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Modeling and Simulation of Five-level Five-phase Voltage Source Inverter for Photovoltaic Systems

***Abstract**. This paper presents a space vector pulse width modulation (SVPWM) control for a five-level five-phase cascaded H-bridge multilevel inverter (CHMLI) for photovoltaic (PV) systems. The maximum power point tracking (MPPT) is solved by fuzzy logic controller (FLC) and it is capable of extracting maximum power from PV array connected to each DC link voltage level. The fuzzy MPPT is integrated with the inverter so that a DC-DC converter is not needed and the output shows accurate and fast response. This is done to achieve high dynamic performance with low total harmonic distortion (THD). The simulation results are compared with sinusoidal pulse width modulation (SPWM) controlled CHMLI and diode clamped multilevel inverter (DCMLI) in terms of THD. The results prove the viability and verify the effectiveness and accuracy of the proposed system.*

***Streszczenie.** W artykule zaprezentowano pięciopoziomowy, pięciofazowy kaskadowy przekształtnik CHMLI z modulacja szerokości impulsu SVPPWM przystosowany do pracy w układach fotowoltaicznych. Do śledzenia maksimum mocy zastosowano sterownik fuzzy logic FLC. Otrzymano dobre właściwości dynamiczne i mały poziom zniekształceń. (**Modelowanie i symulacja pięciopoziomowego, pięciofazowego przekształtnika w zastosowaniu do układów fotowoltaicznych**)*

Keywords: Voltage source inverter (VSI), Pulse width modulation (PWM), Maximum power point tracking (MPPT).
Słowa kluczowe: przekształtnik, modulacja PWM, śledzenie mocy, układy fotowoltaiczne.

1. Introduction

Multilevel inverters are increasingly being used in high-power medium-voltage applications due to their superior performance compared to two-level inverters. Different types of multilevel inverter topologies were presented [1]. The major advantages of using a multiphase machine instead of a standard three-phase machine were discussed [2]. The initial attempt to integrate a multilevel inverter with a multiphase machine carried out in [3] demonstrated the advantages of combining both technologies. Many methods of PWM techniques are used to control the inverter [4]. The multilevel SVPWM ON-time calculation problem is converted to a simple two-level SVPWM ON-time calculation problem was discussed [5].

The installation of PV generation systems is rapidly growing due to concerns related to environment, global warming, energy security, technology improvements and decreasing costs [6]. The modelling and an experimental investigation of SVPWM technique on a multilevel voltage source inverter for PV system with fuzzy MPPT was explained [7]. The reduction of harmonics on output voltage of the multilevel CHMLI for PV system was proposed [8], [9]. This paper proposes a system consisting of PWM technique is used to control the five-phase five-level VSI which is connected to the five-phase load as shown in Fig. 1.

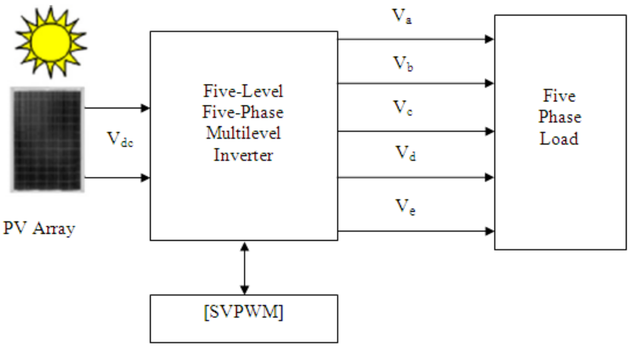


Fig.1. General diagram of the proposed system

The following are the salient features of the proposed scheme. The multilevel multiphase inverter is used to control DC bus voltage, to convert DC input to AC output at the same waveforms as the five phase lines and to ensure high quality of the output power. SVPWM leading to a simplicity and flexibility of optimizing the switching sequence with switching state redundancy. An intelligent control technique using FLC is associated to an MPPT control of the PV system. It aims to control the active and reactive power in an inverter connected to the five-phase load.

