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Generation of a Very High DC Gain Power Electronic Circuit Based Parallel Charging and Series Discharging Active Switched-Capacitor-Inductor Network

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Abstract:

The voltage gain of traditional boost converter is limited due to the high current ripple, high voltage stress across active switch and diode, and low efficiency associated with large duty ratio operation. High voltage gain is required in applications, such as the renewable energy power systems with low input voltage. A high step-up voltage gain active-network converter with switched capacitor technique is proposed in this paper. The proposed converter can achieve high voltage gain without extremely high duty ratio. In addition, the voltage stress of the active switches and output diodes is low. Therefore, low voltage components can be adopted to reduce the conduction loss and cost. The operating principle and steady-state analysis are discussed in detail. The results obtained in MATLAB/SIMULATION on a switched capacitor based active network converter show the effectiveness of the proposed configuration.

I. INTRODUCTION:

High step-up dc–dc converter is a class of converters which can boost a low voltage to a relatively high voltage. As we known, the output voltage of fuel cell stacks, single PV module, battery sources, or the super capacitors is relatively low; it should be boosted to a high voltage to feed the ac grid or other applications like uninterruptible power supplies, new energy vehicles, and so on. High step-up dc–dc power conversion has become one of the key technologies in these fields. As a matter of fact, when the output voltage is high, it is important to reduce the voltage stress on the active switch and output diode; otherwise, it will cause high conduction loss and expensive cost. Due to the existence of parasitic parameters such as the inductor’s equivalent series resistance (ESR), traditional boost converters cannot provide a high voltage gain. The extremely narrow turn-off time will bring large peak current and considerable conduction and switching losses. Lots of research works have been done to provide a high step-up without an extremely high duty ratio. The isolated converters can boost the voltage ratio by increasing the turns ratio of the high-frequency transformer. However, the leakage inductor should be handled carefully; otherwise, it will cause voltage spike across the power switches or diodes. Moreover, isolated dc/dc converters have the shortages in system volume and efficiency due to multistage dc–ac–dc conversion. Various switched-inductor and switched-capacitor structure to extend the voltage gain have been discussed in. With the transition in series and parallel connection of the switched inductor, an inherent high voltage gain can be achieved.

The switched-inductor-based boost converter is then derived, but the voltage gain is still limited, and the voltage stress of active switch and diode is also high. Based on the concept of switched-inductor and switched capacitor, this paper proposes a novel switched-capacitor-based active-network converter (SC-ANC) for high step-up conversion, which has the following advantages: high voltage conversion ratio, low voltage stress across switches and diodes, and self-voltage balancing across the output capacitors. The operating principle and steady-state analysis are discussed in detail, and the experimental results are given to verify the analysis.

II. PROPOSED CONVERTER TOPOLOGY:

Fig. 1 shows the basic structure of active-network derived from the concept of switched inductor, to perform both the series and parallel connection of two inductors. The switchesS1 and S2 share the same switching signal, when the switches are turned ON simultaneously, the inductors L1 and L2 are parallel connected; when S1 and S2 are turned OFF, L1 and L2are connected in series seen from the input port of the two-port network. Multiple capacitors and diodes on the output-stacking forma switched-capacitor unit, with the series or parallel connections between the capacitors, high voltage gain can be achieved, shown in Fig. 2. The two active switches (S1 and S2) share the same switching signal. Diodes D1,D2, D3 and capacitorsC1, C2, C3 are adopted in the switched-capacitor unit. Fig. 3 shows some typical waveforms obtained during continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The operating principles and steady-state analysis are presented in detail as follows.

