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Analysis of Modulation Strategies for Two-Stage Interleaved Voltage Source Inverter Employed for PV Applications

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***Abstract*- This paper deals with the investigation of interleaved voltage source inverter for photovoltaic applications. This topology focuses on the reduction of inductor current ripple content, total harmonic distortion (THD) of the proposed topology. In addition, the filter size is reduced when compared to single-stage voltage source inverter. The design of filter for the proposed topology is highlighted. The paper discusses the different modulation strategies for the proposed topology with different values of modulation index. A comparison made between the different strategies is reported. And comparison is done between single-stage and two-stage voltage source inverter with chosen modulation strategies. Simulation studies of the proposed VSI are carried out in MATLAB/SIMULINK.**

***Index Terms* --- Interleaved voltage source inverter, total harmonic distortion (THD), modulation strategies, and filter size.**

I.INTRODUCTION

PV panel is connected to the ac grid through voltage source inverter (VSI). The technique proposed in this paper is interleaving which increases the efficiency of the inverter topology. This paper deals with a two-stage VSI due to reduced component requirement and space restriction. The interleaving inverter is a special type of voltage source inverter which phase shifts two or more voltage source inverter connected in parallel. The angle between two inverter is chosen based on minimization of rams grid current ripple of the interleaved inverters [1].Interleaving uses the paralleling technique, which means single channel is replaced by N number of channels connected in parallel. Converter channel are paralleled with phase shifted switching instant. By introducing a phase shift, the amplitude of the total ripple current is N times less and its frequency is N times greater than that of a conventional inverter. A two-level inverter topology reduces the inductor current ripple current for a given switching frequency, thus reducing the size of the filter requirement. [2].Use of smaller lower current power switches which can switch at high frequency is enabled because of current sharing among a number channels thus allowing a reduction in inductor size. Hence filter size and overall size of the system are reduced [3]. The multiphase interleaved topology has been recently gaining popularity especially in dc/dc converters for different power applications such as electric and hybrid electric vehicles, communication power supplies, power factor correction for small handheld tools, and power boost circuit for photovoltaic systems. The main motive for employing this topology in the above mentioned applications is increased power density, better dynamic performance, and increased efficiency. In addition, the interleaved topology has been used in dc/ac and ac/dc converter applications. The reduction in total current ripple and the high frequency also eliminates the need for a second output filter inductor.

Different modulation strategies have been analysed for the proposed topology and the performance of two-stage interleaved voltage source inverter is analysed. The modulation strategies investigated are

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fundamental frequency switching, unipolar PWM and space vector PWM. The performance parameters taken into consideration for comparison are total harmonic content (THD) of load current and ripple content of inductor current. From the analysis, the best modulation strategy is applied to the interleaved inverter and further it is compared with single- stage voltage source inverter. The results are verified.

II. INTERLEAVED VOLTAGE SOURCE INVERTER

Interleaving voltage source inverter is nothing but paralleling N number of voltage source inverter with phase shifting the carrier wave [4]. In this paper, two voltage source inverter is interleaved with phase shift of 180 degree. The phase shifting pattern is shown in Fig.1. The PWM technique interleaves or phase-shifts the converter switching cycles, which is done by phase shifting the gate control signals of the converters. To represent such phase-shifted switching cycles, the interleaving angle k is (0≤ ß≤2π, or 0°≤ ß≤360°).