2. PV array modeling and simulation

The PV array used in the proposed system is KC200GT and it is simulated using a model based on [8] [10]. In this PV array, mathematical model can be expressed as Eq. (1)

$$I = I_{Photo} - I_{RSat}\ \{\exp[\frac{q}{A_D K_B T}(V + IR_{Se})] - 1\} - \frac{V + R_{Se} I}{R_P} \quad (1)$$

Eq. (1) shows that the non-linear output characteristics of solar cell. It is affected by temperature, radiation of solar and condition of load, where I_{Photo} is the photo current, I_{RSat} is the reverse saturation current, q is the electron charge $(1.6021747 \times 10^{-19} C)$, R_{Se} is the series resistance and R_P is the parallel resistance. Photocurrent I_{Photo} is directly proportional to the solar irradiation (G_{ira}). In Eq. (1) A_D is dimensionless factor, K_B is the Boltzmann constant $(1.38 \times 10^{-23}\ J/K)$ and T is the temperature.

$$I_{Photo}\ (G_{ira}) = I_{SC}\ (\frac{G_{ira}}{G_{iraS}}) \quad (2)$$

where I_{SC} short circuit current depends linearly on cell temperature and G_{iras} is the standard irradiation $(1000 W/m^2)$.

$$I_{SC}(T) = I_{SCSat}\,[1 + \Delta I_{SC}\,(T - T_{St})] \quad (3)$$

where ΔI_{SC} is the temperature coefficient and T_{St} is the standard temperature $(298° K)$. I_{Photo} and I_{RSat} depend on the cell temperature and solar irradiation and these can be mathematically expressed as

$$(4)\quad I_{Photo}(G_{ira},T) = I_{SCSat}\left(\frac{G_{ira}}{G_{iraS}}\right)\left[1+\Delta I_{SC}(T-T_{St})\right]$$

$$(5)\quad I_{RSat}(G_{ira},T) = \frac{I_{Photo}(G_{ira},T)}{e^{\left(\frac{V_{OC}}{V_t}\right)}-1}$$

where, V_t is thermal voltage.

3. MPPT control

FLC is associated to an MPPT in order to improve energy conversion efficiency under different environment conditions. To control a switch of the multilevel inverter, fuzzy logic MPPT control is used. The fuzzy logic consists of three stages: fuzzification, interference system and defuzzification. The fuzzification comprises the process of numerical crisp inputs in to linguistic variables based on the degree of membership to certain sets. The seven fuzzy levels are used: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). The value of input error (E) and the change in the error (ΔE) are normalized by an input scaling factor. FLC depend on shape of membership functions and rule base in [7]. The error can be chosen as $\Delta P/\Delta V$ because it is zero at the maximum power point. Then E and ΔE are defined as given in Eqs. (6-7)

$$(6)\quad E = \frac{P(k)-P(k-1)}{V(k)-V(k-1)}$$

$$(7)\quad \Delta E = E(k)-E(k-1)$$

The interference system of this paper Max-Min method is used. The defuzzification is used to convert from linguistic variable to a numerical crisp one again using membership functions.To compute the output of the FLC, centre of gravity method is used and the FLC output modifies the control output. The tracking of maximum power of a PV system by using FLC is shown in Fig. 2. It can be seen that the FLC tracks the operating point very quickly and faster than other MPPT techniques.