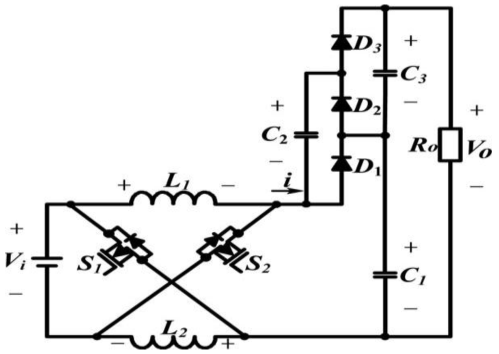

Fig 1: Proposed switched-capacitor-based active-network converter

Voltage Gain:

The expressions of the voltage gain in ideal situation (i.e., the ESR of the device and the voltage drop of the diodes are ignored) is

Gain of SC−ANC $=\frac{3+D}{1-D}$

Gain of SC−Boost $=\frac{2}{1-D}$

Gain of SL−Boost $=\frac{1+D}{1-D}$

Gain of Boost $=\frac{1}{1-D}$

Voltage Stress of Power Switch:

The normalized voltage stress on the power switch (Vs/Vi)of the four converters is

$$\left.\frac{V_s}{V_i}\right|_{\mathrm{SC-ANC}} = \frac{1+G_{\mathrm{CCM}}}{4} \quad \left.\frac{V_s}{V_i}\right|_{\mathrm{SC-Boost}} = \frac{G_{\mathrm{CCM}}}{2}$$

$$\left.\frac{V_s}{V_i}\right|_{\mathrm{SL-ANC}} = G_{\mathrm{CCM}} \quad \left.\frac{V_s}{V_i}\right|_{\mathrm{Boost}} = G_{\mathrm{CCM}}.$$

To realize the same voltage ratio, the boost converter and SL-Boost converter present the high voltage stress across the switches; while the switch voltage stress is greatly decreased in SL-ANC and SC-Boost. That means the switches with low Rds on can be utilized, which is beneficial to the efficiency and cost.

Voltage Stress of Output Diodes:

The normalized voltage stress on the diodes (VD/Vi) of the four converters is

$$\left.\frac{V_D}{V_i}\right|_{\mathrm{SC-ANC}} = \frac{1+G_{\mathrm{CCM}}}{2} \quad \left.\frac{V_D}{V_i}\right|_{\mathrm{SC-Boost}} = \frac{G_{\mathrm{CCM}}}{2}$$

$$\left.\frac{V_D}{V_i}\right|_{\mathrm{SL-ANC}} = G_{\mathrm{CCM}} \quad \left.\frac{V_D}{V_i}\right|_{\mathrm{Boost}} = G_{\mathrm{CCM}}.$$

To realize the same voltage ratio, the boost converter and the SL-Boost present the high voltage stress across the diodes; while the switch voltage stress is greatly decreased in SC-ANC and SC-Boost; therefore, low voltage diodes can be selected, which may mitigate the reverse recovery problem.

Inductor Current:

The normalized average inductor current (IL/Io) of the four converters is

$$\frac{I_L}{I_o}\Big|_{\mathrm{SC-ANC}} = \frac{G_{\mathrm{CCM}}+1}{2}\frac{I_L}{I_o}\Big|_{\mathrm{SC-Boost}} = G_{\mathrm{CCM}}\frac{I_L}{I_o}\Big|_{\mathrm{SL-ANC}}$$

$$= \frac{G_{\mathrm{CCM}}+1}{2}\frac{I_L}{I_o}\Big|_{\mathrm{Boost}} = G_{\mathrm{CCM}}.$$

Though two inductors are utilized in the proposed converter, the average current through the inductors is decreased greatly. In addition, the two inductors in SC-ANC can be integrated into one to decrease the magnetic components.

III. DESIGNING PARAMETERS:

The parameters in the converter are: input voltage Vi = 20–40 V; output voltage Vo = 200 V; rated power Po = 200 W; switching frequency: fs = 50 kHz.