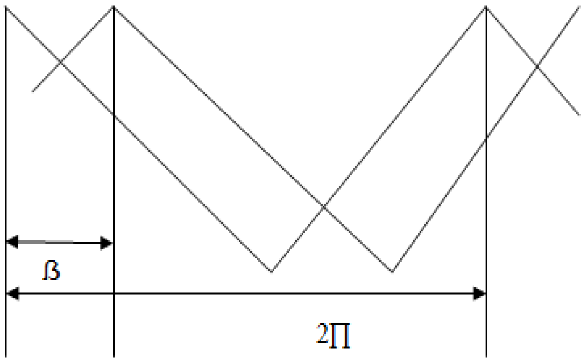

Fig.1. Phase-shifted carrier waves of two parallel-connected inverters

The schematic circuit diagram and modes of operation are depicted in Figs.2 &.3. Two voltage source inverter is interleaved through filter inductance. The output of each channel is connected to a point of common coupling (PCC) to grid through filter inductance. Increasing the value of filter inductance reduces the size of circulating current. When two voltage source inverter is interleaved, the circulating current is generated due to differential component flow between two modules. Inverter with space vector pulse width modulation (SVPWM) also mitigates the circulation current. With interleaving technique, the top switches are connected to positive supply and bottom switches are connected to negative supply. When switches are turned off, the three-phase current will flow through the top switches of one module, filter inductance and bottom switches of another module, this is circulating current which increase the stress over the source and power loss and hence it has to mitigated. Due to this phase shift, the total harmonic distortion (THD) in the output current and ripple content present in the inductor current is reduced. Inverter works on180 degree conduction mode. At any interval, three switches will conduct and zero voltage level is eliminated compared to single-stage voltage source inverter. During each interval, two upper switches of inverter1 and one lower switch of inverter2 will conduct and vice-versa. With this working principle, zero vectors are eliminated.

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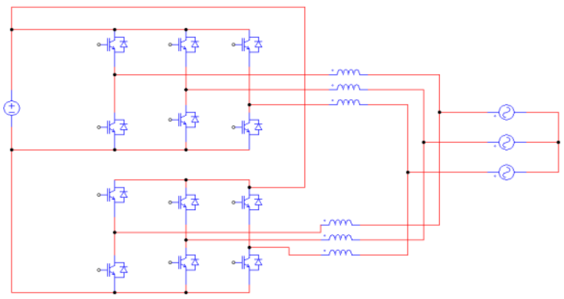
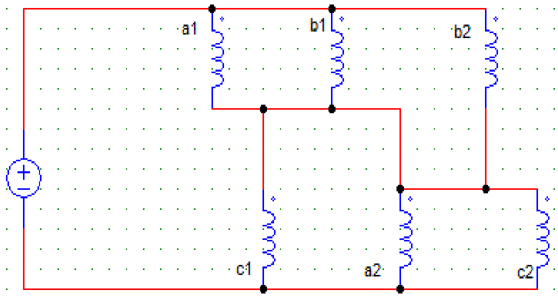
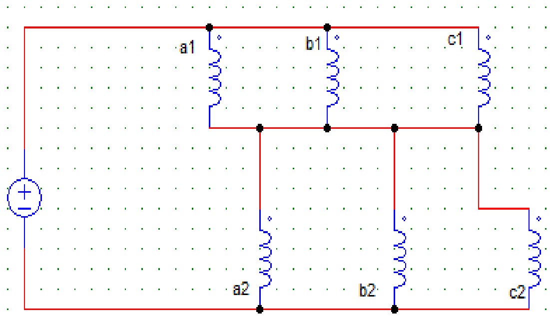


Fig.2. Circuit diagram of a two-stage interleaved voltage source inverter.



(a)



(b)

Fig.3 Circuit diagram during switching states, suffix 1 denotes inverter 1 and suffix 2 denotes inverter 2 (a) during period T_3 and (b) during period T_4.

