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Source-load-variable voltage regulated cascaded DC/DC converter for a DC microgrid system

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ABSTRACT

Solar energy is available abundantly, the utilization of solar energy is developing rapidly and the photovoltaic based direct current (DC) microgrid system design is under demand but the stability of the DC voltage is of most important issue, as the variation of the output DC voltage is a common problem when the load or source voltage varies, hence a regulated DC output voltage converter is proposed. This paper presents source-load-variable (SLV) voltage regulated cascaded DC/DC converter which is used to obtain regulated output voltage of 203.1 V DC at 0.4 duty ratio with ±2% voltage fluctuations for the variation in the input source voltage and ±1.5% voltage fluctuations for the variation in load resistance of the nominal value with lower output voltage ripple and without use of sub circuits. A simulation model of SLV voltage regulated cascaded DC/DC converter in LTspice XVII software environment for the assessment of converter performance at different input source voltages and load resistances are verified.

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NOMENCLATURE

CIBC - Cascaded interleaved boost converter
V_{IN} - DC input source voltage
V_{O1} - DC output voltage of stage1 at C_5
V_{O2} - DC regulated output voltage at C_6
V_{C2} - Voltage across capacitor C_2
V_{C4} - Voltage across capacitor C_4
V_{C6} - Voltage across capacitor C_6
V_{L2} - Voltage across inductor L_2
V_{L4} - Voltage across inductor L_4
V_{L6} - Voltage across inductor L_6
$*$ Off state value of each component
PC - Proposed converter
V_{in1} - DC input source voltage of 22V
V_{in2} - DC input source voltage at stage2
V_{C1} - Voltage across capacitor C_1
V_{C3} - Voltage across capacitor C_3
V_{C5} - Voltage across capacitor C_5
V_{L1} - Voltage across inductor L_1
V_{L3} - Voltage across inductor L_3
V_{L5} - Voltage across inductor L_5
V_{OUT} - Regulated output voltage
D - Duty ratio of switches = 0.4

1. INTRODUCTION

In current years, direct current (DC) microgrids are increasing rapidly in electric power grids and other isolated systems, storage units, DC loads and renewable energy resources [1]. A DC microgrid is essential for an unconventional control system and in the main grid when error occurs it is best to work in an islanded method. There are a large number of advantages by using photovoltaic (PV) systems when compared to other renewable energy resources [2] but as solar energy is intermittent energy, regulated output is necessary for stable operation of the microgrids. Solar energy production industries have increased to 150 GW from 21 GW between 2010 to 2020 [3], [4]. In the year 2020, in spite of the coronavirus disease (COVID-19) pandemic, reports in the worldwide renewable energy sources, there was an increase in investment by 2% [5] and also show that new solar capacity reserves have improved by 12% and reached USD 148.6 billion. The initial data displays that the new PV capacity has increased by almost 20% which is nearly 140 GW [6], [7]. In India new installations dropped during this period from stronger marketing in 2019 [8]. There are more possibilities of reduction in the cost which will drive the development of PV installations in the coming decades. In 2022, higher progress rate is expected according to most of the market estimates along with new installations and also breaking 1 TW barrier [9].

There is a necessity for incorporating the system into the DC microgrid to enhance the power management, stability and consistency in the power distribution system. When the alternating current (AC) system is compared with DC microgrid, it gives the option of improved efficient integration for any residential renewable energy source and the storage battery systems [10]. DC microgrids are dominant in consistency, efficiency and control systems but the power quality issues and voltage levels in the DC microgrid system have to be handled accurately. It is easier for the integration of the DC source renewable generation with the energy storage system in a DC microgrid system [11]. In DC microgrids unlike in AC microgrids, the difficulties like synchronization, phase unbalanced and harmonics do not occur. Hence, there is a large growth in the usage of DC sources in commercial, residential and industrial systems [12]–[15].

