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by Metta Savitri

Carrier Based PWM Methods of Dual Cascaded Inverter for Solar Power Plant Solid State Transformer

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***Abstract*— A new structure of solid state transformer (SST) for grid connected solar power plant is introduced in this paper. The SST utilizes dual cascaded multi-level inverter configuration. This paper investigates the performance of various PWM methods for the proposed SST. The dual cascaded inverter is controlled by using carrier based PWM methods, i.e Phase Shifted PWM, Level Shifted PWM and its variations. Simulation results show that the Overlapping Carrier (OC)-PWM method generates the highest fundamental component in the output. The Phase Disposition (DP)-PWM produces the best quality output voltage with the lowest value of THD (16,92%) among the PWM methods while the PS-PWM method provides the worst THD (39,41%). However, after filtering, the PS-PWM method generates the most sinusoidal waveform that indicates by significant improvement in the value of THD (0.029%). The PS-PWM is able to remove the low order harmonics better and send them into the around 4 kHz and it side band which is twice of the applied switching frequency (2 kHz).**

Keywords*— *Grid connected solar power plant, Solid state transformer, Carrier based PWM, dual cascaded inverter, THD

I. Introduction

Solid state transformer (SST) has been subject of research for decades. It attracts many interest since SST offers a lot of advantageous over the conventional transformer such as significant reduction in volume and weight, ability in voltage regulation and voltage disturbance rejection, bidirectional power flow and better automation and control algorithm [1,2]. Various configuration of SST has been discussed in literatures [3-5]. The most common structure consists of three stages of conversion procedures i.e input stage that consists of DC to AC conversion, middle stage consists of high frequency transformer and output stage consists of combination AC to DC and DC to AC conversion to convert the high frequency voltage into low frequency voltage (50 Hz). Recently, a new topology of SST has been proposed in [6]. Reference [6] proposes a SST for step down distribution transformer that comprises power electronics devices without applying high frequency transformer. In the proposed structure, the value of voltage is reduced using cascaded Buck Converter.

In Solar Power Plants, the DC voltage output of PV panels is converted into AC voltage and then increased into a certain level voltage hence it is suitable to connect with the other electricity sources. A step up transformer is required to increase the voltage to 20 kV to connect with the National Distribution Line. This paper proposes a Solid-State Transformer (SST) that is applied for a grid connected PV power plant.

The proposed SST adopts the same technique as proposed in [6]. Here, the voltage is increased by using Boost Converter. Since the gain of the Boost Converter is limited, a new structure is proposed by applying four inverters that are operate in dual mode of operation. Fig. 1 shows the proposed SST configuration. Output voltage of PV array is assumed has a fixed value and then increased by Boost Converter. The four inverters are set to produce a 50 Hz, 20 kV AC voltage. Fig. 2 shows the wiring of the dual cascaded inverter. The configuration is developed based on the structure that is proposed in [7] and [8]. It is shown that two of three-phase inverters are connected in cascaded to construct a three-level inverter configuration. Further the two set three-level inverters are operated in dual mode to achieve a higher gain and improved quality inverter output.

This paper investigates various PWM methods to control the inverters in the proposed structure as shown in Fig. 2. The PWM methods are based on Carrier Based PWM (CB-PWM). In CB-PWM method the output of the inverters are depend on the position of the carrier signals over the reference signal. A necessary adjustment is required due to the system applies the dual supply inverter configuration.

II. Carrier Based PWM Method

Carrier Based Sinusoidal PWM (CB-PWM) is a classical PWM method that operates by comparing the sinusoidal reference signal and the carrier signals. Carrier signals can be in form of triangular or saw-tooth signals. The pulses are generated using a simple logic as presented in equation (1)

$$M_i = \begin{cases} \text{If } v_{ref} \geq v_{car} \text{ then } 1 \\ \text{If } v_{ref} < v_{car} \text{ then } 0 \end{cases} \quad (1)$$

Equation (1) implies that if the reference signal (v_{ref}) is higher or the same with the carrier signals (v_{cr}) then the value of pulses is high (1) or switches are conducted (ON). In contrast, when the reference signal is lower than the carriers, then the pulses are low (0) means that and the switches are turned OFF. The number of the carrier signals used depends on the level of the inverter [9]. The number of the applied carrier signals is governed by equation (2). In the case of a 5-level inverter, 4 carrier signals are required.