The switching interval T_{sw} is divided into six periods T_1 to T_6. During every switching interval, different switching states are applied. Fig.3 shows the inverter's equivalent circuit diagram during the periods T_3 and T_4. The different switching states are shown inn Table I. which shows that the voltage across the inductor during T_3 is VL1 a = $+V_{dc}/3$ and zero during T_4. However, if two interleaved inverters are employed, the voltage across the inductor is V_{L1} a = $V_{dc}/2$ during T_3 and T_4. During T_3, with single-stage inverter, two upper switches will conduct and produces $+V_{dc}/3$ and with interleaved inverter, three switches will conduct and produces $+V_{dc}/2$. During T_4, with single-stage inverter voltage across the inductor is zero but with interleaved inverter, the voltage level is $+V_{dc}/2$. This shows that the voltage levels appear across the inductor are $+V_{dc}/3$, $-V_{dc}/3$, and 0 if single inverter is employed but with two interleaved inverter, the inverter voltage levels appear across the inductor are only $\pm V_{dc}/2$. The same principle applies when $N > 2$ [5].

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TABLE I. Inverter Switching States

Period	Inverter1 Space vector ($A_1 B_1 C_1$)	Inverter 2 Space vector ($A_2 B_2 C_2$)	V_{L1-a}	
			Single inverter	Two inverter
T_1	000	111	0	$-V_{dc}/2$
T_2	010	110	$-V_{dc}/3$	$-V_{dc}/2$
T_3	110	010	$+V_{dc}/3$	$+V_{dc}/2$
T_4	111	000	0	$+V_{dc}/2$
T_5	110	010	$+V_{dc}/3$	$+V_{dc}/2$
T_6	010	110	$-V_{dc}/3$	$-V_{dc}/2$

III. MODULATION STRATEGIES

By performing different gating pattern, the performance of the topology differs and its performance parameter is evaluated. With different modulation strategies, the switching pattern varies and hence total harmonic distortion varies [6-7]. The proposed inverter topology is simulated in MATLAB/SIMULINK with different modulation strategies and simulation results are presented. The gating pattern of different modulation strategies is illustrated. Initially, the proposed topology is simulated with fundamental frequency reference signal and variable frequency reference signal. The generation of gating pattern of fundamental frequency is shown fig.4. The pulse is generated at fundamental frequency and pulse generated is given to the respective switches. With variable frequency reference signal, the modulation strategies implemented is unipolar PWM. Further, space vector PWM is also discussed. The pulse generation of different PWM techniques are presented. In unipolar PWM, the sine wave is compared with triangle carrier wave and generated pulse is given to the inverter1 but to inverter2, switching instant is interleaved at 180 degree. In unipolar PWM, ripple content present in the inductor current is minimized [8]. Space vector modulation is implemented for the proposed topology. The magnitude and angle of space vector is determined and confirms that magnitude of space vector remains the same.

A. FUNDAMENTAL FREQUENCY SWITCHING

The pulse to the inverter1 is generated at 50Hz frequency and to the inverter 2 the pulse pattern is phase shifted to 180 degree. The pulse generation pattern and pulse generated in MATLAB/SIMULINK is shown in Fig.4. and Fig.5.

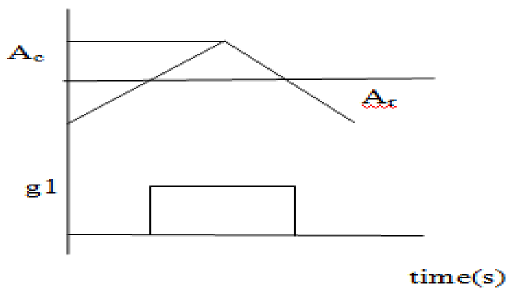

Fig.4. Pulse Generation of fundamental frequency switching

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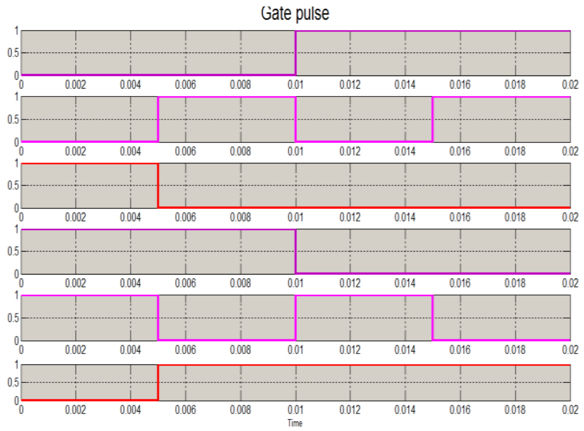