A DC microgrid configuration is as shown in Figure 1. It consists of a PV panel, battery storage system, DC microgrid, DC/DC converters and DC loads. A DC/DC boost converter is used between the PV panel and the DC bus to step up the voltage to the required level and the battery is connected to the DC bus through a bidirectional buck-boost DC/DC converter and finally, the loads are connected to a DC bus through the buck DC/DC converter. The DC microgrid system, due to the nature of the DC/DC converters, PV system and the load is basically a nonlinear system. The International Space Station is a standard example of a DC microgrid. When the solar rays in connection with illumination deliver power to the loads and batteries, the batteries discharge if the solar arrays cannot generate enough power to the loads in order to supply the remaining power. To regulate voltage, DC/DC converters are being used [16]. In recent years, various researchers have contributed their works in the DC microgrid system mainly consisting of photovoltaic systems particularly concentrating on the energy management, stability issues and control system techniques. In various control strategies, DC bus voltage controlling in a proper manner is an important controlling issue. In this paper a new modest method named, source-load-variable (SLV) voltage regulated cascaded DC/DC converter is being proposed to regulate the output voltage with minimum voltage fluctuations.

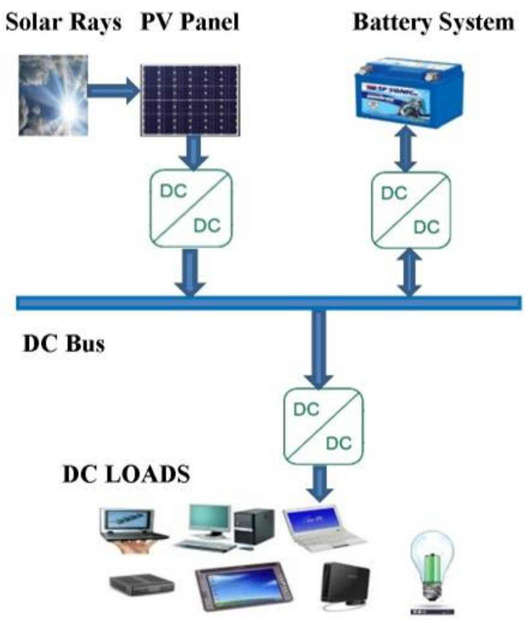

Figure 1. A DC microgrid system configuration

This paper is structured as: discussion about conventional circuits and the proposed method in section 2, section 3 presents details of proposed converter with mathematical model. Then, discussion on the simulation results of voltage regulated which validates theoretical results is described in section 4 along with the simulation graphs of converter DC output voltage for variation in input source voltage and load resistance. Discussion on assessment of operation of the performance of the proposed and cascaded interleaved boost converter along with PV converter in section 5 and finally, overall work conclusion in section 6.

2. PROPOSED METHOD

In a conventional proportional integral controller (PI), the performance is affected by the load variations when connected to DC microgrids, hence a feed forward control method has been studied by considering the mismatched power/current disturbances to obtain an enhanced dynamic performance of the dc link voltage to handle this difficulty. The main aim was to regulate the dc link voltage to a constant value [17]–[19]. To have more reliable and comprehensive operation of the system, various refined control schemes and energy management systems are being proposed and to maintain constant voltage at DC bus which was based on comprehensive control system and the power management system, a nonlinear adaptive backstepping controller design was being used which was a method for stabilizing DC bus voltage and it also implemented flexibly in the power flow of the system [20]. In order to obtain the steady operation of a DC microgrid, voltage regulators and load sharing controllers are the main requirements. To improve the stability and for proper control of the load sharing, a primary controller with droop control method was being used in the DC microgrid system but there was poor voltage regulation and load sharing in the system [21]–[23]. The review of different methods proposed in the recent literature confirmed that to develop voltage regulated DC/DC converters there are a number of techniques that are being proposed with various additional sub circuit requirements like proportional integral derivative controllers (PID), droop control methods, and feedback passivation method with high system complexity and poor voltage regulation.

