Simulation of Closed Loop Control of High Voltage Gain Converter Based on Modified Dickson Charge Pump Voltage Multiplier

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Abstract—DC distribution systems have gained popularity recently as they offer better efficiency, higher reliability and low cost as compared to ac distribution systems.They help in easier integration of renewable energy and its storage systems. But the main challenge faced by such dc distribution systems is the use of power electronic converters for integrating renewable sources into the dc bus. So a high-voltage-gain dc-dc converter is introduced in this paper. The converter consists of a two-phase interleaved boost converter on its input side and a Dickson charge pump based voltage multiplier on its output side so that it provides an output voltage of 400 V for an input voltage as low as 20V.The voltage multiplier circuit associated with the converter offers low voltage across the capacitors which potentially leads to reduction in size. The converter can be fed to a three phase induction motor so that analysis can be done efficiently and its simulation results are obtained using MATLAB/ Simulink.

Index Terms— Voltage multiplier; modified Dickson charge pump;interleaved boost converter.

I. INTRODUCTION

High step-up dc–dc converters are those converters which can boost a low voltage in the range of 20V to a relatively high voltage. We all know that the output voltage of fuel cell stacks, PV module, battery sources etc is comparatively low, it is required to be boosted to a high voltage to feed the ac grid and other applications like UPS, energy vehicles, feeding induction motors etc. Though PV cells can be made into an array and can connected in series to produce high voltage there exist some serious problems such as shadowing effects, short circuit etc which drastically reduces its efficiency. In order to overcome such adverse effects, a high step up converter is required. Thus high step up dc-dc converters are used as front end converters to step up from voltage as low as 20V to high voltage.

When the output voltage is high, it becomes necessary to reduce the voltage stress on the active switches and

diodes; otherwise, it will cause high conduction loss and becomes more expensive. Due to the presence of parasitic parameters such as the equivalent series resistance of inductor, conventional boost converters cannot provide a high

voltage gain and thus results in high duty ratio. However this extreme duty ratio can cause serious reverse recovery problems and electromagnetic interferences. The extremely narrow turn-off time will result in large peak current and considerable conduction and switching losses. A typical choice would be using two cascaded converters; but it results in inefficient operation, reduced reliability, increased size, and can even result in stability issues .Another option is the use of isolated topologies like, half-bridge, full-bridge, fly back, forward and push-pull converters; but it has a disadvantage that it will produce discontinuous input currents and hence would require bulky input capacitors.

Lots of research work has been done to provide a high step-up voltage without an extremely high duty ratio. The isolated converters can boost the voltage ratio by using high frequency transformer by increasing the turns ratio. However, the leakage inductor must be handled carefully; otherwise, it will cause large voltage spike across the power switches or diodes.

Converters without transformers can be used as high step up dc-dc converters as they can achieve high efficiency. These converters can be divided into coupled and non-coupled inductor type. A number of coupled inductor-based high step-up converters have been developed. By increasing the turns ratio of the coupled inductor similar to that in isolated converters, high voltage can be achieved.However the leakage inductance of the coupled inductor is inevitable. Like in isolated converters, it may cause voltage spike which increases the voltage stress across main switches. The non coupled inductor type converters can achieve high voltage gain with minimum number of magnetic components. Moreover the switch voltage and current stress are very high.

Various switched-inductor and switched-capacitor structures can be used to extend the voltage gain. With the transition in series and parallel connection of the switched inductor, a high voltage gain can be achieved. The switched-inductor-based boost converter has limited voltage gain and the voltage stress of active switches and diodes is also very high.So they would require clamping circuitry to reduce the voltage stress on the switches. These clamping circuits have a negative impact on the voltage gain of the converter.