Fig.5. Pulse pattern of fundamental frequency switching

B. UNIPOLAR PWM

In unipolar pulse width modulation techniques, during positive half cycle, upper switches will conduct and during negative half cycle, lower switches will conduct. With unipolar PWM, the carrier signal at 1050Hz switching frequency is generated and compared with sinusoidal reference wave and generated pulse is given to the inverter1. To inverter2, carrier is phase shifted and compared with reference sinusoidal wave. The reference and carrier signal and pulse pattern is shown in Fig. 6, Fig.7 (a) and Fig.7 (b).

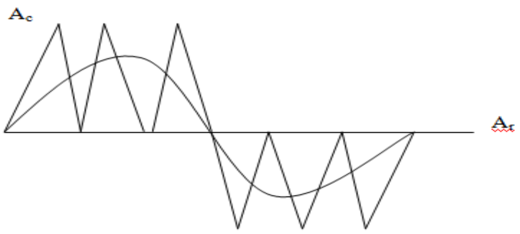

Fig.6. Reference and carrier wave of Unipolar PWM

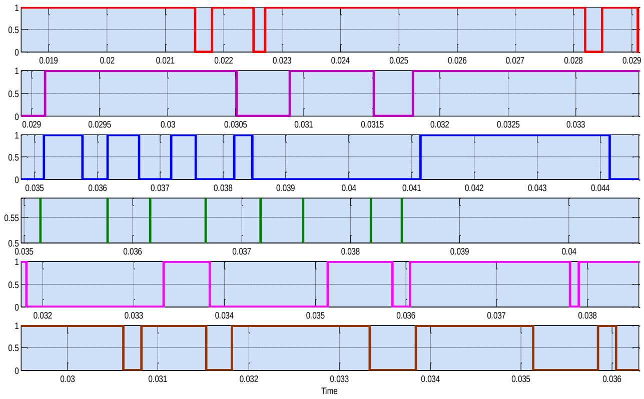

Fig.7 (a). Unipolar PWM pulse to inverter1

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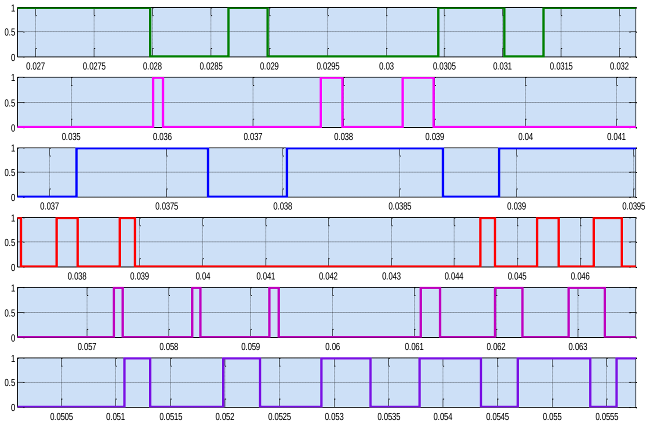

Fig.7 (b). Unipolar PWM pulse to inverter2

C. SPACE VECTOR MODULATION

Space vector modulation is a PWM technique which samples the reference periodically and after every sample, non-zero and zero switching vector is calculated. And suitable zero switching vector is selected to synthesize the reference signal [9]. With space vector modulation technique, switching state is analysed and space vector amplitude and angle is determined. The generated pulse is given to inverter1 and inveter2. Pulse pattern is shown in Fig. 8(a) and Fig.8 (b).

