A New Single-Phase Dual-Mode Active Neutral Point-Clamped Five-Level Inverter for Renewable Applications

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2024 Third International Conference on Power, Control and Computing Technologies (ICPC2T) | 979-8-3503-4920-7/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICPC2T60072.2024.10474640

***Abstract*—The paper presents a new single-phase Dual-Mode Active Neutral Point-Clamped Five-Level (ANPC-5L) inverter for Renewable applications. It overcomes the shortcoming of ANPC multilevel converters proposed in the recent literature such as excessive voltage stress on devices, utilization of half the dc-link voltage and the requirement of larger than double the dc-link voltage as compared to the grid peak voltage. Therefore, in this paper, a dual-mode ANPC converter is presented which promises the merits of reduced device stress over a wide range of dc input voltages for grid connected operation. The proposed topology is designed with standard T-type modules using 10 power devices and four dc-links and has the features of bidirectional power flow with an integrated flying capacitor (FC) technique. Moreover, it can be operated in two distinct modes such as boost mode and buck mode for a wide range of the input voltage. Simple level-shifted/phase-shifted pulse width modulation scheme is used for both the boost and a buck mode operation to realize the five-level output voltage waveform. A simple proportional-resonant (PR) controller is developed to study the dynamic response of the system under input voltage and their modes of operation using MATLAB/PLECS software and their results are presented. Finally, a detailed comparison is made with the recent ANPC-5L inverter topologies to highlight the merits of the proposed topology.**

***Index Terms*—Active neutral point-clamped inverter, T-Type structure, PR controller, Pulse width modulation.**

I. Introduction

Ever increasing interest on low voltage and widely varying dc sources such as battery, fuel cell and photovoltaic-based power generations, has led to the government and industries looking at various applications like Electric vehicles, Transportations, smart grids, Micro grids and Telecommunication systems etc. Power electronics is a key technology to interface effectively the renewable sources into the power grid [1],[2]. Recently, multilevel converters have been extended to the low voltage applications with reduced device counts and to provide better quality of output voltage.

This work was supported by the Science and Engineering Research Board under SIRE Fellowship Award SIR/2022/000864.

Among the various multilevel inverters(MLIs), the neutral point-clamped (NPC), flying capacitor (FC) and cascaded H-bridge (CHB) inverters are popular and often used. Whereas the new version of active neutral point-clamped converter (ANPC) with integrated flying capacitor (FC) structure is getting more attention due to features that make it simple to operate, and easily scalable for more output voltage levels with single dc source for both single-phase and three-phase applications. It finds applications in electric vehicles and can operate in two distinct modes of vehicle to grid(V2G) and grid to vehicle(G2V) operations with an added advantages of reduced voltage/current stress on the power devices. The conventional ANPC is derived from the concept of NPC replacing the diodes with two power devices with the addition of one flying capacitor for medium voltage industrial applications given in [3]. The same concept is extended to T-type structure in the modified structure with 8 power devices in [4]. Efforts have been made on the improved in topologies and also their modulation schemes to improve the FC/dc-link voltage balancing. However, the major shortcoming of these topologies is half dc-link voltage utilization demands double the grid peak voltage to produce the desired ac output voltage for grid connected renewable energy applications.

In order to overcome the above limitations, an improved ANPC is proposed with eight power devices to realize the 5L operation and with reduced dc-link voltage to two-fold to achieve the unity gain operation [5]. This topology is built with the concept of switched-capacitor(SC) based voltage gain, and it is modular, and can be extended for large number of output voltage levels. Moreover, a novel six switch-based ANPC-5L is reported in [6] as the number of components and dc-link voltage is reduced to half making it easy for various low voltage applications like rolling mills, fans, pumps, tractions etc. Numerous investigations are going on to achieve high voltage gain based on ANPC-MLIs using SC-based/FC concepts. However, the challenge is the effective utilization of dc-link and the resultant voltage stress across the power devices. This challenge necessitated the development of a new dual-mode (DM) operation based ANPC inverters for wide input voltage variations in [7]-[9]. Fig. 1 shows the two distinct operating conditions with the polarization characteristics of fuel-cell and output characteristics of lithium-ion battery. It can be operated in boost mode for the input voltage in the range of $\sqrt{2}V_{rms}$ to $2\sqrt{2}V_{rms}$ and in the buck mode for the higher input dc-link of $2\sqrt{2}$ V_{rms} to $4\sqrt{2}$ V_{rms}. The typical duty ratio for the above transitions is for the modulation index (M_a), which ranges between 0.5 to 1. However, the large dc-link voltage can overstress the converters during the buck mode i.e. more than $4\sqrt{2}V_{rms}$ [10]. The DM concept is tested for the different structures of ANPC-5L operations in [12]. Further, the same concept is extended for dual boost-ANPC-5L inverter with reduced device stress.