The proposed, SLV voltage regulated cascaded DC/DC converter using voltage lift method with the gate control circuit aims to attain regulated output voltage at lower duty ratio with minimum voltage fluctuations with lower switching losses and without use of sub circuits. This system is suitable for applications like battery charging and interconnecting to DC microgrids. The highlights of this converter are: i) the application of voltage lift technique, ii) the operation of the converter at a lower duty cycle for minimization of switching losses, and iii) regulated output voltage with minimum voltage fluctuations.

3. METHOD

This paper is an extension work of [24], which gives the operation of the circuit comprising of inductors of 70 µH and capacitors of 100 µF which is the modified double voltage lift converter designed with the arrangement of voltage lift technique and the boost circuit that results in obtaining enhanced output voltage from the fixed input source voltage of 15 V DC at lower duty ratio varying from 0.4 to 0.6 which was the preferred duty ratio of the converter. The inductors are represented with a dot notation pattern to comprehend the flow of current in the circuit. The SLV voltage regulated cascaded DC/DC converter circuit is as shown in Figure 2. The circuit operates based on the switches being in the “ON” and “OFF” states. The inductors act as charging in parallel in the “ON” state and inductors discharge in series in the “OFF” state, hence the output voltage can be enhanced as the inductor voltage gets added up. When the input source voltage is varied between 14 to 30 V DC, the regulated output voltage is obtained which is constant at 203.1 V DC with ±2% voltage fluctuations and also when the load resistance is varied between 40 to 1 KΩ, the output voltage is regulated at 203.1 V DC with ±1.5% voltage fluctuations at a switching frequency of 50 KHz with the gate control circuit comprising of the PWM signals in order to drive the switches to “ON” state and “OFF” state at a lower duty ratio of 0.4. The control technique is based on the gate control circuit consisting of the driver circuit and the PWM circuit which regulates the voltage in the converter to the nominal value with minimum voltage fluctuations for the variations in the input source voltage and load. The load resistance is varied to justify that constant power load can be attained as the output voltage is regulated with slight variation in the output current of the converter.

3.1. Operation of switch T_1

The SLV voltage regulated cascaded DC/DC converter is cascaded with two stages, the operation of the converter is according to the “ON” and “OFF” states of the switches T_1 and T_2. When the switch T_1 is “ON”, the inductors are in a charging state which is indicated by the (1) to (3). As the inductor voltage is equal to the product of D/(1–D) and “ON” state value [25], the capacitor and inductor voltages are as in (4) to (6). When the switch T_1 is “OFF”, the inductors are in discharging state and hence voltage enhances as in (7). Finally, the output of stage 1 of the converter is as in (9).

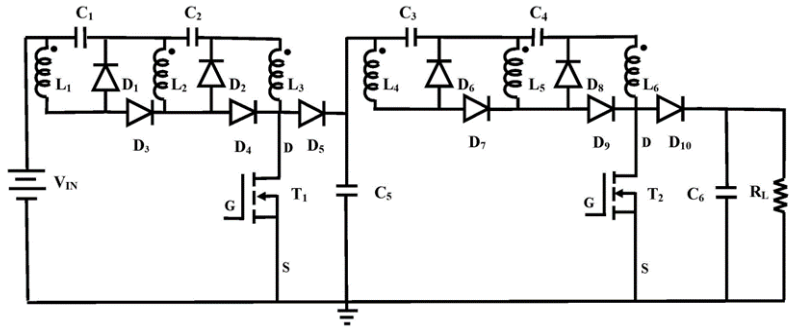

Figure 2. SLV voltage regulated cascaded DC/DC converter [24]