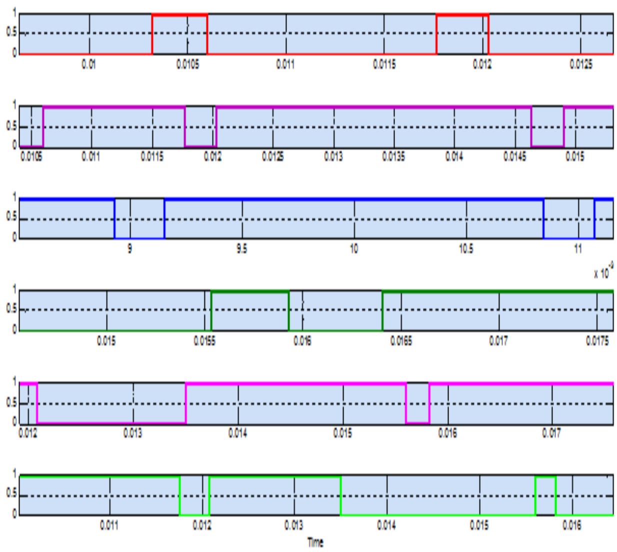

Fig.8 (a). Gating signal to inverter1 by Space vector modulation technique

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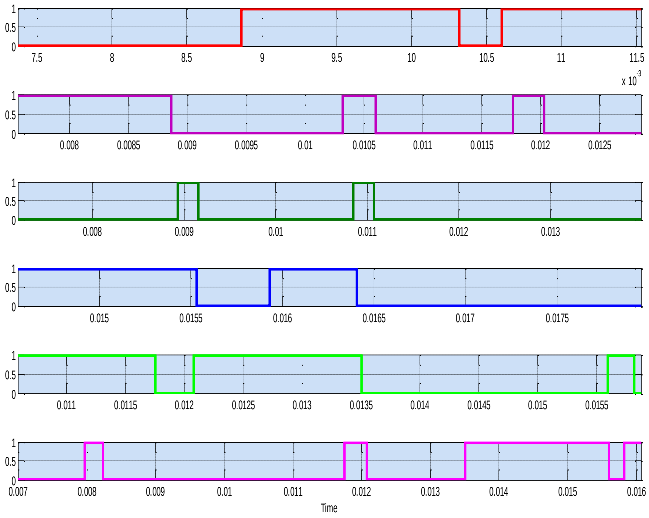

Fig.8 (b). Gating signal to inverter2 by Space vector modulation technique

IV. SIMULATION RESULTS

To simulate and analyse the performance of two-stage interleaved inverter, the software used is MATLAB/SIMULINK. Using MATLAB/SIMULINK two-stage VSI is analysed and compared with single-stage VSI [10].The THD of inverter grid current of two-stage voltage source inverter for different modulation strategies is compared. The result shows that the harmonic content is low for unipolar PWM technique with modulation index (m_a) equal to 0.8. The inverter output voltage and output current of two-stage voltage source inverter with fundamental frequency and other modulation strategies are shown in Figs.9 to Fig.15. The output current of single-stage voltage source inverter is shown in Fig.16.