During the switch ON period $V_{L1} = V_{L2} = V_i$

$$V_i = L\frac{\Delta I}{t_1}$$

$$\Delta I = \frac{V_i t_1}{L}$$

During the switch OFF period: $V_{L1} = V_{L2} = \frac{3}{4}V_i - \frac{1}{4}V_o$

$$\frac{3}{4}V_i - \frac{1}{4}V_o = -\frac{L\Delta I}{t_2}$$

$$\Delta I = \frac{(V_o - 3V_i)t_2}{4L}$$

By comparing both the ΔI equations

$$V_i t_1 = (V_o - 3V_i)t_2/4$$

$$V_o t_2 = 4t_1 V_i + 3V_i t_2$$

$$V_o = \frac{V_i(4DT + 3(1-D)T)}{(1-D)T}$$

$$\frac{V_o}{V_i} = \frac{DT + 3T}{(1-D)T}$$

$$\therefore \frac{V_o}{V_i} = \frac{3+D}{1-D}$$

Total time period $T = \frac{1}{f} = t_1 + t_2$

Sub t1 and t2 values $\frac{1}{f} = \frac{\Delta IL}{V_i} + \frac{\Delta I4L}{V_o - 3V_i}$

$$= \Delta IL\left(\frac{V_o + V_i}{V_i(V_o - 3V_i)}\right)$$

$$\therefore L = \frac{V_i(V_o - 3V_i)}{\Delta If(V_o + V_i)}$$

Sub Vo value

$$L = \frac{V_i\big((3+D)V_i - 3(1-D)V_i\big)}{\Delta If\big((3+D)V_i + (1-D)V_i\big)}$$

$$L = \frac{V_i(4DV_i)}{\Delta If(4V_i)}$$

Inductor value $\therefore\ L = \frac{DV_i}{f\Delta I}$

When the switch is ON the capacitor supplies the load, when $C_{1,}$ $C_{2,}C_3$ are being charged, the electric charge can be written as follows;

$$\Delta V_{c3} = \frac{1}{C_3}\int_0^{t_1} I_o\, dt$$

$$= \frac{I_o t_1}{C_3}$$

Sub $t_1 = \frac{\Delta IL}{V_i}$ and $L = \frac{DV_i}{f\Delta I}$

$$\Delta V_{c3} = \frac{I_o \Delta I\, L}{C_3 V_i}$$

$$\Delta V_{c3} = \frac{I_o \Delta I D V_i}{C_3 V_i f \Delta I}$$

$$\therefore C_3 = \frac{I_o D}{\Delta V_{c3} f}$$

$$\Delta V_{c2} = \frac{1}{C_2}\int_0^{T} I_o dt$$

$$= \frac{I_o T}{C_2}$$

Where T=t1+t2

$$C_2 = \frac{I_o t_1}{\Delta V_{c2}} + \frac{I_o t_2}{\Delta V_{c2}}$$

Then sub t1, t2 and L values

$$= \frac{I_o D}{\Delta V_{c2} f} + \frac{I_o \Delta IL4}{\Delta V_{c2}(V_o - 3V_i)}$$

$$\frac{I_o D}{\Delta V_{c2} f} + \frac{I_o D}{\Delta V_{c2} f} \cdot \frac{4V_i}{V_o - 3V_i}$$

$$C_2 = \frac{I_o D}{\Delta V_{c2} f} \frac{V_o + V_i}{V_o - 3V_i}$$

Sub Vo value

$$V_o = \frac{(3 + D)V_i}{1 - D}$$

$$\therefore\ C_2 = \frac{I_o}{\Delta V_{c2} f}$$

$$\Delta V_{c1} = \frac{1}{C_1} \int_0^{T+t_1} I_o \, dt$$

$$= \frac{I_o T}{C_1} + \frac{I_o t_1}{C_1}$$

Sub T, t1 and L values

$$C_1 = \frac{I_o D}{\Delta V_{c1} f} \frac{V_o + V_i}{V_o - 3V_i} + \frac{I_o D}{\Delta V_{c1} f}$$

Sub Vo value

$$\therefore\ C_1 = \frac{I_o}{\Delta V_{c1} f} + \frac{I_o D}{\Delta V_{c1} f}$$