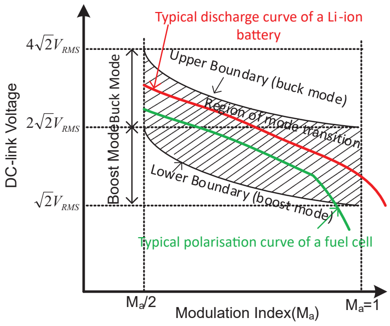


Fig. 1. Illustration of dual-mode converter boundary conditions in both boost mode and buck mode operations and its applications to Li-ion battery or fuel-cell [12].

Therefore, the present study aims to develop a new single-phase DM-ANPC-5L inverter with the features of reduced stress across the devices and FCs during buck operation. The proposed DM-ANPC-5L converter is constructed based on two standard T-type modules available in market and two discrete bidirectional power devices with four dc-link capacitors. The main merit of the proposed topology is to reduce the stress voltage across the devices/FCs making it more applicable for transient operation conditions, i.e., varied dc-link voltage from 400 V to 800 V and vice versa. Therefore, the complete operation of the proposed topology in both boost and buck mode and their control schemes are extensively analyzed in Section II. Section III gives a comprehensive analysis of various five-level inverters. Section IV presents the simulation work carried out in MATLAB/PLECS software for a wide range of input voltage and the stress across the devices. Finally, Section V concludes the paper.

II. Proposed DM-ANPC-5L Inverter

Fig. 2 shows the proposed single-phase DM-ANPC-5L inverter for renewable applications. The structure is constructed using two cascaded T-type circuit as S_2, S_3, S_5, *and* S_6, S_7, S_8, and two bidirectional dc decoupling switches S_1, S_4 with a total of 12 power devices. It demands single gate driver circuits for the four-quadrant operation of each power device S_1, S_4, S_5, and S_6. It is capable of operating in both boost mode as well as a buck mode with reference to the input dc voltage. It is apparent that the dc-link capacitors C_{FC1}, C_{FC2} remain the same during the boosting and act as Flying capacitors (FCs) during buck operation. One of the modest advantages of these operations is the allowance for wide input dc voltage changes with reduced stress across the devices and full utilization of the dc-link voltage.

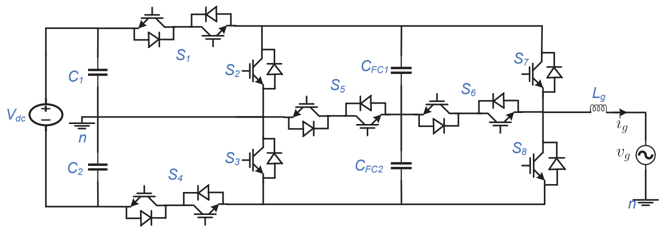


Fig. 2. Single-phase DM-ANPC-5L inverter structure.

Fig. 3 illustrates the current direction path for the DM-ANPC-5L inverter during boost mode operation. It has five distinct modes such as 0, $\pm\frac{V_{dc}}{2}, and \pm V_{dc}$ The capacitor C_{FC1}, C_{FC2} act as dc-links and supply power to the grid and the full dc-link voltage is utilized during this boost mode. Moreover, only two switches are in conduction in every level, which is an added benefit of the proposed topology and leading to higher efficiency of operation.