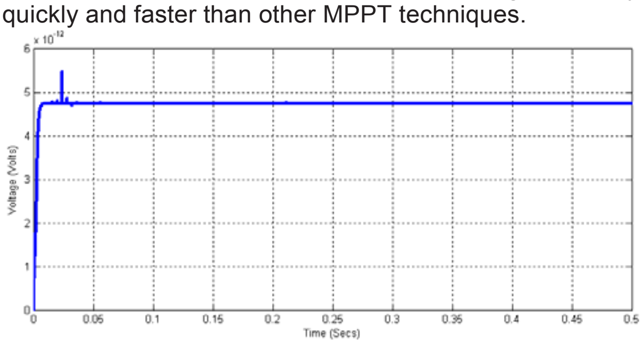


Fig.2. Fuzzy MPPT tracking

4. Five-phase five-level CHMLI topology

A one-leg circuit of five-phase five-level CHMLI circuit diagram is shown in Fig. 3. The phase output voltage is synthesized by the sum of four inverter output voltages $V_{an} = V_{a1}+V_{a2}+V_{a3}+V_{a4}$. Each inverter level can generate three different voltage outputs, $+V_{dc}$, 0 and $-V_{dc}$, by connecting the dc source to the ac output side by different combinations of the four switches, S_{p1}, S_{p2}, S_{n1} and S_{n2}. When the switches S_{p1} and S_{p2}, are turned *ON*, it gives $V_{a4} = +V_{dc}$. When the switches S_{n2} and S_{n1} turned *ON*, it gives $V_{a4} = -V_{dc}$. When the all switches are turned *OFF*, it gives $V_{a4} = 0$. If N_S is the number of dc sources, the output phase voltage level is $n = N_S + 1$. The relationship between the output voltage levels and switching states for the five-level CHMLI topology was discussed in [8]. Switches S_{px} and S_{nx} $(x = 1,2,3,4)$ are arranged in pairs and operate in a complementary mode where S_{px} as positive switches and S_{nx} as negative switches is discussed in [8].

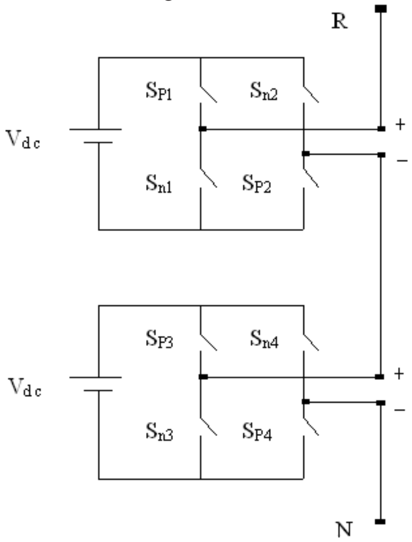


Fig.3. One-leg circuit of five-phase five-level CHMLI

5. Five-phase five-level DCMLI toplology

A five-phase five-level DCMLI circuit diagram for one-leg is shown in Fig. 4. The output voltage levels possible for one-phase of the inverter with negative DC rail voltage V_0 as a reference lists in [7]. The complementary switch pairs for phase leg a are $(S_{a1}, S_{a'1})$, $(S_{a2}, S_{a'2})$, $(S_{a3}, S_{a'3})$ and $(S_{a4}, S_{a'4})$. For a five-level inverter, a set of four-switches is ON at any given time. The each active switching device is required to block only a voltage level of V_{dc}, the clamping diodes require different ratings for reverse voltage blocking. Using phase a as an example, when all the lower switches $S_{a'1}$ through $S_{a'4}$ are turned on, D_3 must block four voltage levels, or $3V_{dc}$. Similarly, D_2 must block $2V_{dc}$, and D_1 must block V_{dc}.

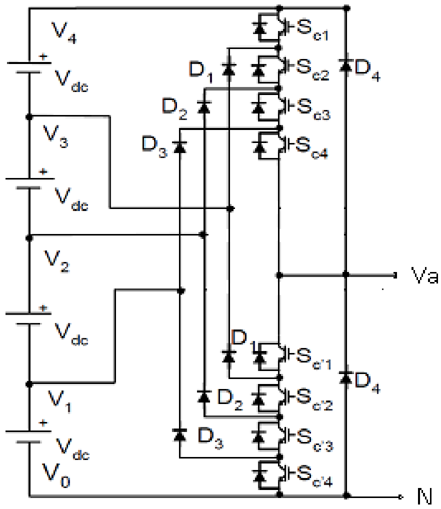


Fig.4. One-leg circuit of five-phase five-level DCMLI

6. PWM modulation

6.1. Five-level five-phase SPWM algorithm

Two sinusoidal five-phase leg voltage reference are generated on the basis of the required frequencies and voltage magnitude of the two machines as