IV. SIMULATION RESULTS:

Boost Converter

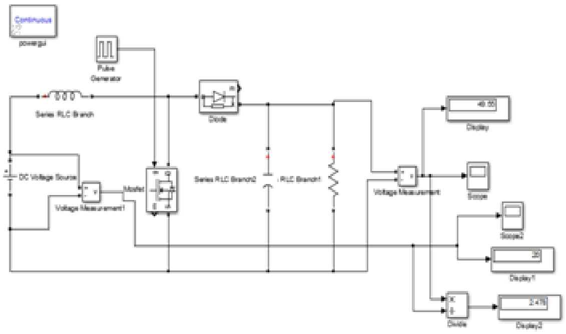

Fig 2: Simulation model of Boost converter

The input voltage of the boost converter is given as 20V

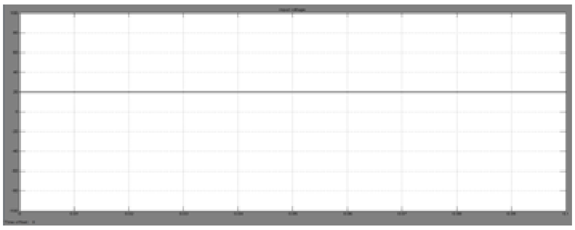

Fig 3: input voltage of boost converter

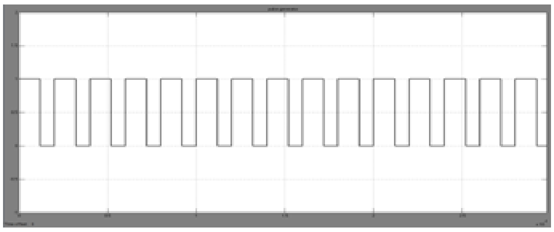

Fig 4: pulses given to the boost converter

The boost converter is operated at the duty ratio 0.6. And the switching frequency is 50KHZ.The capacitor and inductor values are given at the duty ratio 0.6. The output voltage simulation is shown in fig 5.

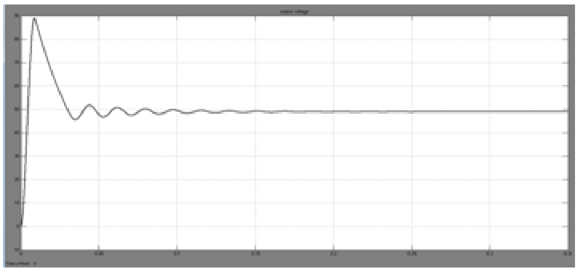

Fig 5: output voltage of the boost converter

Switched Inductor Boost Converter

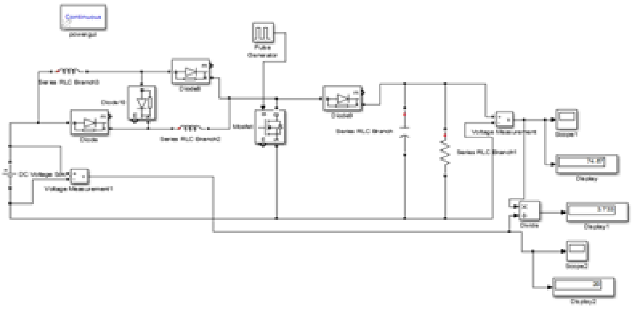

Fig 6: Simulation model of switched inductor boost converter

The switched inductor boost converter is operated at the duty ratio of 0.6.

The switching frequency is 50KHZ. The output voltage simulation is shown in fig 8. The input voltage of the switched inductor boost converter is 20V.