a. During the “ON” state of switch T_1

$$-V_{L1} = V_{in1} \tag{1}$$

$$-V_{L2} = V_{in1} + V_{C1} \tag{2}$$

$$-V_{L3} = V_{in1} + V_{C1} + V_{C2} \tag{3}$$

$$V_{C1} = V_{C1}^{*} = V_{L1}^{*} = \frac{-D}{(1-D)} V_{L1} \tag{4}$$

$$V_{C2} = V_{C2}^{*} = V_{L2}^{*} = \frac{-D}{(1-D)} V_{L2} \tag{5}$$

$$Similarly, V_{L3}^{*} = \frac{-D}{(1-D)} V_{L3} \tag{6}$$

b. During the “OFF” state of switch T_1

$$V_{O1} = V_{in1} + V_{L1}^{*} + V_{L2}^{*} + V_{L3}^{*} \tag{7}$$

$$V_{O1} = V_{in1} + \frac{-D}{(1-D)} V_{L1} + \frac{-D}{(1-D)} V_{L2} + \frac{-D}{(1-D)} V_{L3} \tag{8}$$

$$Therefore, V_{O1} = \frac{V_{in1}}{(1-D)^3} \tag{9}$$

3.2. Operation of switch T_2

When the switch T_2 is “ON”, the output of stage 1 is the input to stage 2 of the converter as given in (10) and as the inductor voltage is equal to the product of D/(1–D) and “ON” state value, the capacitor and inductor voltages are as in (11) to (16). When the switch T_2 is “OFF”, the inductors are in discharging state and hence voltage gets added up and the converter output voltage is given by the (17).

a. During the “ON” state of switch T_2

$$V_{O1} = V_{in2} = \frac{V_{in1}}{(1-D)^3} \tag{10}$$

$$-V_{L4} = V_{in2} \tag{11}$$

$$-V_{L5} = V_{in2} + V_{C3} \tag{12}$$

$$-V_{L6} = V_{in2} + V_{C3} + V_{C4} \tag{13}$$

$$V_{C3} = V_{C3}^{*} = V_{L4}^{*} = \frac{-D}{(1-D)} V_{L4} \tag{14}$$

$$V_{C4} = V_{C4}^{*} = V_{L5}^{*} = \frac{-D}{(1-D)} V_{L5} \tag{15}$$

$$Similarly, V_{L6}^{*} = \frac{-D}{(1-D)} V_{L6} \tag{16}$$

b. During the “OFF” state of switch T_2

$$V_{O2} = V_{in2} + V_{L4}^{*} + V_{L5}^{*} + V_{L6}^{*} \tag{17}$$

$$V_{O2} = V_{in2} + \frac{-D}{(1-D)} V_{L4} + \frac{-D}{(1-D)} V_{L5} + \frac{-D}{(1-D)} V_{L6} \tag{18}$$

$$V_{O2} = 2\, V_{in2} = \frac{2\, V_{in1}}{(1-D)^3} \tag{19}$$

$$= \frac{2\, V_{in1}}{(1-D)^3} \tag{20}$$

Therefore,

$$V_{OUT} = 2 \frac{V_{in1}}{(1-D)^3} \tag{20}$$

Theoretically, regulated output voltage, V_{OUT} = 203.7 V for 22 V input source voltage at 0.4 duty ratio is as in (20), which is the nominal voltage and is approximately equal to the simulated value of 203.1 V for an input source voltage of 22 V at 0.4 duty ratio.

4. RESULTS AND DISCUSSION

The simulation model of SLV voltage regulated cascaded DC/DC converter is as shown in Figure 3 which has been carried out using LT spice XVII software to obtain regulated DC output voltage for the variation in the input source voltage from 14 to 30 V DC and load resistance from 40 to 1 KΩ at 0.4 duty ratio. The simulation results of the converter show that, when the resistance of the load is varied from 40 to 1 KΩ at the output terminals, output voltage with ±1.5% voltage fluctuations of the nominal value is obtained and when the input source voltage is varied from 14 to 30 V DC, output voltage with ±2% voltage fluctuations of nominal value is attained.