II. DICKSON CHARGE PUMP VOLTAGE MULTIPLIER

The Dickson charge pump voltage multiplier circuit offers a boosted dc output voltage by charging and discharging its capacitors. The input voltage is a modified square wave voltage. The voltages of the capacitors in the Dickson charge pump gets doubled at each stage as one traverses from the input side capacitor C_1 to the load side capacitor C_4. For an output voltage of $V_{out} = 400V$, the voltages of capacitors C_1, C_2, C_3 and C_4 are 80V, 160V, 240V, and 320V respectively. The voltage rating of each voltage multiplier cell capacitor is twice that of its previous cell. Also, the switches (S_1, S_2) and inductors (L_1, L_2) experience different current stresses when even number of VM cells are used.
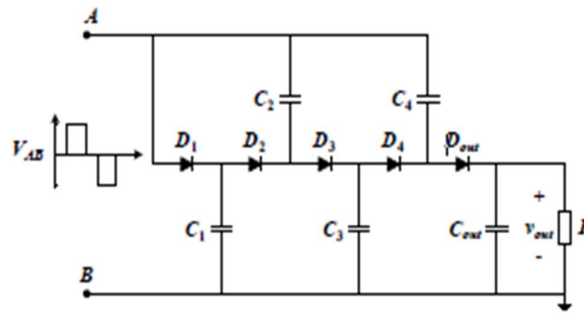

Fig.1. Conventional Dickson charge pump

For a same output voltage, the voltages across all the capacitors in the modified Dickson charge pump are smaller than the voltage of capacitor C_2 in the Dickson charge pump. For an output voltage of 400V, the voltages of capacitors C_1, C_2, C_3 and C_4 are only 150V, 50V, 50V, and 150V, respectively. Therefore the volume of the capacitors used in the modified Dickson charge pump circuit is potentially less compared to the conventional one.
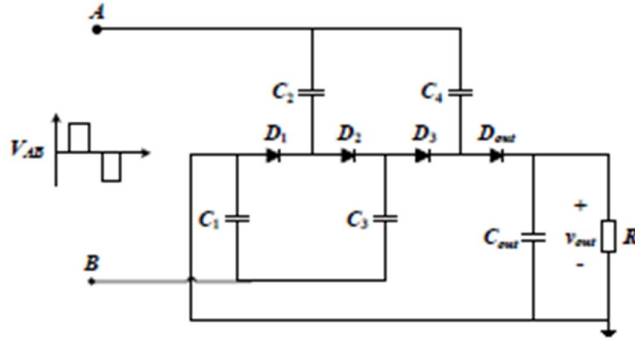
Fig.2. Modified Dickson charge pump

III. CONVERTER STRUCTURE AND WORKING

The converter provides a high voltage gain due to the modified Dickson charge pump voltage multiplier circuit. The converter is made up of two stages. The first stage is a two-phase boost converter which outputs a modified square wave voltage between its output terminals *A* and *B*. The second stage is the modified Dickson charge pump voltage multiplier circuit that boosts the square wave voltage (*VAB*) to provide a higher dc output voltage. For the converter to operate normally, both switches S_1 and S_2 must have an overlap time where both switches are ON and also one of the switches must be ON at any point of time. The switches must be triggered in such a way that they have duty ratios greater than 50% and they operate at 180 degrees out of phase with each other.
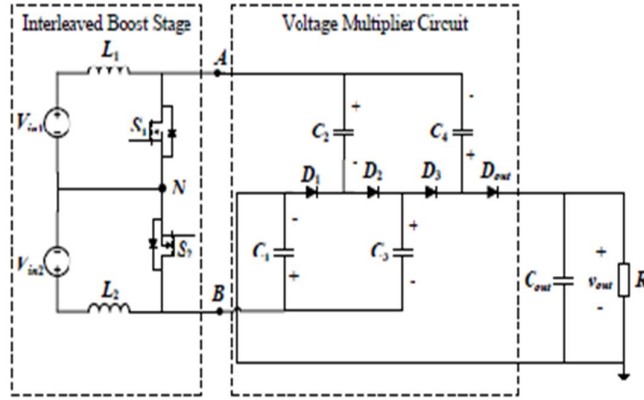

Fig.3. Converter with two independent sources

This converter is capable of stepping up low voltages in the range of 20V to 400V. The converter offers continuous input current and low voltage stress; approximately 1/4th of its output voltage on its switches. This converter can draw power from a single source or two independent sources. In both cases, it draws continuous input current and thus it becomes suitable for applications like solar panels. The converter requires low voltage rating capacitors for its VM circuit and also one less diode. Thus the size of the entire circuit can be reduced. The inductors and switches experience identical current stresses so that component selection process for the converter can be done easily simpler.