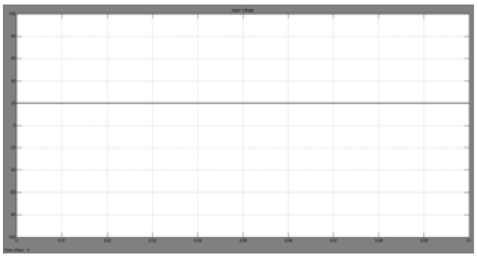

Fig 7: Input voltage of the switched inductor boost converter

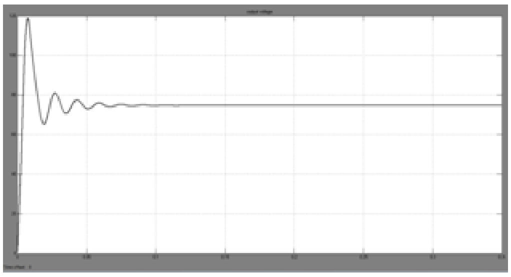

Fig 8: Output voltage of the switched inductor boost converter

Switched Capacitor Boost Converter

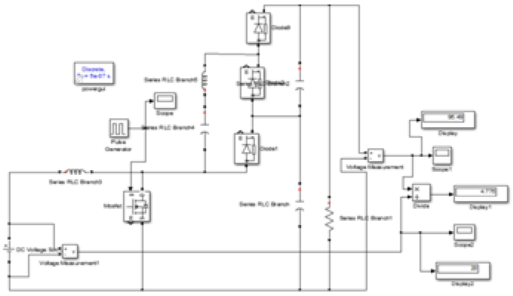

Fig 9: Simulation model of switched capacitor boost converter

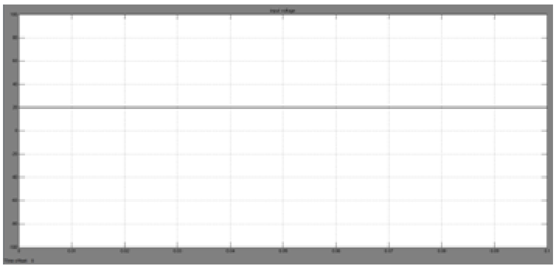

Fig 10: Input voltage of the switched capacitor boost converter

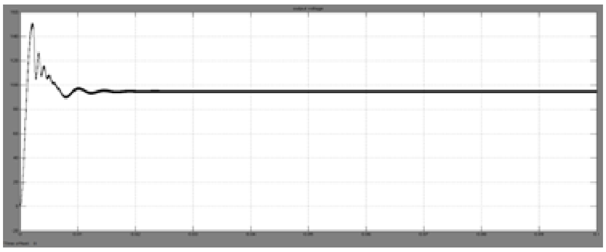

Fig 11: Output voltage of the switched capacitor boost converter

Switched Capacitor Based Active Network Converter

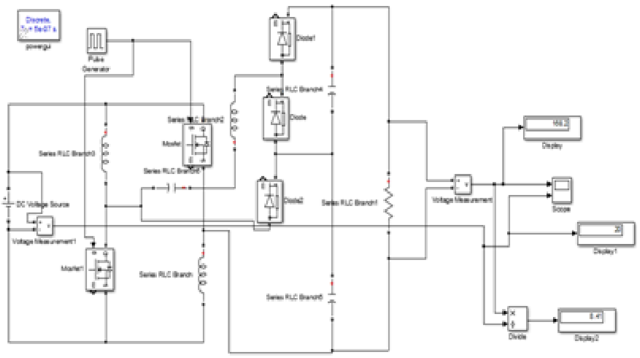

Fig 12: Simulation model of switched capacitor based active network converter

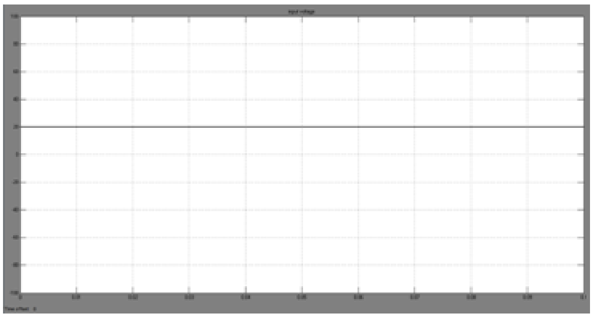

Fig 13: Input voltage of the proposed converter

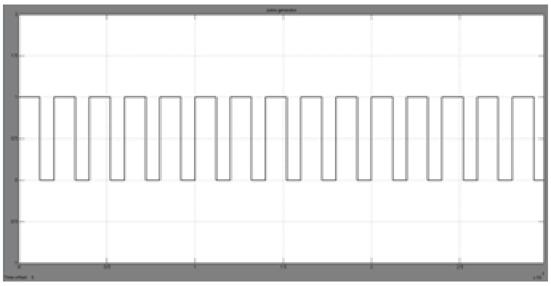

Fig 14: Pulses given to the proposed converter

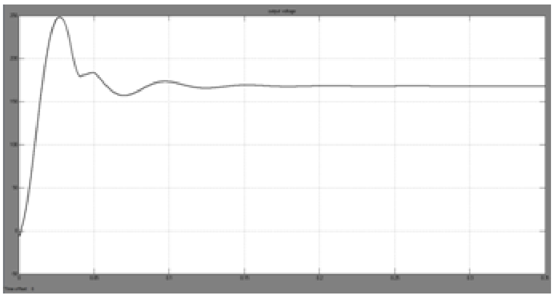

Fig 15: Output voltage of the proposed converter

Proposed Converter with R-L Load

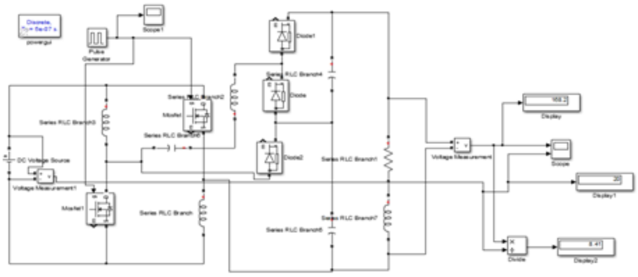

Fig 16: switched capacitor based active network converter with R-L load