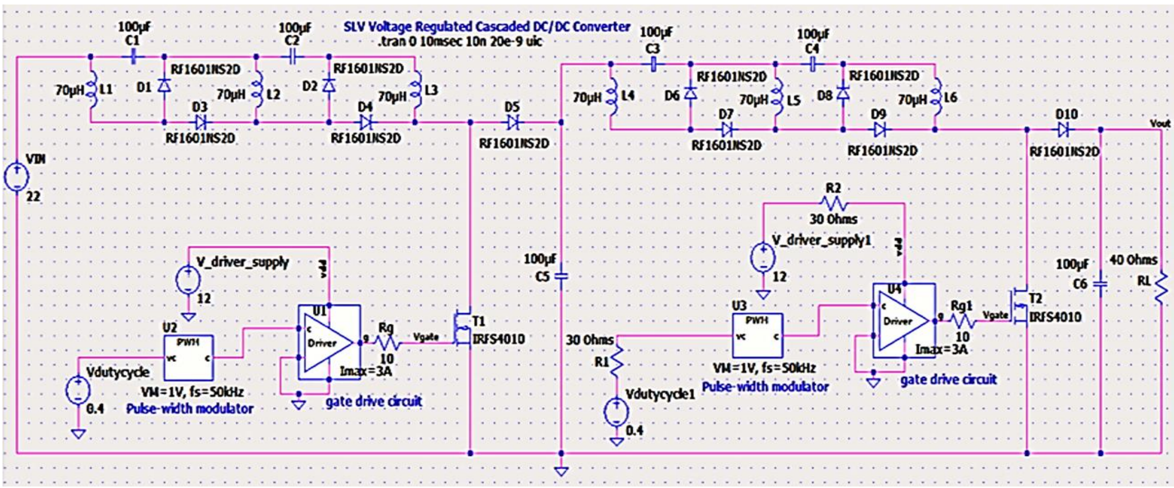

Figure 3. Simulation setup of SLV voltage regulated cascaded DC/DC converter model

4.1. Discussion on the converter regulated output voltage with the variation in the input source voltage and load resistance

The converter ability to respond to input source voltage and load variations is as shown in Figure 4. When the input source voltage is varied from 14 to 30 V at 0.4 duty ratio at constant load resistance of 40 Ω, the converter gives output voltage of 201.1 to 205.4 V indicating ±2% voltage fluctuations. Similarly, simulation is carried out for various load resistances of 50 Ω, 100 Ω, 500 Ω and 1 KΩ at constant but with the variation in the input source voltage. When the load resistance is varied from 40 Ω, 50 Ω, 100 Ω, 500 Ω and 1 KΩ at 0.4 duty ratio with constant input source voltage of 22 V, the converter gives output voltage of 203.1 V, 203.3, 203.6, 203.8 and 203.8 V respectively indicating ±1.5% voltage fluctuations. Similarly, simulation is carried out for various input source voltages from 14 to 30 V DC at constant but with variation in the load resistance.

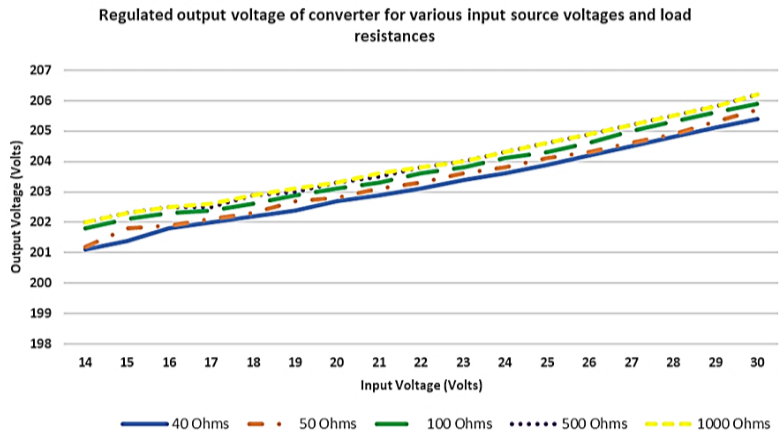

Figure 4. Converter output voltage for variation in input source voltages and load resistances

4.2. Simulation graphs for variation in the input source voltage

The converter output voltage at various input source voltages for 14, 22 and 30 V are as shown in Figures 5(a) to 5(c) at 0.4 duty ratio and load resistance of 40 Ω at constant. The Figure 5(d) gives the variation of input source voltage from 14 to 30 V DC with output voltage of 201.1 to 205.4 V DC having ±2% voltage fluctuations for load resistance of 40 Ω at 0.4 duty ratio. As the input voltage increases, the settling time of the output voltage decreases while the ripple in the output voltage increases.