(8) $V_{A1}^{*} = M_{M1}\,0.5V_{dc}\cos(\omega_{M1}t)$

$V_{B1}^{*} = M_{M1}\,0.5V_{dc}\cos(\omega_{M1}t-\alpha)$

$V_{C1}^{*} = M_{M1}\,0.5V_{dc}\cos(\omega_{M1}t-2\alpha)$

$V_{D1}^{*} = M_{M1}\,0.5V_{dc}\cos(\omega_{M1}t+2\alpha)$

$V_{E1}^{*} = M_{M1}\,0.5V_{dc}\cos(\omega_{M1}t+\alpha)$

(9) $V_{A2}^{*} = M_{M2}\,0.5V_{dc}\cos(\omega_{M2}t-\phi)$

$V_{B2}^{*} = M_{M2}\,0.5V_{dc}\cos(\omega_{M2}t-\alpha-\phi)$

$V_{C2}^{*} = M_{M2}\,0.5V_{dc}\cos(\omega_{M2}t-2\alpha-\phi)$

$V_{D2}^{*} = M_{M2}\,0.5V_{dc}\cos(\omega_{M2}t+2\phi-\phi)$

$V_{E2}^{*} = M_{M2}\,0.5V_{dc}\cos(\omega_{M2}t+\alpha-\phi)$

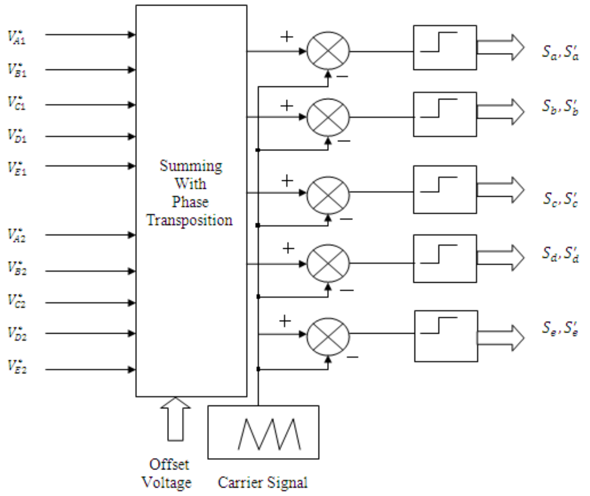


Fig.5. SPWM principle

Here M_{M1} and M_{M2} are the modulation indices of the two machines, subscripts $M1$ and $M1$ stand for the two machines, $\alpha = 2\pi/5$ and ϕ is the phase shift between two sets of leg voltage references. The voltage equations of the machines are summed according to phase transposition Eq. (10) to obtain total leg voltage references. The offset voltage is given as

(10) $offset = -0.5(V_{\max} + V_{\min})$ where,

$V_{\max} = \max(V_{A1}^{*}+V_{A2}^{*}, V_{B1}^{*}+V_{C2}^{*}, V_{C1}^{*}+V_{E2}^{*}, V_{D1}^{*}+V_{B2}^{*}, V_{E1}^{*}+V_{D2}^{*})$

$V_{\min} = \min(V_{A1}^{*}+V_{A2}^{*}, V_{B1}^{*}+V_{C2}^{*}, V_{C1}^{*}+V_{E2}^{*}, V_{D1}^{*}+V_{B2}^{*}, V_{E1}^{*}+V_{D2}^{*})$

Hence total inverter leg voltage references can be given

(11) $V_{A}^{*} = V_{A1}^{*} + V_{A2}^{*} + offset$

$V_{B}^{*} = V_{B1}^{*} + V_{C2}^{*} + offset$

$V_{C}^{*} = V_{C1}^{*} + V_{E2}^{*} + offset$

$V_{D}^{*} = V_{D1}^{*} + V_{B2}^{*} + offset$

$V_{E}^{*} = V_{E1}^{*} + V_{D2}^{*} + offset$

The block diagram of the multi-frequency carrier-based SPWM scheme with offset injection is shown in Fig. 5.

6.2. Five-level five-phase SVPWM algorithm

The SVPWM is used to approximate a reference voltage vector V_{ref} by means of a sequence of space vectors $S_l = \{V_{s1}, V_{s2}, ..., V_{sl}\}$ during modulation cycle.