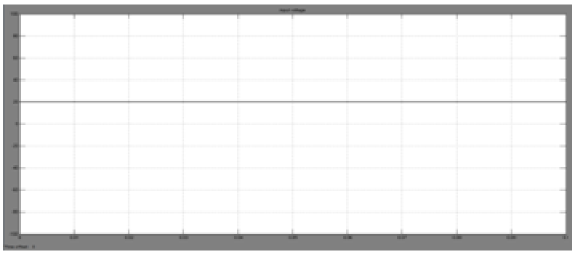

Fig 17: Input voltage of proposed converter with R-L load

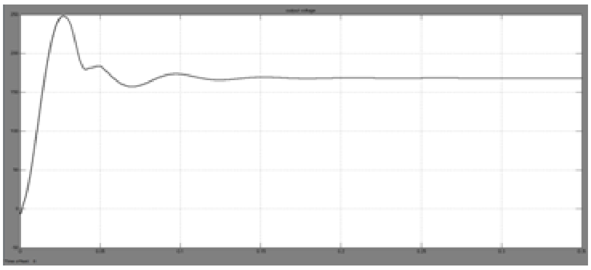

Fig 18: Output voltage of proposed converter with R-L load

Proposed Converter with R-C Load

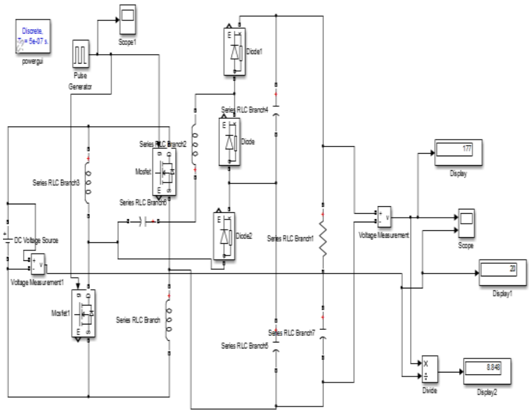

Fig 19: switched capacitor based active network converter with R-C load

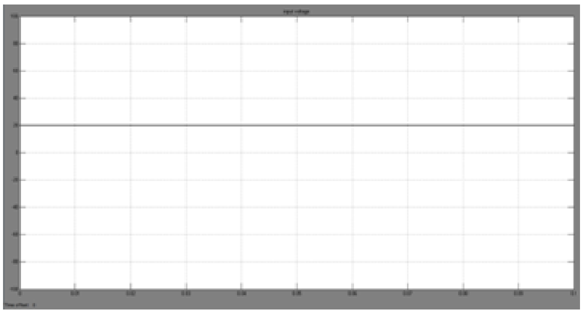

Fig 20: Input voltage of the proposed converter with R-C load

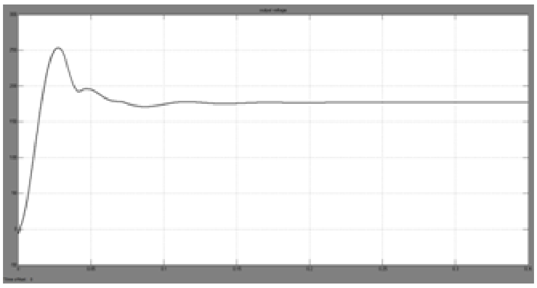

Fig 21: Output voltage of the proposed converter with R-C load

Renewable Energy Application

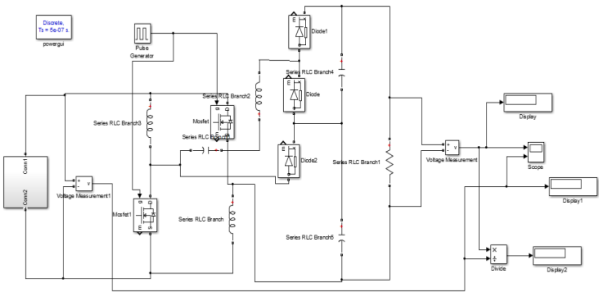

Fig 22: Simulation of proposed converter for renewable energy application

High voltage gain is required in applications, such as the renewable energy power systems with low input voltage. In this the PV cell is taken as the application of the switched capacitor based active network converter. The irradiance to the basic solar cell is given as 1000.And short circuit current is 7.307. The basic solar cell is simulated in matlab 2013a.

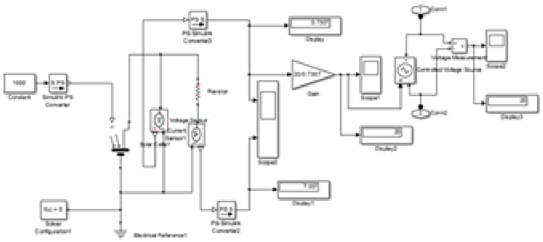

Fig 23: Simulation model of solar cell