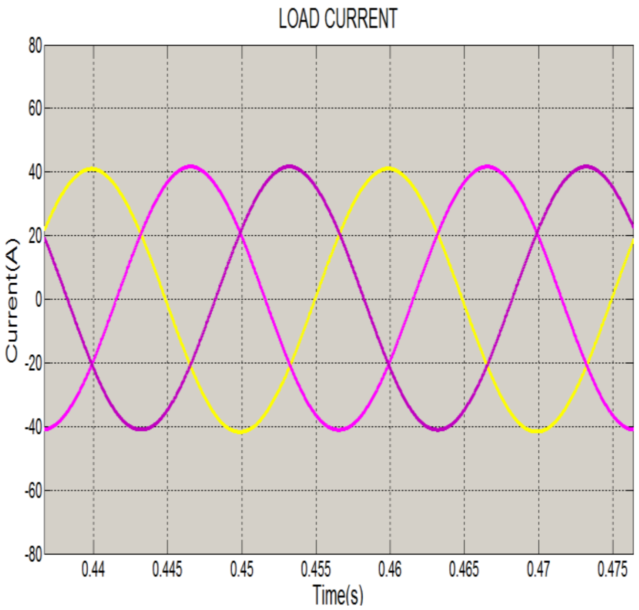

Fig.9. Output Current of two-stage Interleaved Inverter with Unipolar PWM

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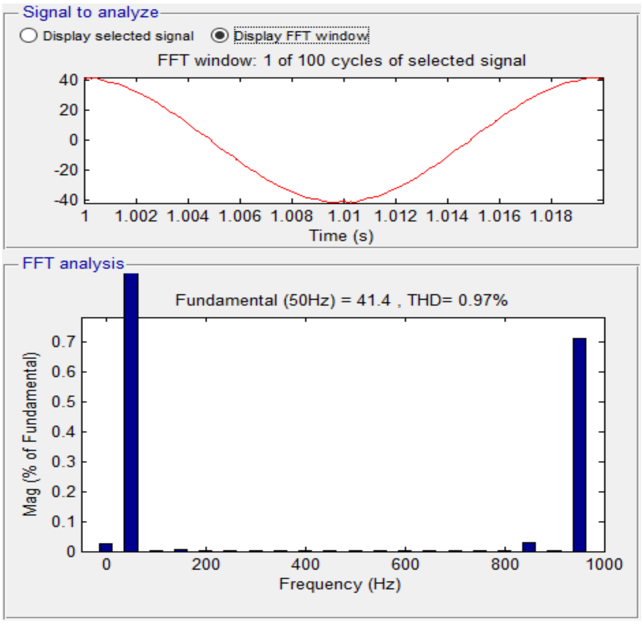

Fig. 10 . FFT analysis of ouput current of Unipolar PWM

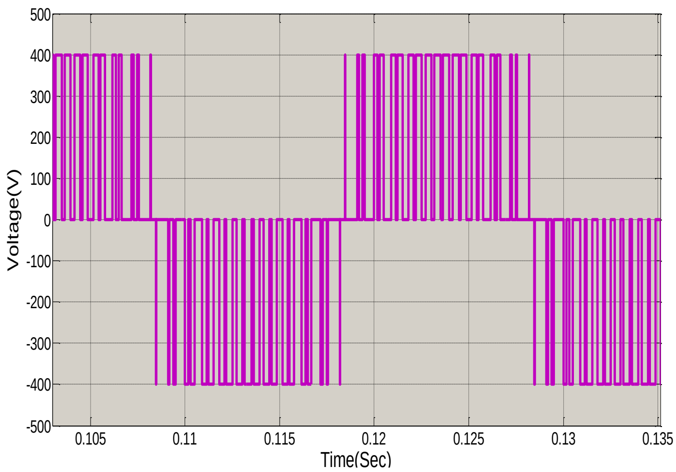

Fig.11. Load voltage of two-stage VSI with unipolar PWM modulation technique

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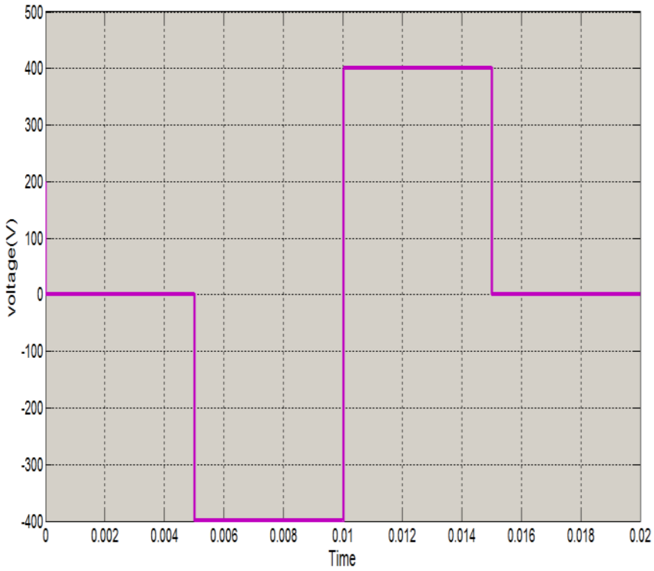