$$m = (l - 1) \quad (2)$$

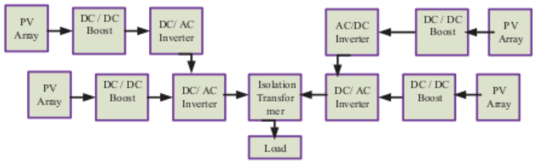


Fig. 1.Proposed Structure of Step up SST for Solar Power Plant

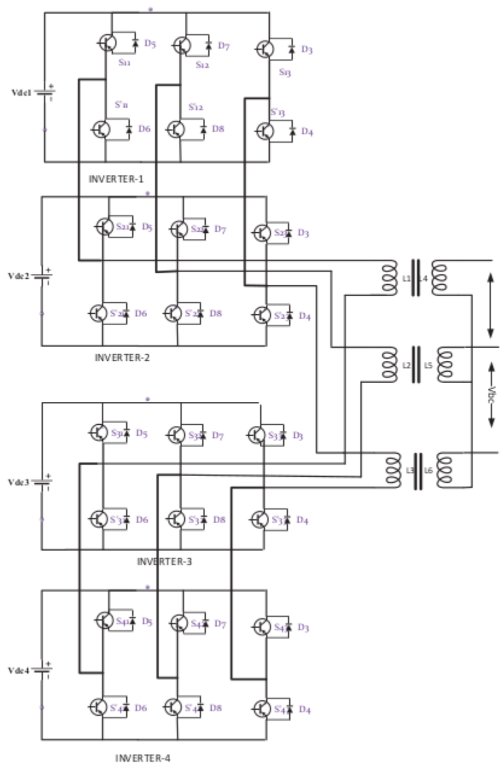


Fig. 2. Dual cascaded three-level inverters configuration

Where, *m* is number of utilized carriers and *l* is number level of inverter.

According to the position of the carriers, CB-PWM can be classified into 2 categories. When the carriers are placed in different phase but it has the same level, the method is known as Phase Shifted PWM (PS-PWM). While when the carriers are located in different voltage level, the method is known as Level Shifted PWM (LS-PWM).

A. Phase Shifted PWM Methods

In Phase Shifted PWM (PS-PWM), position of carriers is governed by using equation (3) [10], where φ_{cr} is phase displacement; *m* is number of the utilized carriers. In the case of 5-level inverter, four carriers is required and placed by 90° for the consecutive carrier, as shown in Fig, 3.

$$\varphi_{cr} = \frac{360^{\circ}}{(m-1)} \qquad (3)$$

B. Level Shipted PWM Methods

Level Shifted PWM methods can be classified into three groups according to the phase position of the carriers. When all carriers have the same phase the method is named as Phase Disposition PWM (PD-PWM) as shown in Fig. 4 (a). When the carriers in the positive side have the opposite phase with the carriers in the negative side, the method is named as Phase Opposition Disposition PWM (POD-PWM) as shown in Fig 4(b). The last, when the phase of the adjacent carrier is opposite in phase the method is termed as Alternative Phase Opposition and Disposition PWM (APOD-PWM) as shown in Fig. 4 (c) [11].

C. Adjustment of Carrier Position in Cascaded Inverter Configuration

In the system that applies dual supply configuration as shown in Fig. 2, the generated voltage is governed by equation (4) [12]. Hence, in order to achieve the proper value of the output voltage of inverters, the reference signal of the right side inverter must be opposite in phase with the reference of inverter in the left side. It is therefore the carrier position must be adjusted with respect of the respective reference signal.

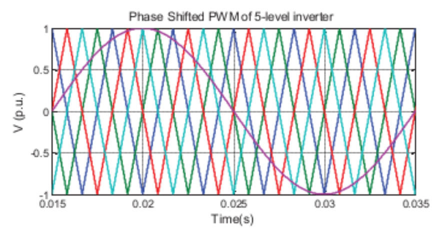


Fig. 3. Carrier arrangement of Phase Shifted PWM of 5-level inverter.