Similarly, Fig. 4 depicts the current direction path for the buck operation. It has eight distinct modes of operation such as 0, $\pm\frac{V_{dc}}{4}, and \pm \frac{V_{dc}}{2}$. Here the switched capacitor is acts as a flying capacitor and is charged to a voltage of $\pm\frac{V_{dc}}{4}$ which is 25% of the dc-link voltage. The current flowing to the grid (i_g) is similar for all the devices as well as capacitor. It is worth mentioning that the charging of FCs is carried out through the switches S_1 *and* S_4. It has two redundant states (RSSs) and utilized for generating $\pm\frac{V_{dc}}{4}$ output voltage levels. The current stress is same as the grid current stress during this buck operation. It also requires two switching devices for every level generation much like boost operation mode which results in reduced conduction losses in the proposed DM-ANPC-5L inverter. Moreover, the following expression highlights the above discussed mode of operation for maximum output voltage of the inverter and the FCs voltage under steady-state condition are as follows:

$$V_{in} = \begin{cases} M_{max}V_{dc}, & \text{for boost mode} \\ 0.5M_{max}V_{dc}, & \text{for buck mode} \end{cases} \tag{1}$$

$$V_{FC1} \& V_{FC2} = \begin{cases} 0.5V_{dc}, & \text{for boost mode} \\ 0.25V_{dc}, & \text{for buck mode} \end{cases} \tag{2}$$

Where, M_{max} is the maximum modulation index.

Figs. 5(a)–(d) depicts the details of modulation strategy used for both the modes of operation, various switching states, and the maximum stress voltage across the power devices. Level-shifted pulse width modulation scheme (LS-PWM) is implemented during the boost operation mode since there are redundant states for FC voltage balancing during this mode. On the other hand, two redundant states are available

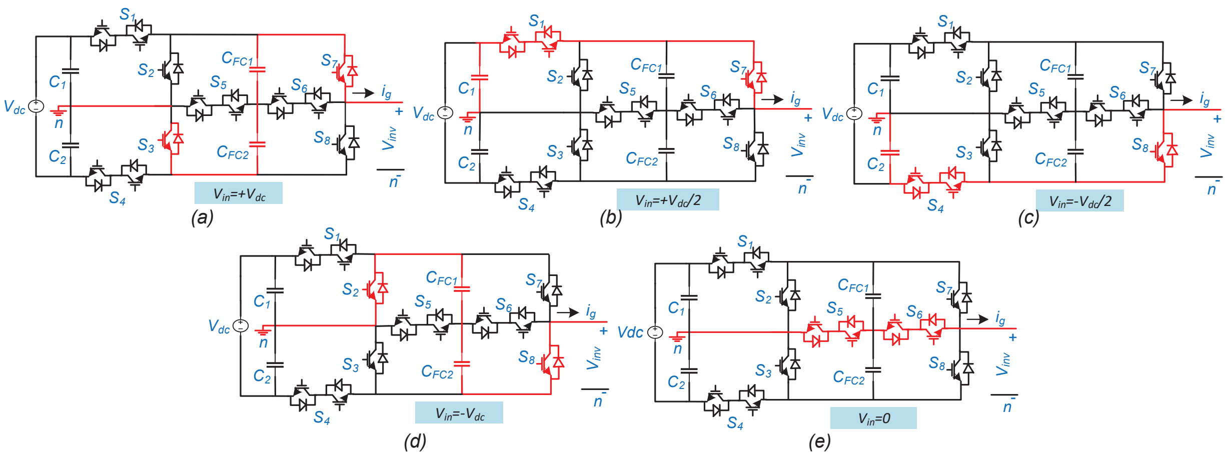


Fig. 3. Different current flowing path for the proposed DM-ANPC-5L inverter during boost operation mode at (a) V_{in}=+V_{dc}, (b) V_{in}=V_{dc}/2, (c) V_{in}=-V_{dc}/2, (d) V_{in}=-V_{dc} and (e) V_{in}=0

in the buck mode operation during the middle level $\pm\frac{V_{dc}}{4}$ generations. In order to balance the FC voltages and ensure effective utilization of the dc-link voltage, in this mode phase-shifted pulse width modulation (PS-PWM) scheme is used. The switching signals generated for the eight power devices are apparent. It consists of two carriers (A_a & A_b) compared with one modulated (M_a) fundamental sine waveform. The major difference between LS-PWM and PS-PWM is so well known that the effective switching and apparent switching are same in LS-PWM whereas the apparent is double the amount in case of PS-PWM compared to effective switching.