Fig.12. Load voltage of two-stage VSI with fundamental frequency switching

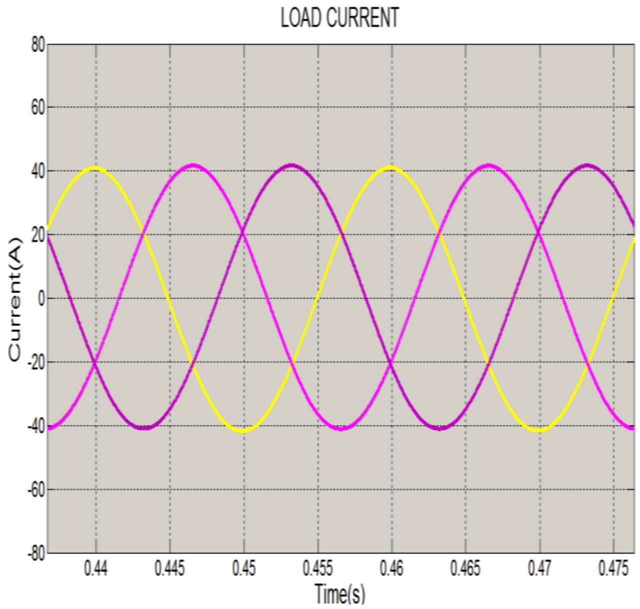

Fig.13. Output Current of two-stage Interleaved Inverter with Fundamental Frequency switching