(12) $V_{ref} = \frac{1}{T}\sum_{i=1}^{l} V_{swi} T_i$

where the sum of the intervals T_i must be equal to the modulation period T

(13) $\sum_{i=1}^{l} T_i = T$

The normalized reference V_{ref} must be calculated from the reference voltage vector and switching times can be normalized by the voltage step and switching period using the Eqs. (14-16).

(14) $V_{ref} = \frac{V_{ref}}{V_{dc}} \in R^{P}$

(15) $V_{swi} = \frac{V_{swi}}{V_{dc}} \in Z^{P}$

(16) $t_i = \frac{T_i}{T}$

Therefore, the reference vector and switching vectors belong to the multidimensional space R^{p}, where p is the number of phases of the converter. The normalized switching vectors V_{swi} belong to the multidimensional space of integer numbers Z^{p}. The normalized reference has to be decomposed into the sum of its integer part V_i and its fractional part V_f by using the Eq. (17).

(17) $V_{ref} = V_i + V_f$, $V_i = \mathrm{int}(V_{ref}) \in Z^{P}$

The elements of the fractional part of the reference have to be sorted out in descending order to obtain the vector V_f. The sorting process are summarized in the permutation matrix p will be used to rearrange the rows of the matrix $D^{\wedge}$ to obtain the matrix D. To extract the displaced switching vectors V_{di} from the matrix D.

(18) $$\begin{bmatrix} 1 \\ V_f^1 \\ V_f^2 \\ \vdots \\ V_f^P \end{bmatrix} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ V_{d1}^1 & V_{d2}^1 & \cdots & V_{dp+1}^1 \\ V_{d1}^2 & V_{d2}^2 & \cdots & V_{dp+1}^2 \\ \vdots & \vdots & \vdots & \vdots \\ V_{d1}^P & V_{d2}^P & \cdots & V_{dP+1}^P \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ \vdots \\ t_{p+1} \end{bmatrix}$$

The final switching vectors V_{swi} must be calculated by adding the integer part of the reference V_i to the displaced switching vector V_{di} according to the expression (19).

(19) $V_{di} = V_{swi} - V_i$

The time corresponding to each switching vector is calculated directly from components of $V_f^{\wedge}$ by Eq.(20)

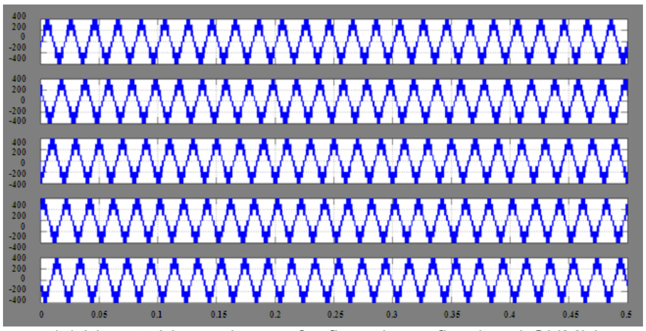
(20) $t_i = \{\, 1 - V_f^{\wedge 1},\ V_f^{\wedge i-1} - V_f^{\wedge i},\ V_f^{\wedge P}$, if

$i = 1, 2 \le i \le P, i = P+1$

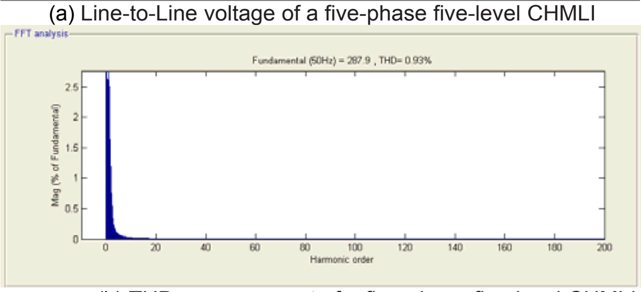
Finally trigger signals have to be generated from the switching vectors and the switching times.