The converter operation can be explained in three modes.

A. Mode I

In this mode, both switches S_1 and S_2 of the two-phase interleaved boost converter are ON. Input sources V_{in1} and V_{in2} charge inductors L_1 and L_2 respectively. Inductor currents iL_1 and iL2 increase linearly. All the diodes of the voltage multiplier circuit are reverse-biased and hence are in OFF state. The voltages of the charge pump capacitors remain same and the output diode D_{out} is reverse biased. The load is supplied by the output capacitor.
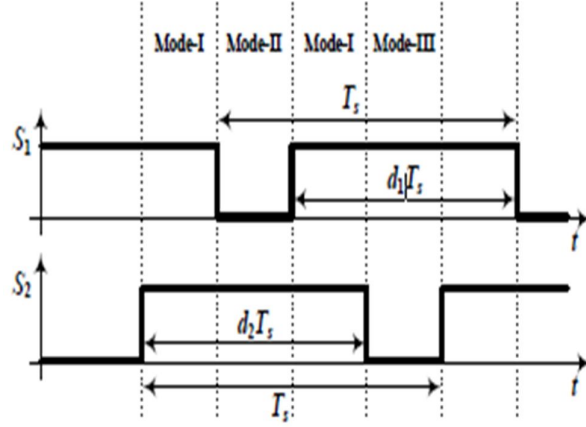
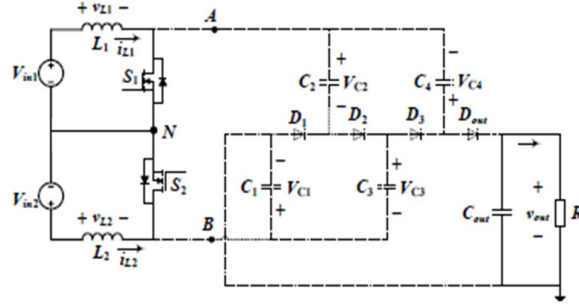Fig.4. Input boost converter switching signals for converter

Fig.5. Converter operation in Mode I

B. Mode II

In this mode, switch S_1 is OFF and switch S_2 is ON. Diodes D_1 and D_3 are reverse biased and are in OFF state while diodes D_2 and D_{out} are ON as they are forward biased. A part of inductor current iL1 flows through capacitors C_2 and C_3 and thus charges them. The remaining current flows through the capacitors C_4 and C_1 discharging them to charge the output capacitor and supply the load.
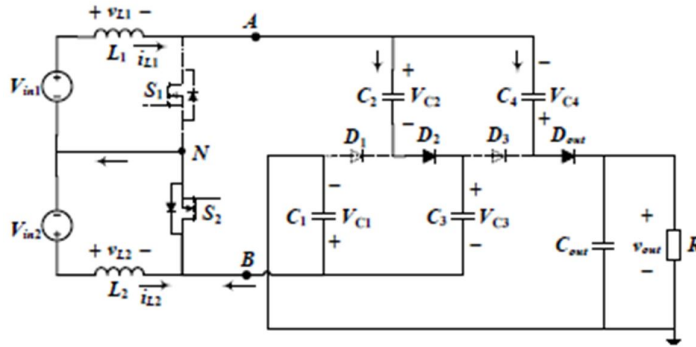

Fig.6. Converter operation in Mode II

C. Mode III

In this mode switch S_1 is ON and switch S_2 is OFF. Diodes D_1 and D_3 are ON and are forward biased while diodes D_2 and D_{out} are OFF and are reverse biased. Inductor current iL_2 flows through diode-capacitor voltage multiplier cell capacitors C_1, C_2, C_3, and C_4. Capacitors C_1 and C_4 are charged while discharging capacitors C_2 and C_3. In this mode, the output capacitor supplies the load.
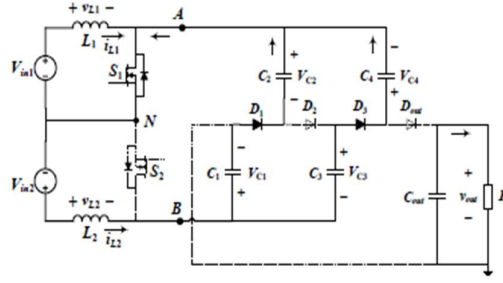
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Fig.7Converter operation in Mode III