Fig. 6 shows a complete closed loop controller implemented in this study to regulate the output voltage of the DM-ANPC-5L inverter. It inherits the features of dc-link neutral point regulation, FC voltage balance and injecting current in the grid at the desired output voltage. During the boost operation mode, the capacitors are self-balanced while the regulation of dc-link capacitor and flying capacitor balancing is not mandatory. In buck mode, however, these two additional control blocks are required to balance the dc-link as well as the flying capacitor voltage. Simple phase-locked loop (PLL) is used to detect the phase and amplitude of the grid voltage (v_g) and for the synchronization of converter with the grid. The injected grid current is calculated from the given real and reactive power reference as desired using the following simple equation:

$$i_g^* = \frac{2P_g^*}{V_m}\cos\omega t \pm \frac{2Q_g^*}{V_m}\sin\omega t \tag{3}$$

The grid reference is compared with the actual injected grid current, and the error is passed through PR controller which is close to the sinusoidal modulated output waveform. Simple proportional-integral (PI) controllers are used to balance the dc-link voltage (u_0) as well as flying capacitor voltage balancing (Δu) and these states are enabled during the buck operation mode and added to the modulated sine waveform ($M_a\pm\Delta u$) which is compared through LS/PS-PWM signals. When the flying capacitor voltage changes from V_{dc} to $V_{dc}/4$ is becomes challenging task during the mode changes and also inrush current flowing through it needs to be limited by using some value of parasitic resistance in the charging path. Moreover, to achieve a smooth transition between the modes of operation the reference value is adjusted as per the desired values in the control loop.

III. Comparative Analysis

Table I shows the comparison of various ANPC-5L inverter proposed in the recent literatures [3]-[12]. It can be noticed that the comparison is primarily focused on the device count, output voltage gain, maximum voltage stress, FC balancing and bidirectional capability. Some of the topologies like active boost neutral-point clamped (ABNPC) and common grounded based converters do not have the bidirectional features and also possess larger gain in output voltage in the buck mode. The switched capacitor concept leads to large current stress on the device in both modes of operation. The DM-ANPC based topologies require more components unlike proposed topology which demands very few components. However, the structure of the proposed DM-ANPC-5L using T-Type is simpler and compact as compared to the other DM-ANPC-5L inverters. In addition, only two devices are in conduction, which shows that the proposed topology as higher efficiency compared to other ANPC-5L inverter even it requires two more additional devices. The maximum voltage stress across the devices is also same as in other ANPC-5L inverters with the features of dual mode operation and effective utilization of dc-link input voltage, which is an added advantage of the proposed DM-ANPC-5L inverter.

IV. Simulation Results

In order to realize the five-level output voltage waveform during the boost and buck operation modes, the simulation work was carried out in MATLAB/PLECS software. The study was performed for a switching frequency of 20 kHz and the modulating fundamental sine waveform of 50 Hz. The dc-link capacitors of 670μF and FCs of 470μF with some parasitic