7. Simulation results

Simulations are performed by using MATLAB/simulink for the proposed system. The SVPWM control signal is generated for CHMLI and the SPWM control signal is generated for CHMLI and DCMLI. The VSI operates with an input voltage of 100V dc source for each cell from PV array. This involves determining the position of reference vector according to fundamental frequency $(f = 50\,Hz)$, sampling frequency $(f_S = 10\,kHz)$ and time. According to sector wherein the reference vector, switching sequence is determined and to calculate the time for different switching states.

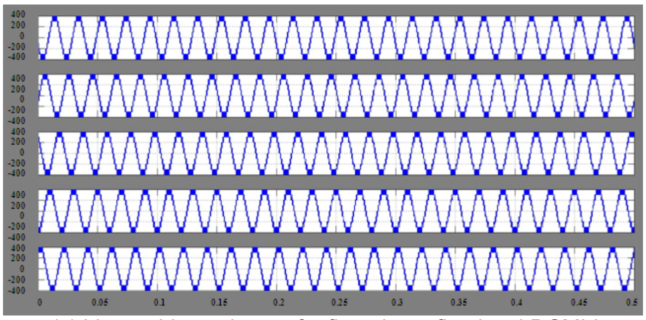


(a) Line-to-Line voltage of a five-phase five-level CHMLI

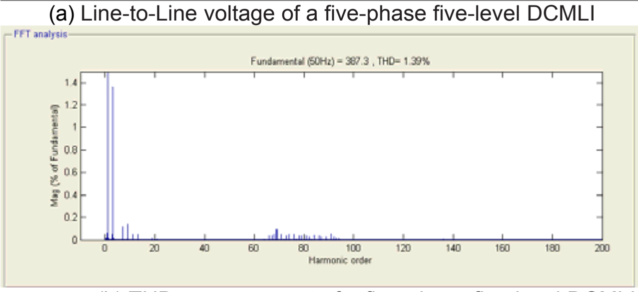


(b) THD measurement of a five-phase five-level CHMLI

Fig.6. Simulation result of a five-phase CHMLI with SPWM



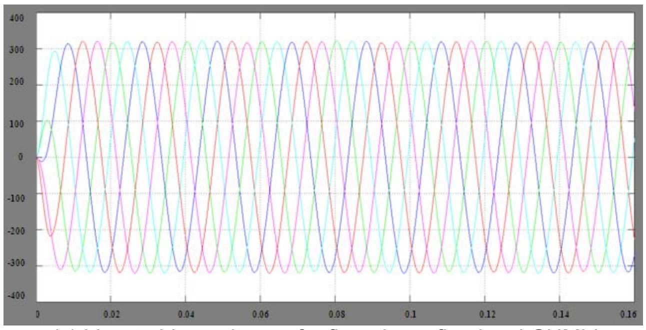
(a) Line-to-Line voltage of a five-phase five-level DCMLI



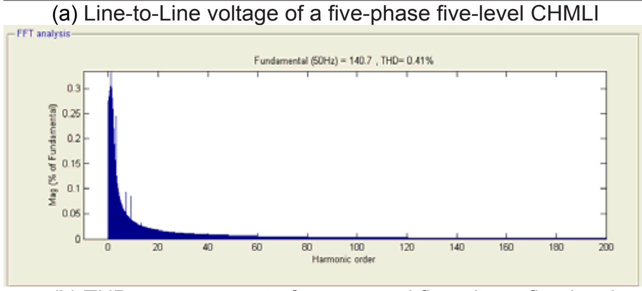
(b) THD measurement of a five-phase five-level DCMLI

Fig.7. Simulation result of a five-phase DCMLI with SPWM

FLC controlled MPPT tracks the operating point quickly and accurately with and without change irradiance level. Simulation result for the SPWM five-level five-phase CHMLI and THD measurement is shown in Fig. 6. Simulation result for the SPWM five-level five-phase DCMLI and THD measurement is shown in Fig. 7. This shows that the generated line-to-line voltage is much improved with the level of inverter. The simulation result for the proposed SVPWM five-level five-phase CHMLI and THD measurement is shown in Fig. 8. The THD measurement of SPWM for five-phase three-level and five-level DCMLI are 2.62% and 1.39%. This reveals that THD is highly reduced as the level of inverter increases. The THD measurement of SPWM for five-phase three-level and five-level CHMLI are 1.54% and 0.93%. The THD measurement of the proposed SVPWM five-level five-phase CHMLI is 0.41%. From the results it is observed that the generated voltage spectrum is very much increased with the level of inverter with using SVPWM.