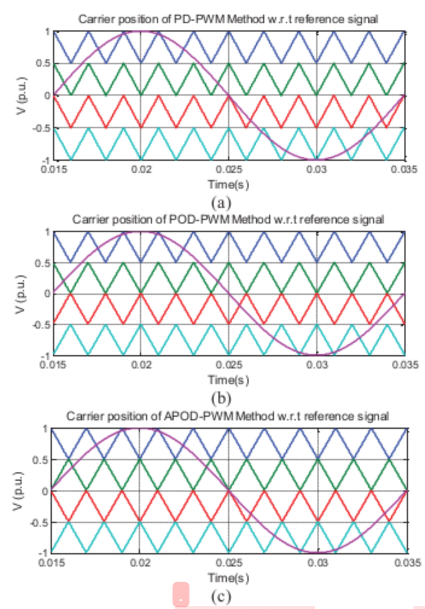


Fig. 4. Carrier position various Level Shifted PWM Methods; (a) Phase Disposition (PD) PWM (b) Phase Opposition Disposition (POD) PWM (c) Alternative Phase Opposition Disposition (APOD) PWM

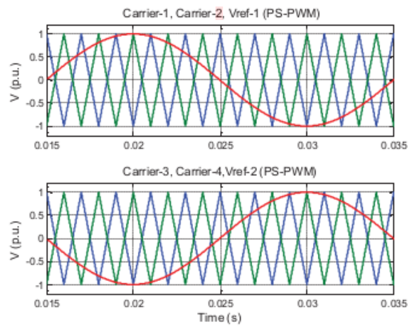


Fig. 5. Phase Shifted PWM method of the cascaded inverter.

$$v_a = v_a^* - v_a^{**},$$
$$v_b = v_b^* - v_b^{**}, \quad (4)$$
$$v_c = v_c^* - v_c^{**}$$

Where, v_x^* $_{(x = a,b,c)}$ is output voltages of the upper inverter and v_x^{**} $_{(x=a,b,c)}$ is output voltages of the lower inverter

The adaptation of the position of the carriers for the PS-PWM, PD-PWM is shown in Fig. 5 and Fig. 6 respectively. Adjustment of the carriers position of POD-PWM and APOD-PWM is not shown since they are applied the same way as PD-PWM. Fig. 5 and Fig. 6 apply 500 Hz frequency switching carriers in order to aid the clarity.

D. Variation of Level Shifted PWM Methods

Further development of LS-PWM methods are discussed in [13, 14]. In [13] variation of LS PWM is carried out by varying the frequency of the applied carriers. The frequency of the carriers in the top and in the bottom side can be lower the carriers in the middle side. In [14] variation also made by making the adjacent carriers overlap each other that affects the pattern of PWM pulses. Hence the output voltage is also influenced. Fig 7 and Fig 8 show the VF-PWM and OC-PWM methods applied in dual cascaded inverter structure respectively.

III. Results and Discusion

The proposed PWM methods are verified via simulation using Matlab/Simulink. The PWM signals are generated using Simulink and the Converters are modeled using SimPower BlockSet. DC-link input of the four inverters are 600 V and all inverters operate in 2 kHz switching frequency except for VF-PWM method. A three phase static RL load is attached in the middle point of inverter-2 and inverter 3. Simulation neglects the dead-time effect and the switches are assumed as ideal switches.

A. Patterns of the PWM Signals

PWM signals for phase 'a' upper switches of inverter 1, inverter 2, inverter 3 and inverter 4 for LS-PWM, PD-PWM are shown in Fig. 9 and Fig. 10. It is obvious that the LS-PWM operates the switches more frequently than the PD-PWM. Meanwhile the PD-PWM operates the switches alternately among the inverter. Further investigation revealed that the pattern of PWM signals of the PD-PWM, POD-PWM and APOD PWM is similar except the wide of