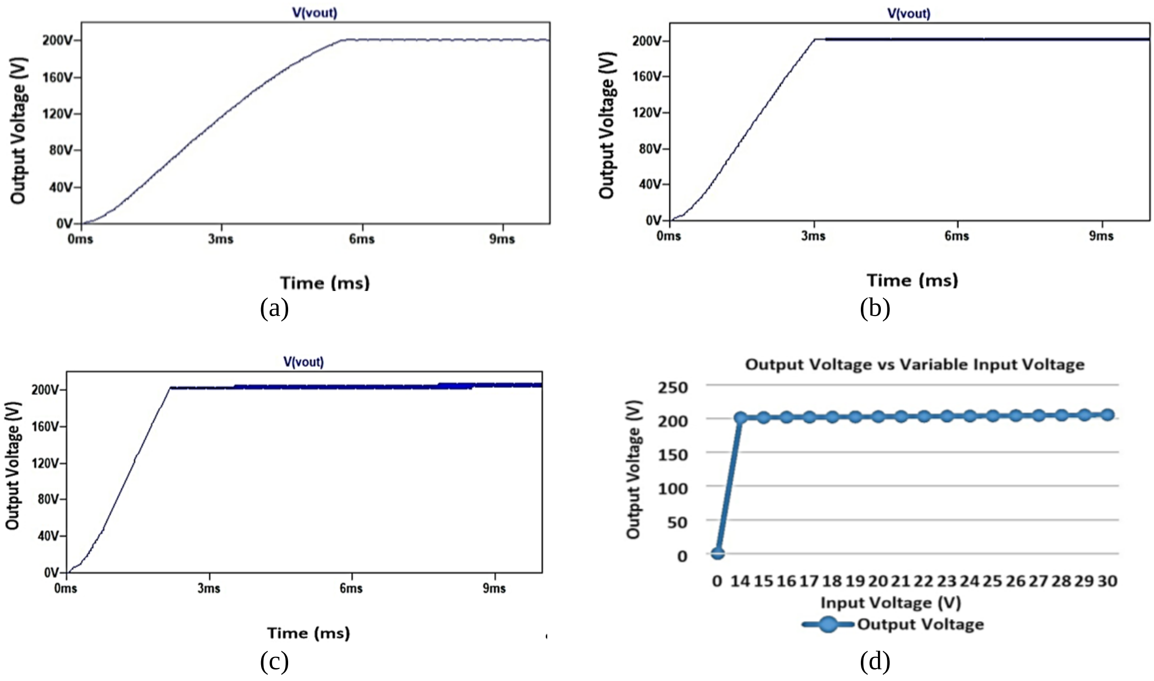

Figure 5. Simulation graphs of converter DC output voltage for variation in input source voltages (a) V_{IN}=14 V and R_L=40 Ω, (b) V_{IN}=22 V and R_L=40 Ω, (c) V_{IN}=30 V and R_L=40 Ω, and (d) variable input source voltage and R_L=40 Ω

4.3. Simulation graphs for variation in the load resistance

The converter output voltage at various load resistances for 50 Ω, 500 Ω and 1 KΩ are as shown in Figure 6(a) to 6(c) at 0.4 duty ratio and 22 V DC input source voltage at constant. The Figure 6(d) gives the variation of load resistance from 40 Ω to 1 KΩ with output voltage of 203.1 to 203.8 V DC having ±1.5% voltage fluctuations for input source voltage of 22 V DC at 0.4 duty ratio. The settling time of the output voltage remains constant with the increase in the load resistance.