(a) Line-to-Line voltage of a five-phase five-level CHMLI



(b) THD measurement of a proposed five-phase five-level CHMLI

Fig.8. Simulation result of a five-phase five-level CHMLI with SVPWM.

Table 1.Comparison of SPWM for DCMLI and CHMLI

No of levels	DCMLI (THD %)	CHMLI(THD %)
3	2.62%	1.54%
5	1.39%	0.93%

Table 2.Comparison of SPWM and SVPWM for CHMLI

No of levels	SPWM for CHMLI (THD %)	SVPWM for CHMLI (THD %)
5	0.93%	0.41%

The THD levels of SPWM five-phase three-level and five-level for both CHMLI and DCMLI are compared in Table 1. The THD levels of SPWM and SVPWM five-phase five-level for CHMLI are compared in Table 2. This proves that the proposed scheme can reduce the THD which is necessary criterion for PV system. The results obtained are full of promise to use the CHMLI for improved output voltage quality with less THD for PV system.

8. Conclusion

This paper presents a five-phase five-level for CHMLI with SVPWM algorithm for photovoltaic system. The proposed system produces low harmonic distortion and reduced switching losses. The SVPWM can provide proper selecting switching states of the inverter, optimization of switching patterns, and improving dc-link voltage utilization. It is seen from the simulation results that the generated voltage spectrum is very much improved with increase in the five-level five-phase CHMLI with SVPWM technique (0.41%) and five-level five-phase of the CHMLI (0.93%) with SPWM technique and five-level five-phase of the DCMLI (1.39%) with SPWM technique. Thus, the output voltage quality increases with less THD for PV system.

REFERENCES

[1] Jose Rodriguez, Jih-Sheng Lai, Fang ZhengPeng, Multilevel inverters: a survey of topologies, controls, and applications, IEEE Trans. Ind. Electron. 49 (2002), n.4, 724-738.

[2] E. Levi, Multiphase electric machines for variable-speed applications, IEEE Trans. Ind. Electron. 55 (2008), n.5, 1893-1909.

[3] S. Lu, K. Corzine, Multilevel multi-phase propulsion drives, in Proc. IEEE ESTS. (2005) 363-370.

[4] Colak, Ilhami, Kabalci, Ersan, Bayindir, Ramazan, Review of multilevel voltage source inverter topologies and control schemes, Energy Convers. Manage. 52 (2011),1114-1128.

[5] A.K. Gupta, A.M. Khambadkone, K.M. Tan, A two-level inverter based SVPWM algorithm for a multilevel inverter, in Proc. IEEE Industrial Electronics Society Conf. 2 (2004) 1823-1828.

[6] Marcelo GradellaVillalva, Jonas Rafael Gazoli, Ernesto RupperrtFilho, Comprehensive approach to modelling and simulation of photovoltaic arrays, IEEE Trans. Power Electron. 24 (2009), n.5, 1198-1208.

[7] ValanRajkumar M., Manoharan P.S., Ravi A. Simulation and an experimental investigation of SVPWM technique on a multilevel voltage source inverter for photovoltaic systems, 52 (2013), 116-131.

[8] ValanRajkumar M., Manoharan P.S., FPGA based multilevel cascaded inverters with SVPWM algorithm for photovoltaic system, Elsevier Solar Energy, 87 (2013), 229-245.

[9] ValanRajkumar M., Manoharan P.S., Modeling, simulation and harmonic reduction of three-phase multilevel cascaded inverters with SVPWM for photovoltaic system, International Review on Modeling and Simulation, 6 (2013), n.2, 342-350.

[10] Ravi A., Manoharan P.S., Modeling and simulation of three-phase multilevel inverter for grid connected photovoltaic systems, Elsevier Solar Energy, 85 (2011), 2811-2818.

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