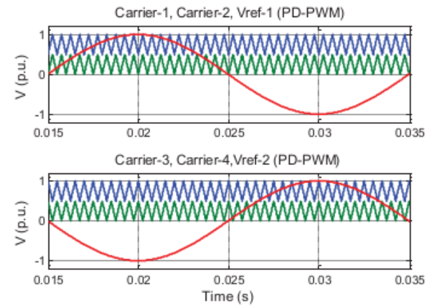


Fig.6. Phase Disposition (PD-PWM) Method of cascaded inverter

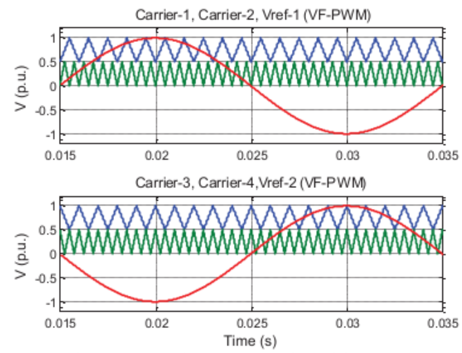


Fig. 7. Variable Frequency of PD PWM Method of the cascaded inverter

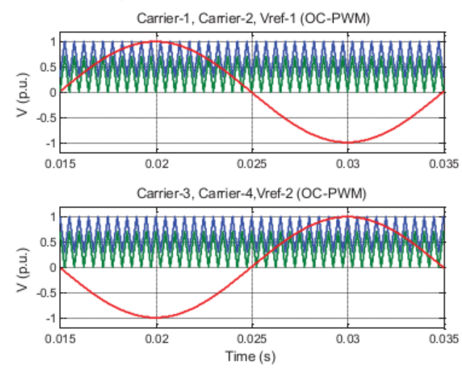


Fig. 8. Overlapping Carrier PD-PWM of the cascaded inverter

the pulses are vary due to the different position of the carriers hence they are not shown.

B. Inverter Output Voltages

The aforementioned PWM methods are applied in the cascaded inverters configuration that is shown in Fig. 2. Fig 11 shows the phase 'a' output voltage of inverters using PS-PWM method. It is revealed that the voltage waveform contains of 7 voltage level. The harmonics spectrum shows that the output voltage is free from the low order harmonics. The harmonics are successfully shifted into around 4 kHz and its side band. Although the harmonics component are removed into twice of switching frequency the THD of the voltage is still relatively high (39.68%).

Further the output voltages of the cascaded inverters controlled by PD-PWM, POD-PWM and APOD-PWM are shown in Fig. 12. It is clear that the voltage waveform is considerably improved which is denoted by higher number of voltage level in the outputs. The low order harmonics are shifted into around switching frequency of 2 kHz and its side band. The value of THD is also improved significantly as shown in the harmonics spectra. The value of THD are 16.9% 21.41% and 24.87 % for PD-PWM, POD-PWM and APOD-PWM respectively.

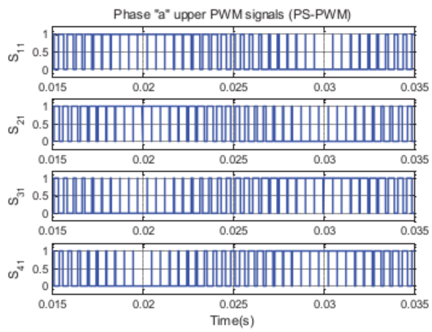


Fig. 9. Phase "a" upper switches PWM pattern of inverters using PS-PWM

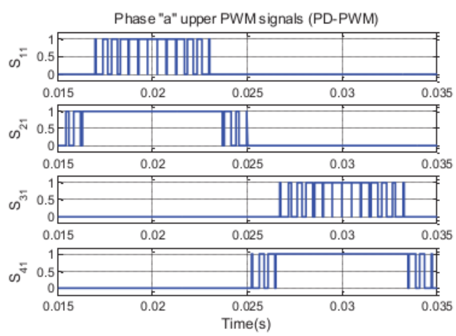


Fig. 10. Phase "a" upper switches PWM pattern of inverters using PD-PWM

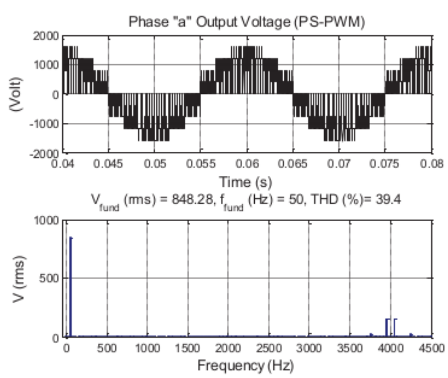


Fig. 11. Phase "a" inverter output voltage using PS-PWM method and harmonics spectra

Next, the performance of VF-PWM and OC-PWM are discussed. The output voltages of the dual cascaded inverters using VF-PWM and OC-PWM are shown in Fig, 13. It depicts that the performance of VF-PWM and OC-PWM is improved compared with the PS-PWM, POD-PWM and APOD PWM but the THD is still higher than the PD-PWM.