IV. DESIGN OF CONVERTER

The input power is transferred to the output by charging and discharging the VM circuit capacitors.
Based on the volt-second balance of inductor L_1, we can write

$$V_{AN} = V_{C2} + V_{C3} = \frac{V_{in1}}{(1-d_1)} \qquad (1)$$

$$= \frac{20}{(1-0.8)} = 100V$$

where d_1 is the duty cycle of switch S_1. Based on the volt-second balance of the inductor L_2, we can write

$$V_{BN} = V_{C1} - V_{C2} = \frac{V_{in2}}{(1-d_2)} \qquad (2)$$

$$= \frac{20}{(1-0.8)} = 100V$$

Assuming capacitors C_2 and C_3 are identical, the voltage across them would be equal and can be written as

$$V_{C2} = V_{C3} = \frac{1}{2} * \frac{V_{in1}}{(1-d_2)} \qquad (3)$$

$$= \frac{1}{2} * \frac{20}{0.2} = 50V$$

$$V_{C1} = V_{C4} = \frac{1}{2} * \frac{V_{in1}}{(1-d_1)} + \frac{V_{in2}}{(1-d_2)} \qquad (4)$$

$$= \frac{1}{2} * \frac{20}{0.2} + \frac{20}{0.2} = 150V$$

The output equation is derived by

$$V_{out} = \frac{2*V_{in1}}{(1-d_1)} * \frac{2*V_{in2}}{(1-d_2)} \qquad (5)$$

$$= \frac{2*20}{0.2} * \frac{2*20}{0.2} = 400V$$

The high voltage gain converter can be supplied either from two input sources or from an input source. When a single input is used for the proposed converter, switches S_1 and S_2 have the same switching duty cycle d

and they are 180 degrees out of phase from each other. The output voltage when single input is used is given as

$$V_{out} = \frac{4 * V_{in}}{(1 - d)} \qquad (6)$$

$$= \frac{4 * 20}{(1 - 0.8)} = 400V$$

A 20V input source at 80% duty cycle will generate an output voltage of 400V using the converter. Capacitors C_1 and C_4 are charged to 150V and capacitors C_2 and C_3 are charged to 50V. The inductor currents in both phases of the interleaved boost stages are similar. The inductance required for a current ripple of Δi_L is given by

$$L_1 = L_2 = L = \frac{V_{in} * d}{\Delta I_L * f_{sw}} \qquad (8)$$

$$\frac{20 * 0.8}{1.6 * 100000} = 100 \mu H$$

Both of the inductors carry same amount of current and require same inductance for an assumed ripple current. Moreover as the rms currents of inductors L_1 and L_2 are equal, minimal conduction losses will takes place in the inductors as compared to other similar converters having different values of currents flowing through their boost stage inductors.

At 200W output power, both inductors carry a current of 5A with a ripple current of 1.6A in each. The input source is connected to an interleaved boost stage so that the input current is continuous. As the two phases of it are 180 degrees out of phase from each other, the input current ripple is even smaller. This greatly reduces the size of the input filter capacitor required for the converter.

V. SIMULATION OF HIGH GAIN CONVERTER

Simulation of the converter is done using MATLAB software. Simulation of the open loop system is done with one input source. The power rating of the converter is 200W with an input voltage of 20V and an output voltage of 400V. The proposed converter operates at a switching frequency of 100 KHz. For the proposed converter to operate normally, both switches S_1 and S_2 should have an overlap time where both are ON and also one of the switches must be ON at any point of time. This can be obtained by operating switches at duty ratios greater than 50% and having them operate at 180 degrees out of phase from each other.