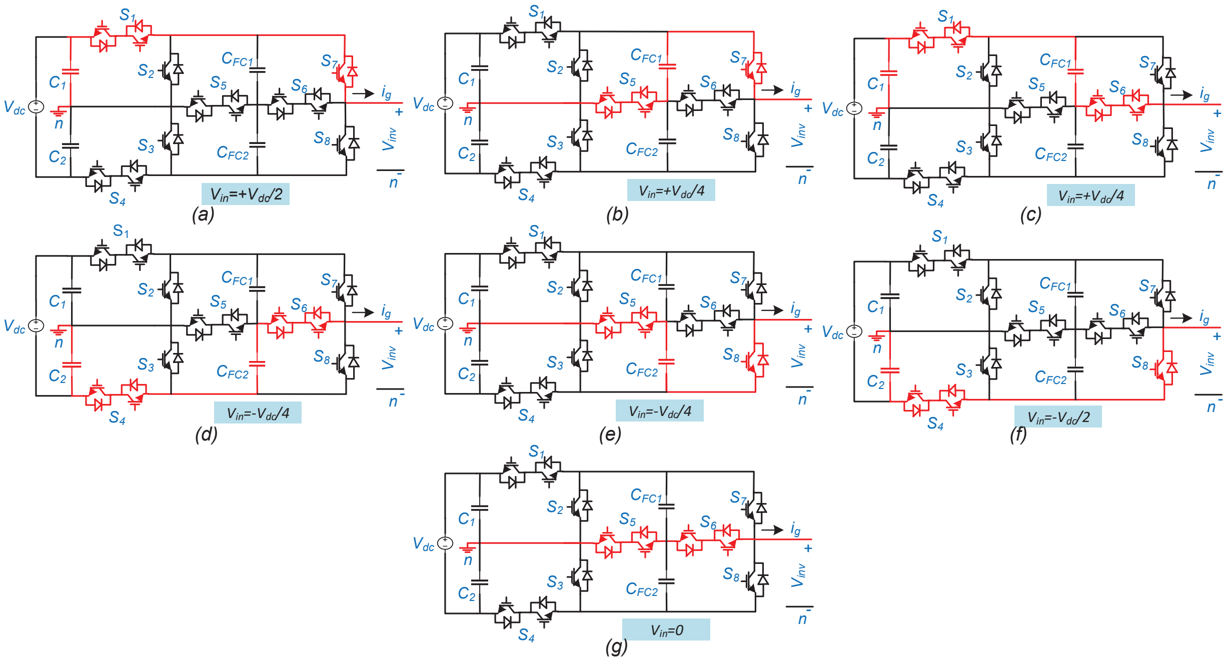
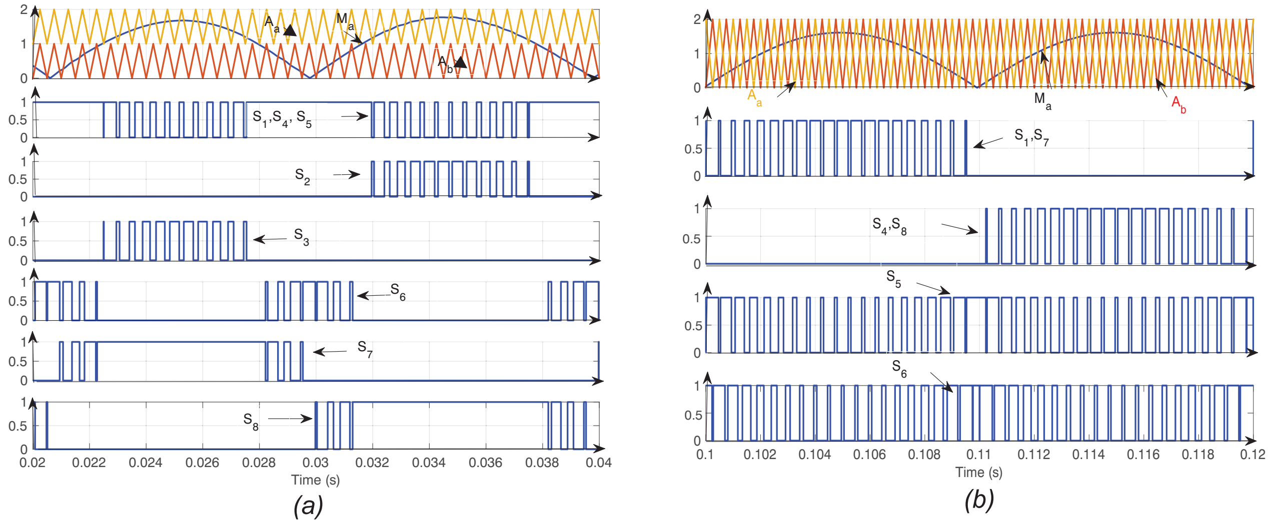
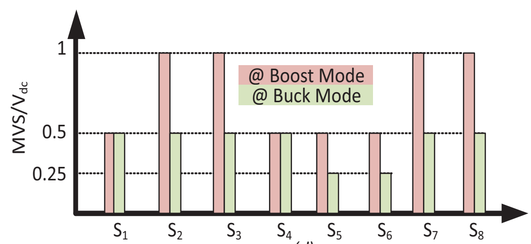