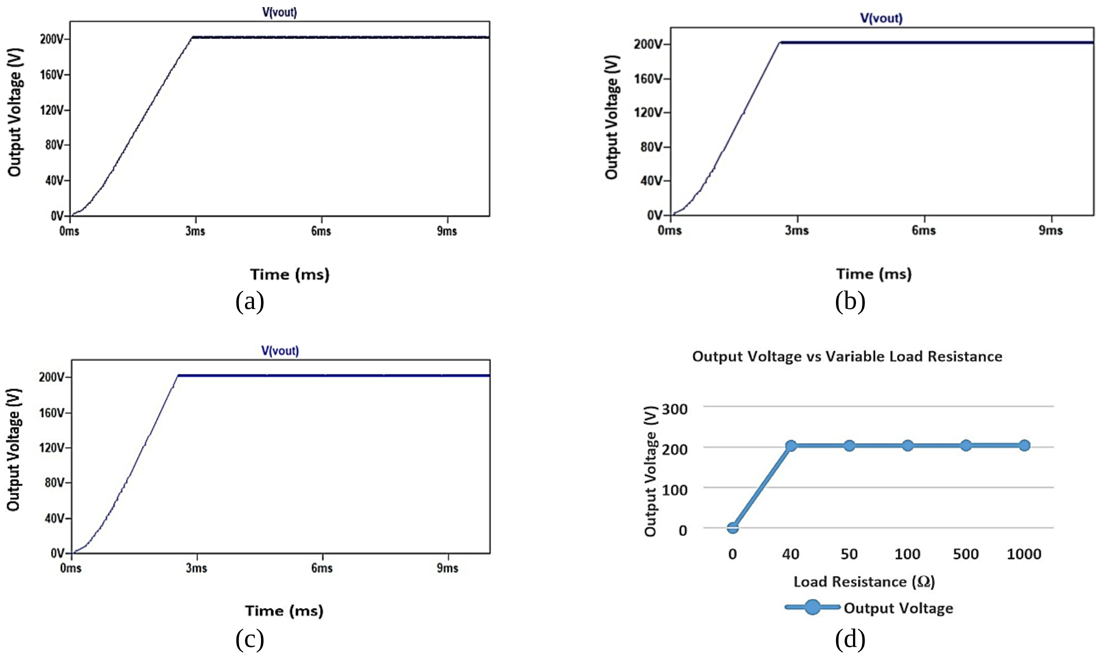

Figure 6. Simulation graphs of converter DC output voltage for variation in load resistances; (a) R_L = 50 Ω and V_{IN}=22 V, (b) R_L=500 Ω and V_{IN}=22 V, (c) R_L=1 KΩ and V_{IN}=22 V, and (d) variable load resistance and V_{IN}=22 V

5. RELATIVE ASSESSMENT OF SLV VOLTAGE REGULATED CASCADED DC/DC CONVERTER

The performance of the SLV voltage regulated cascaded DC/DC converter is compared to analyze the percentage voltage fluctuations with other converters like PV converter in a standalone DC microgrid and cascaded interleaved boost converter. It is observed that, SLV voltage regulated cascaded DC/DC converter gives better results of regulated DC output voltage with minimal voltage fluctuations with variation in input source voltage and load resistance on relative assessment with other converters.

5.1. PV converter in a standalone DC microgrid

The photovoltaic system was operated when the DC bus voltage was at ±5% of the nominal value (600V). Under this condition, the PV converter regulated the bus voltage. When the battery energy storage system was in the idle state, load demand was fulfilled by the photovoltaic system when the bus voltage was -5% Vdc to +5% Vdc and it gives the details of the voltage regulation in standalone DC microgrids using droop control method. In two scenarios, simulation using PSCAD software of the system was carried out [26]. In relative assessment with these details, the PV converter gives regulated DC bus voltage with ±5% voltage fluctuations of its nominal value whereas the SLV voltage regulated cascaded DC/DC converter gives higher performance of regulated DC output voltage with ±2% voltage fluctuations for the variation in the input source voltage from 14 to 30 V DC and ±1.5% voltage fluctuations for variation in load resistance from 40 Ω to 1 KΩ indicating less voltage fluctuations.