TABLE.I. SIMULATION PARAMETERS

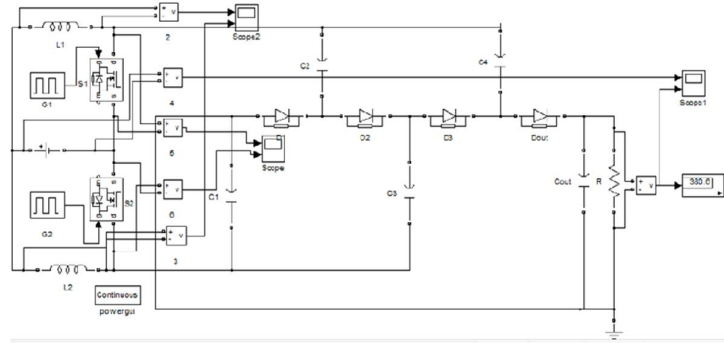| Parameter	Value
Input voltage	20V
Output voltage	400V
Load Resistance	800Ω
Switching Frequency	100KHz
Inductors L1 and L2	100μH
VM capacitors	60μF
Output capacitor	22μF

Fig.8. Simulation circuit of open loop system

For an input voltage of 20V, an output voltage approximately equal to 400V is obtained. The various losses associated with the system are switching losses, diode losses and inductor losses.
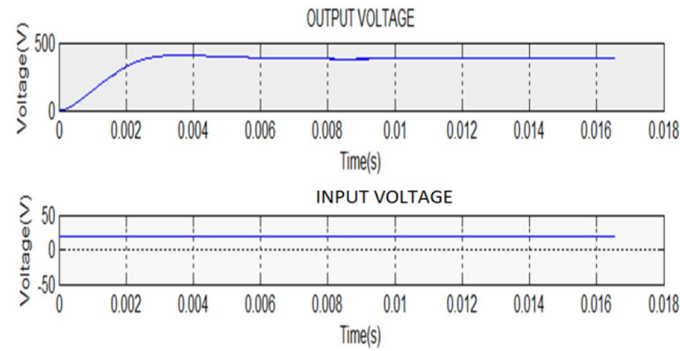

Fig.9. Output and input voltage

The diodes experience two times higher blocking voltages compared to the switches as it depends on the voltages of the voltage multiplier circuit capacitors. In this topology, all the diodes experience the same blocking voltage. Since all the diodes experience same maximum voltage stress, similar diodes can be used for all of them. As the diode losses increase, its junction temperature rises and decreases the forward voltage drop across it. This decrease in forward voltage drop reduces the power loss and helps in preventing a further increase in junction temperature which can lead to diode failure. In the worst case scenario, the losses in the selected diode were estimated to be within its power dissipation limits.
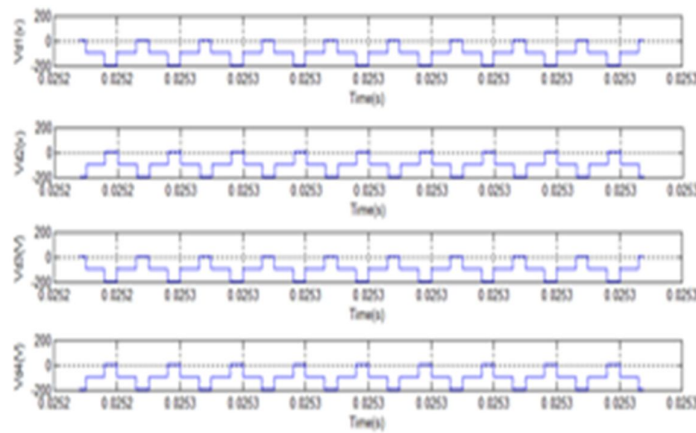

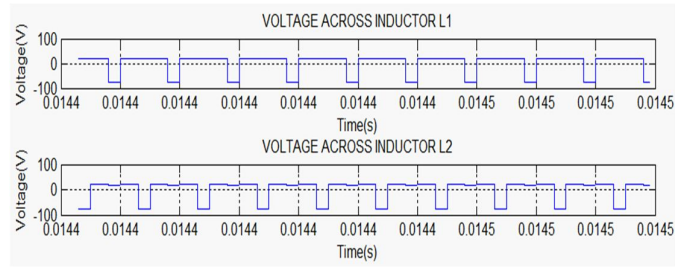Fig.10. Voltage across diodes D_1, D_2, D_3, D_4

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Fig.11. Voltages across inductors L_1 and L_2

The inductor currents are equal and are 180 degrees out of phase from each other. The turn off voltage of both switches is around 100V. The inductor current waveforms are decreasing during the turn off of their switches.