Fig. 4. Different current flowing path for the proposed DM-ANPC-5L inverter during buck operation mode at (a) V_{in}=+V_{dc}/2, (b) V_{in}=+V_{dc}/4, (c) V_{in}=+V_{dc}/4, (d) V_{in}=-V_{dc}/4, (e) V_{in}=-V_{dc}/4, (f) V_{in}=-V_{dc}/2, and (g) V_{in}=0.



Switching States	@ Boost Mode				@ Buck Mode			
	On Switches	C_{FC1}	C_{FC2}	Vinv	On Switches	C_{FC1}	C_{FC2}	Vinv
1	S_5, S_6	--	--	0	S_5, S_6	--	--	0
2	S_1, S_7	▲	▲	+V_{dc}/2	S_1, S_6	▲	--	+V_{dc}/4
					S_5, S_7	▼	--	
3	S_3, S_7	▼	▼	+V_{dc}	S_1, S_7	--	--	+V_{dc}/2
4	S_4, S_8	▲	▲	-V_{dc}/2	S_5, S_8	--	▲	-V_{dc}/4
					S_4, S_6	--	▼	
5	S_2, S_8	▼	▼	-V_{dc}	S_4, S_8	--	--	-V_{dc}/2

(c)



(d)

Fig. 5. Modulation strategy for the proposed DM-ANPC-5L inverter, (a) Level-shifted PWM method in the boost mode, (b) Phase-shifted PWM in the buck mode, (c) switching states and FC balancing and (d) the MVS across the switches in both modes.

TABLE I
COMPARISON OF VARIOUS ANPC-5L INVERTERS

Type of Converter	No. of Components				Output Voltage Gain	MVS/ Vdc	FC-balancing	Bidirectional
	S	D	C	G				
ANPC[3]	8	0	3	8	0.5	0.5	FC	Yes
ABNPC[10]	10	2	3	10	1	0.5	SC	No
CG[11]	9	1	2	8	4	1(2)	SC	No
DM-ANPC[12]	10	0	3	6	0.5(1)	0.75(1)	FC(SC)	Yes
DM-ANPC[12]	10	0	3	8	0.5(1)	0.5(1)	FC(SC)	Yes
Dm-ANPC[12]	10	0	4	7	0.5(1)	0.5(1)	SC	Yes
Proposed	12	0	4	8	0.5(1)	0.5(1)	FC(SC)	Yes

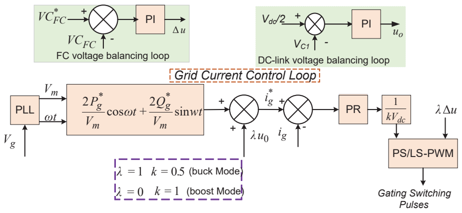


Fig. 6. Grid current control loop with PR controller.

resistance were connected in series to limit the charging current flowing through the FCs as discussed in the above sections. The input voltage changes from 400V to 800V for a grid voltage of 230Vrms. Fig. 7 shows the response of DM-ANPC-5L inverter under boost operation mode. It can be noticed that the dc input voltage changes from 800V to 400V at 2 sec, while the dc-link capacitor voltages are reduced to V_{dc} of 200V and the FCs remain the with the same 200V voltage level. The output voltage maintained constant values of 400V and injected steady current into the grid at 1kW real power. Similarly, Fig.8 shows the response of DM-ANPC-5L inverter under buck operation mode. Here, the capacitors C_{FC1} and C_{FC2} were operated as FCs i.e., both the flying capacitors balancing circuit and dc-link capacitor's balancing circuit were operating and regulating the FCs voltage to $V_{dc}/4$ and the dc-link voltages to $V_{dc}/2$. This shows that the developed controller performs well and changes mode transition from either buck to boost or boost to buck as per the desired condition and injects current into a grid with good quality of output waveforms. Moreover, the current drawn from the source is equal to the grid current under boost operation mode, which shows that the insertion of some parasitic resistance effectively minimizes the inrush current.