5.2. Cascaded interleaved boost converter

The circuit for cascaded interleaved boost converter is as shown in Figure 7. The simulation of cascaded interleaved boost converter has been carried out using LTspice XVII at 50 KHz switching frequency. When the input source voltage is varied from 14 to 30 V DC, cascaded interleaved boost converter using four switches gives regulated output voltage of 94.7 V with ±34% voltage fluctuations at 0.4

duty ratio but at higher duty ratio of 0.65 it gives 204.5 V with ±4% voltage fluctuations with higher output voltage ripple in the waveform. When the load is varied from 40 Ω and 1 KΩ, cascaded interleaved boost converter gives unstable output at 0.4 duty ratio and at higher duty ratio of 0.65 it gives regulated output voltage with ±5.5% voltage fluctuations. In comparison, SLV voltage regulated cascaded DC/DC converter using two switches gives better results of regulated DC output voltage with variation in the input source voltage from 14 to 30 V DC with ±2% voltage fluctuations and for load resistance from 40 Ω to 1 KΩ with ±1.5% voltage fluctuations with lower ripple in the output voltage at lower duty ratio of 0.4 and lesser voltage fluctuations. The comparative results of the converters are as shown in Table 1.

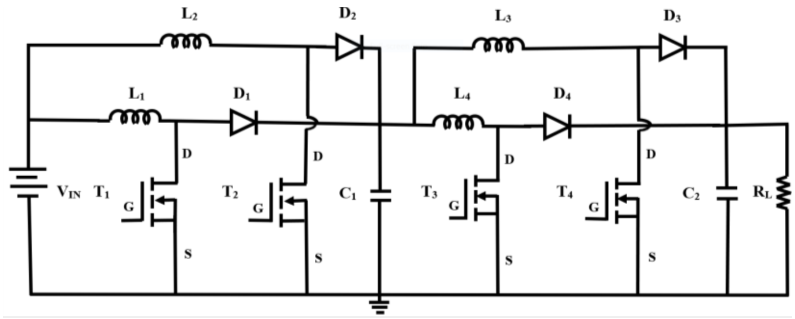

Figure 7. Cascaded interleaved boost converter

Table 1. Comparative assessment of output voltage of SLV voltage regulated cascaded DC/DC converter and cascaded interleaved boost converter

Converter	CIBC	CIBC	CIBC	CIBC	PC	PC
Duty Ratio	0.4	0.4	0.65	0.65	0.4	0.4
V_{IN}	40 Ω	1 KΩ	40 Ω	1 KΩ	40 Ω	1 KΩ
14 V	61.7 V	Unstable	200.6 V	203.3 V	201.1 V	202.0 V
22 V	94.7 V	Unstable	204.5 V	205.2 V	203.1 V	203.8 V
30 V	129.5 V	200.8 V	208.0 V	210.2 V	205.4 V	206.2 V

6. CONCLUSION

In this article, the SLV voltage regulated cascaded DC/DC converter is used to obtain regulated DC output voltage with minimal voltage fluctuations. The performance of the converter is evaluated by varying the input source voltage and load resistance. The inference of the simulation results is that i) the output voltage is regulated at 203.1 V DC with ±2% voltage fluctuations for the variation of input source voltage between 14 to 30 V DC; ii) when load resistance is varied between 40 Ω and 1 KΩ, the output voltage remains constant with ±1.5% voltage fluctuations; iii) this is achieved at 0.4 duty ratio with the PWM gate control circuit. Compared to other topologies, SLV voltage regulated cascaded DC/DC converter gives better results of regulated DC output voltage with minimum voltage fluctuations, without use of sub circuits and at lower duty ratio for reliable and secure operation of a DC microgrid system. In the future work, the implementation of the suggested voltage regulation process is going to be implemented and the likely complications caused from the practical application will be handled and conferred.

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