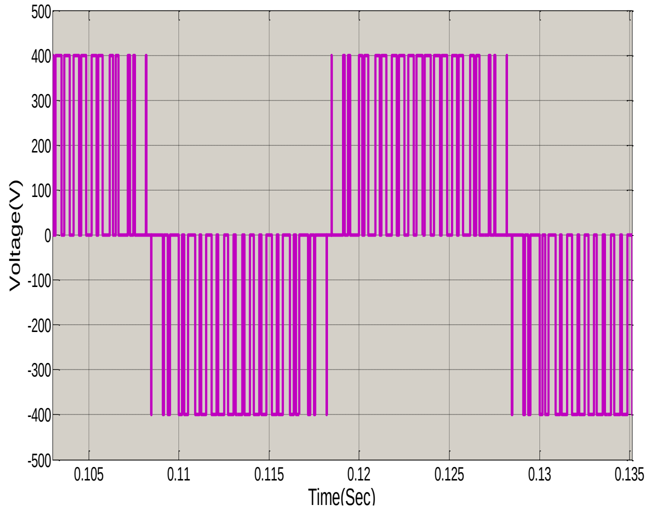

Fig.14. Load voltage of two-stage VSI with Space vector PWM modulation technique

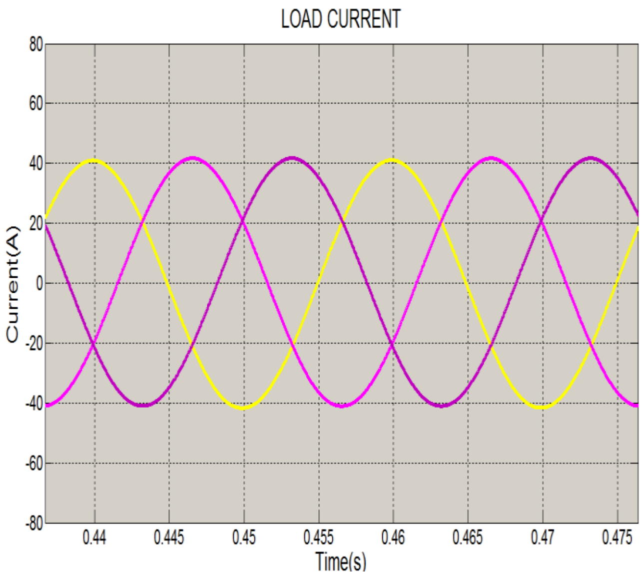

Fig.15. Output Current of two-stage Interleaved Inverter with Space vector modulation

The total harmonic distortion (THD) of output current of proposed VSI with different modulation strategies is computed and compared. From the analysis, it is concluded that unipolar PWM modulation strategy is the best compared to fundamental and space vector because of low harmonic content. The output current of single-stage voltage source inverter is shown in Fig.16.The THD of load current for the different modulation methods are depicted in TABLE II. The result shows that interleaving voltage source inverter with unipolar PWM is the best compared to single-stage voltage source inverter.

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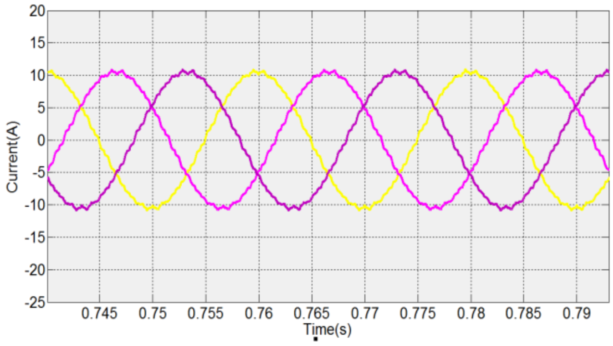

Fig.16. Output current of single-stage voltage source inverter with unipolar PWM

TABLE II. COMPARISON OF VOLTAGE SOURCE INVERTER

TOPOLOGY	OUTPUT CURRENT THD	INDUCTOR CURRENT RIPPLLE CONTENT
Unipolar SPWM	0.97	L_{ia}= 0.82 L_{ib}= 0.82 L_{ic}= 0.82
Fundamental frequency switching	1.07	L_{ia}= 1.46 L_{ib}= 1.38 L_{ic}= 1.20
Space vector PWM	0.92	L_{ia}= 2.59 L_{ib}= 2.60 L_{ic}= 2.59
Conventional single-stage voltage source inverter	2.33	L_{ia}= 2.33 L_{ib}= 2.33 L_{ic}= 2.32

From the above analysis, it is proven that the total harmonic distortion (THD) of two-stage interleaved inverter is lower than the single-stage voltage source inverter. The unipolar PWM is chosen as the best modulation method among other techniques because of lower THD and inductor current ripple content. And also, the analysis shows that at modulation index=0.8, the current THD is low, hence m_a =0.8 is chosen.

V. CONCLUSION

The two-stage interleaved voltage source inverter is investigated with different modulation strategies and its performance is analysed. From the comparison table, it is found that the unipolar PWM technique is effective among various modulation strategies for the proposed topology. And then the single-stage voltage source inverter is simulated with unipolar PWM and compared with two-stage interleaved VSI and proven that two-stage interleaved voltage source inverter has less total harmonic distortion and inductor current ripple content than conventional VSI. The harmonic content is low at 180 degree and hence 180 degree is chosen as interleaving angle. Therefore, interleaved voltage source inverter is a better candidature for PV applications.

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VI. FUTURE WORK

From the investigation, the best modulation strategies is chosen and it is implemented to the proposed topology. PV panel is modelled with MPPT algorithm and interfaced with two-stage interleaved voltage source inverter through DC-DC converter. A prototype is built to verify the simulation results. Performance parameters are computed to validate the chosen topology for PV applications.

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