Fig. 9 shows the current stress and voltage stress across the devices under boost operation mode at steady state conditions. Most of the switches draw current same which is the same as grid current except the switches S_1 and S_4. The voltage stress on four devices is $0.5V_{dc}$ and other four devices as equal to V_{dc}. During the transition from boost to buck operation mode, the FCs and dc-link voltage is reduced to $V_{dc}/4$ to $V_{dc}/2$ which results in three switched are operating at $0.25V_{dc}$ and five devices at $0.5V_{dc}$. This is an advantage of the proposed DM-ANPC-5L inverter and the same is illustrated in Fig.

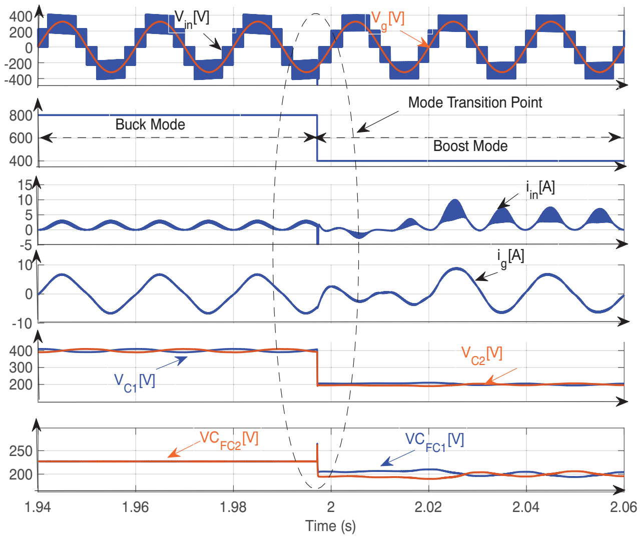


Fig. 7. Response of inverter output voltages, grid voltage, input current, grid current, DC-link and FCs voltage at P=1 kW during buck to boost operation mode.

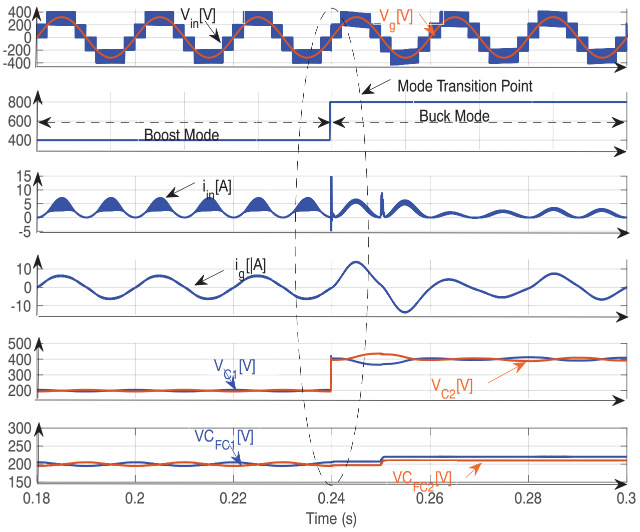


Fig. 8. Response of inverter output voltages, grid voltage, input current, grid current, DC-link and FCs voltage at P=1 kW during boost to buck operation mode.

