals of the power switches and voltage stress of the diodes. The maximum blocking voltage of the diodes except the output diode is obtained lower than 160V from the simulation results, which can be calculated from (9), and the voltage stress of the output diode is obtained 76.7V from the simulation results, which is calculated 80V from (10).

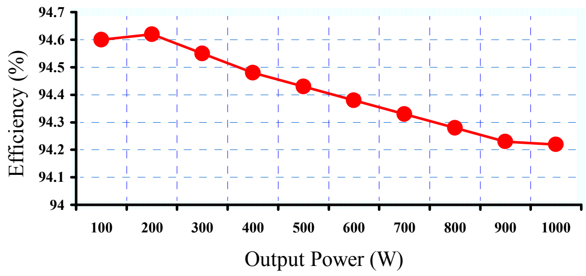

Fig. 9. Efficiency of the proposed converter from simulation results at various output powers.

Fig. 9 shows the simulated converter efficiency at different output powers. The converter efficiency at 500W output power is 94.43% and the maximum efficiency of 94.62% is obtained at 200W output power. Thus the simulation results validate the proposed converter operation.

6. Conclusions

In this paper, an extended high step-up multi-input DC-DC converter has been proposed, which the operation is explained with three input and five diode-capacitor stages. The proposed converter is based on diode-capacitor stages, which are rise the voltage gain of the converter. The main advantage of the proposed structure is the flexibility to be used independent input sources with various voltage-current characteristics while the input current of each boost cell can be controlled by the duty cycle of its power switch independently with continuous input currents. Rising the number of input stages and diode-capacitor stages, increases the voltage gain of the converter and decreases the voltage stress of the power switches and diodes. The voltage stress of the power switches is less than that of the conventional boost converter; therefore, low-voltage power switches can be chosen to achieve high efficiency. Since there is no limit to increase the number of input stages and diode capacitor stages, there is no need to connect the PV modules in parallel and series for providing the required power and voltage, respectively. Thus the proposed converter can act as a high step-up multi-input converter for renewable energy applications such as solar farms.

7. References

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