Fig.12. Voltages across switches S_1 and S_2

The 180 degree out of phase operation of switches S_1 and S_2 can be clearly observed in the switch voltages..The proposed converter is capable of providing voltage gains high enough to step up the output voltage of renewable sources to the distribution level 400V DC. Simulation of closed loop system is also done.The output voltage can be made near to 400 V by controlling it with a PI controller.
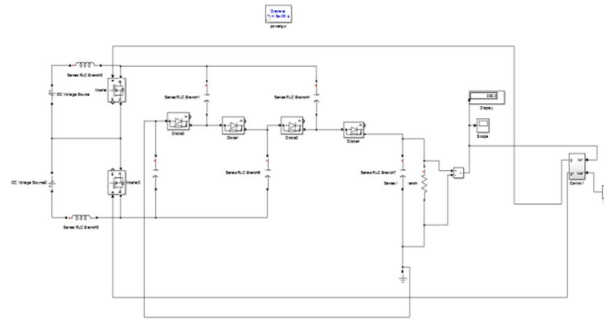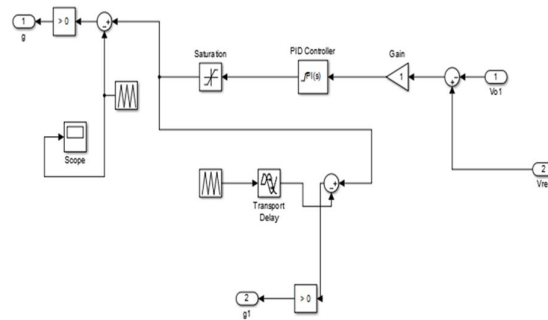

Fig.13. Simulation circuit of closed loop system

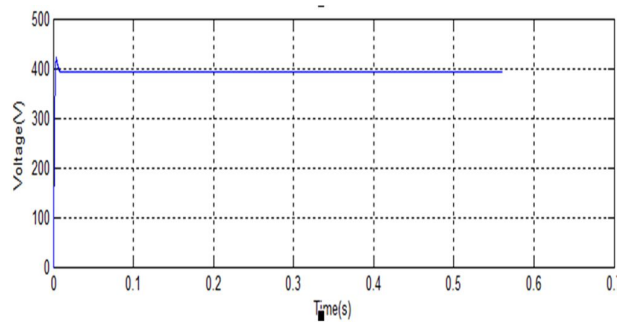Fig.14. Simulation circuit of PWM control

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Fig.15. Output voltage of closed loop system

VI. CONCLUSION

The dc power supply is used in many industries and domestics applications. The non-linear load causes abnormal conditions such as voltage imbalance, sudden actuation, high ripple current and large harmonic currents. During these conditions the power factor will be less. Most of the power electronics applications use inverters to convert DC to AC, these contribute the high total harmonics distortion, low power factor and low efficiency in the power system. These problems can be reduced by using a converter based on voltage multiplier.

Dc-dc converter can achieve a voltage gain of 20, i.e., to step up a 20V input to 400Voutput. The proposed converter is based on a two-phase interleaved boost stage and the modified Dickson charge pump voltage multiplier circuit. It can draw power either from single source or from two independent sources while offering continuous input current in both cases. This makes the converter well suited for renewable applications like solar. The proposed converter is symmetric, i.e., the semiconductor components experience same voltage and current stresses which makes component selection during the system design easier.

The converter has smaller voltage multiplier capacitors compared to conventional converter based on Dickson charge pump voltage multiplier cells; hence it is smaller in size. The converter finds its application in integration of individual solar panels onto the 400V distribution bus in datacenters, telecom centers, dc buildings and microgrids.The converter can also be fed to motors through inverters so that speed of it can be controlled.

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