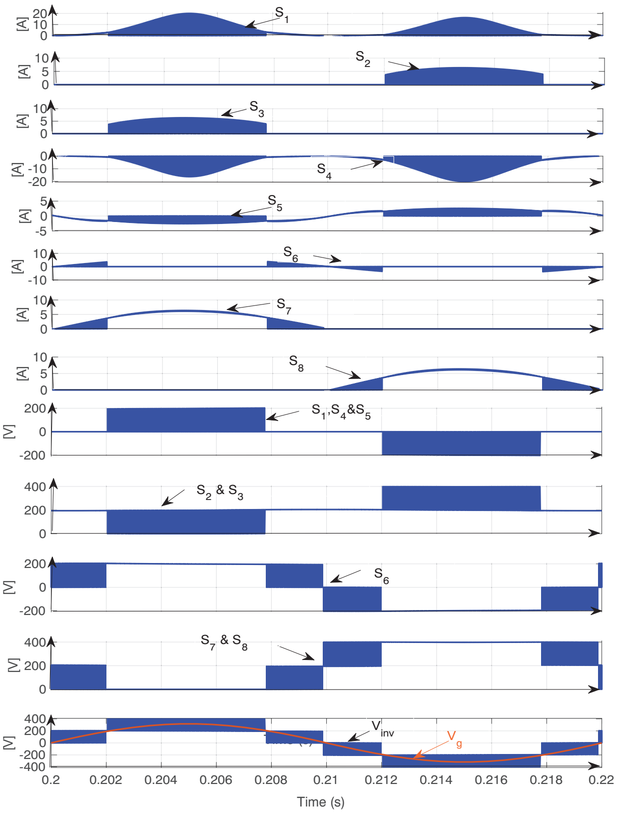


Fig. 9. Simulation results of current and voltage stress across various devices during boost operation mode at steady-state grid connected condition.

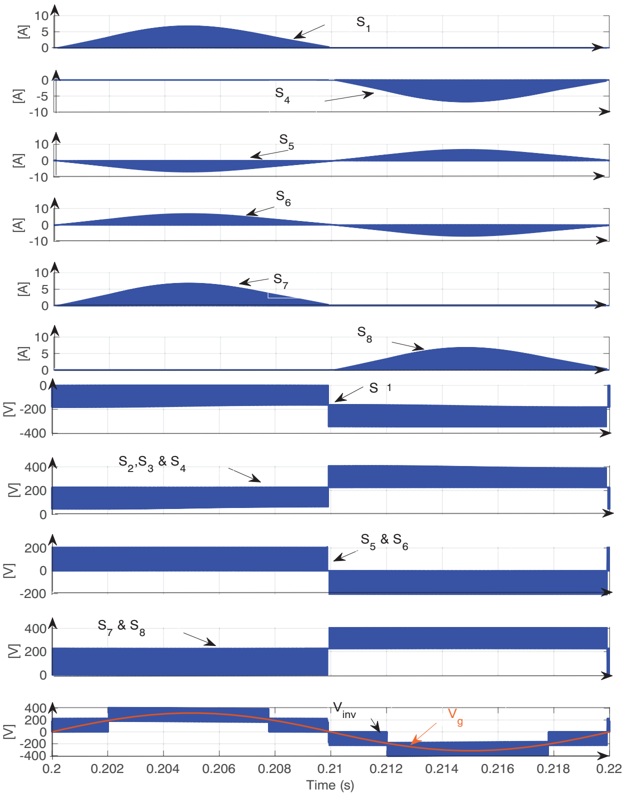


Fig. 10. Simulation results of current and voltage stress across various devices during buck operation mode at steady-state grid connected condition.

10. Form the above analysis, it can be understood that the proposed DM-ANPC-5L inverter performs well during boost and buck mode operations and uses 100% dc-link input voltage with reduced stresses on the devices. This reduced stress is a positive sign and is therefore the most opted for solution for renewable applications for a wide range of input voltage changes.

V. Conclusion

This paper presents a new single-phase DM-ANPC-5L inverter for renewable applications for a wide range of input dc voltage. The advantage of the proposed DM-ANPC-5L inverter is addressed under boost and buck operation modes in terms of full utilization of dc-link, neutral point voltage regulation and effective grid current injection. It is capable of ensuring higher efficiency as compared other ANPC-5L inverters since only two switches were in conduction at each level of power generation. The control scheme developed with LS/PS-PWM performs well and balances both the dc-link and FCs voltage during the mode transition periods. Finally, the proposed DM-ANPC-5L inverter was tested and validated through simulation analysis.

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