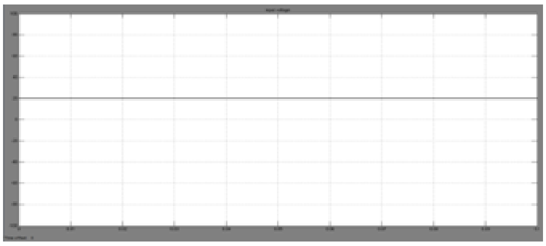

Fig 24: Input voltage for renewable energy application

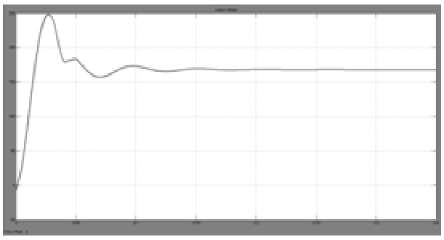

Fig 25: Output voltage for renewable energy application

CONCLUSION:

This paper proposed a switched capacitor-based active network converter with high step-up voltage gain. The operating principles of the proposed converter in CCM and DCM have been discussed in detail. The voltage stress on active switches and diodes is low, which is beneficial to the system efficiency and cost. Comparisons of the proposed topology with the boost converter, switched inductor boost converter, and switched capacitor boost converter are shown. Compared with these converters, the voltage gain of the proposed converter is higher; the voltage across the power devices is lower; the inductor current is smaller. The main disadvantage of the proposed converter is that two switches are utilized, and additional insulated gate drive circuit is needed, which induces additional cost. Simulation results have been given to verify the analysis and merits of the converter.

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