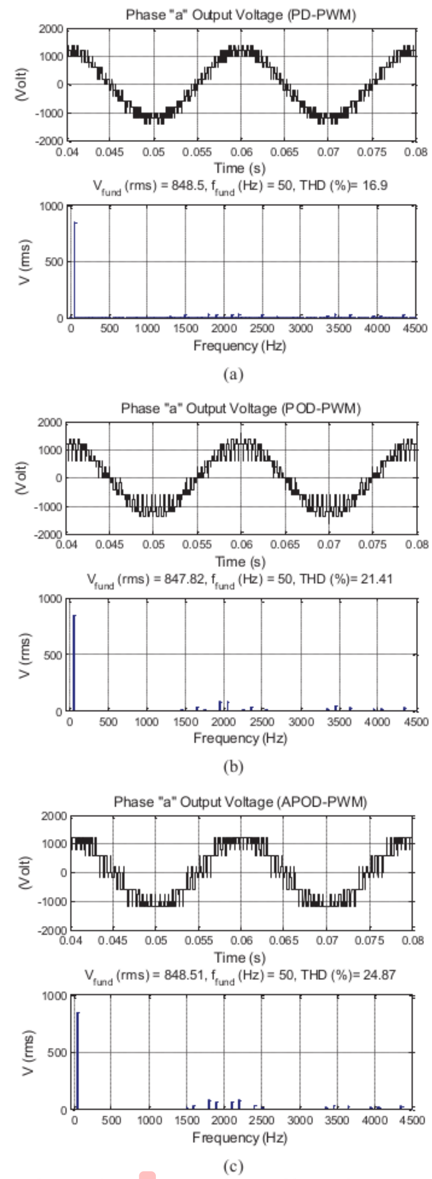
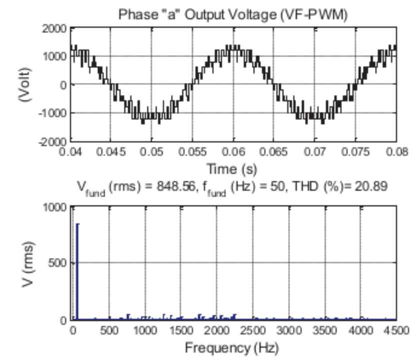


Fig. 12. Phase "a" inverter output voltage and harmonics spectra using various PWM Methods (a) PD-PWM, (b) POD-PWM (c) APOD-PWM

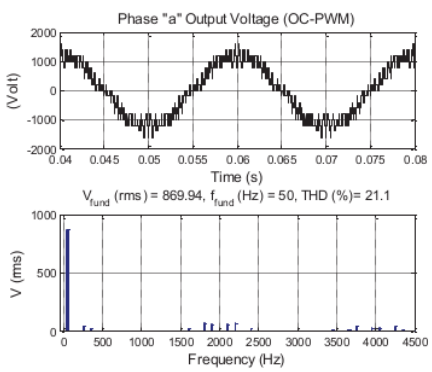
The values of THD of the VF-PWM and OC-PWM are 20.89 and 21,1 respectively. Observing the results above, it is clear that the performance of PD-PWM is the best among the PWM methods in term of the value of THD of the inverter output voltages. This finding has a good agreement with the result that is discussed in literatures [9,10, 11].

C. *Solid Stete Transformer Performance*

Subsequently, performance of the proposed Solid State transformer (SST) is discussed. The cascaded inverter in the SST applies Boost Converter to increase the DC voltage from PV array, hence reaches a particular voltage level for the distribution line. Fig. 14 shows the input and output voltages of the Boost Converter. It can be seen that the Boost Converter increases the 1600 Volt DC into 14400 Volt DC. The DC voltage then is inverted by the cascaded Inverter into around 20 kV AC as shown in Fig. 15 for the voltages with and without filter respectively. Fig. 16 and Fig. 17 show the voltage waveform of SST using PS-PWM for both with and without filter and its harmonics spectra. Performance of the proposed the SST with various PWM methods is resumed in Table I.



(a)



(b)

Fig. 13. Phase "a" inverter output voltage and harmonics spectra using (a) VF-PWM (b) OC-PWM

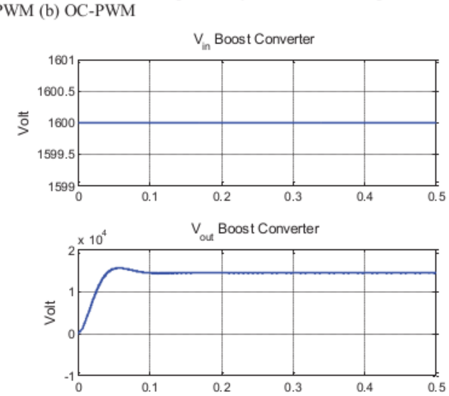


Fig. 14. Input – output voltages of Boost Converter

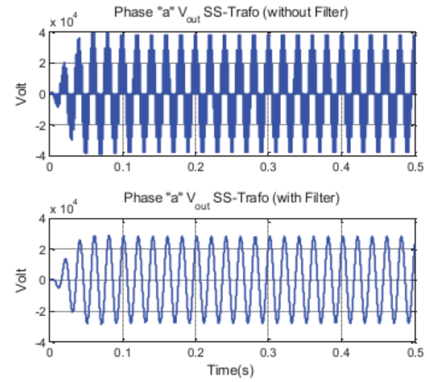


Fig. 15. Input – output voltages of Boost Converter

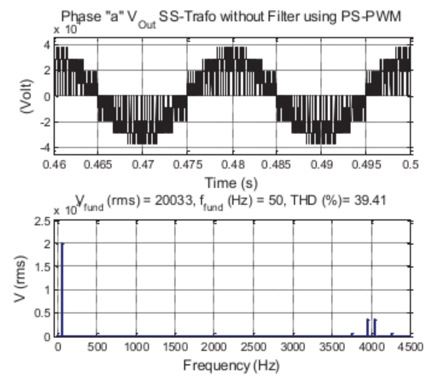


Fig. 16. Output voltage of SST with PS-PWM and harmonics spectra

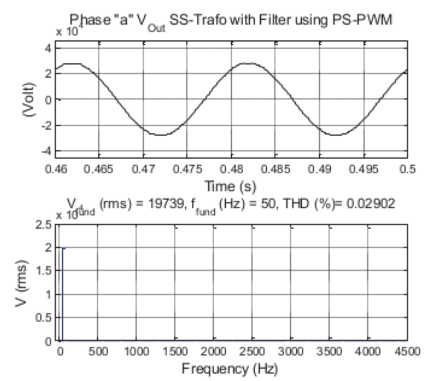


Fig. 17. Filtered output voltage of SST with PS-PWM and harmonics spectra

Table I reveals that the SST output voltages reach the expected value for distribution line i.e 20 kV except for the PS-PWM the output voltage after filter is slightly less than 20 kV (19739 V). Among the PWM methods, the OC-PWM provides the highest value of fundamental component i.e 20843 V and 20537 V for the voltages without and with filter respectively.

TABLE I. THE SST PERFORMANCE FOR VARIOUS PWM METHODS

PWM Methods	Solid State Transformer Performance			
	Without Filter		***With Filter***	
	rms Fund. Voltage (Volt)	***THD(%)***	***rms Fund. Voltage (Volt)***	***THD(%)***
PS-PWM	20033	39.41	19739	0.02902
PD-PWM	20369	16.92	20070	0,1932
POD-PWM	20349	21.43	20050	0.1109
APOD-PWM	20361	24.89	20062	0.2423
VF-PWM	20369	20.91	20070	0.4663
OC-PWM	20843	21.11	20537	1.197

However, in term of quality of the unfiltered voltage, the output voltage generated by the PD-PWM is the best among the PWM methods. This result indicates that the applied PWM method has significant influence to the output waveform. It is also shown in Table I that, after filtering, the PS-PWM performs the best result among the PWM methods. Although unfiltered voltage contains considerably high voltage THD (39.41%), yet the THD is significantly reduced after filtering (0.029%) which is the lowest among the PWM methods under investigation. It is happened because the PS-PWM has better ability in eliminating the low order harmonics by removing them into multiple around twice of its switching frequency.

IV. CONCLUSION

This paper discusses various PWM methods for Solid-State Transformer (SST) applied in Grid connected Solar Power Plant. The proposed SST consists of Boost Converters and Cascaded four three-phase two-level inverters. The PWM methods for the cascaded inverter is based on the carrier based PWM. Simulation results show that the proposed SST is successfully increased the DC output voltage of solar panel and converted into 20 kV AC voltage. Among the PWM methods, the OC-PWM method generates the highest fundamental component in the output. While the PD-PWM method produces the best output voltage before filter that indicates by the value of THD (16.92%) and the PS-PWM method provides the worst value of THD (39.41%). However, after filtering, the PS-PWM method generates the most sinusoidal waveform that is indicated by significant improvement in the value of THD (0.029%). The PS-PWM is able to eliminate the low order harmonics by removing them into multiple twice of its switching frequency.

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PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6