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3-D space vector modulation algorithm for multilevel inverters in abc coordinates for solar PV applications

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Solar PV based Power generation is gaining importance in the present scenario of energy crisis. Precise control of Solar PV inverter is a very important factor deciding the efficiency and performance of Solar PV sources. Space Vector Modulation (SVM) technique is widely used for pulse width modulation in inverters, especially for power supplies for obtaining improved sine wave output. It is based on the representation of the three phase quantities as vectors in a two-dimensional using α and β co-ordinates. Here, a new three–dimensional (3-D) space vector algorithm in a-b-c co-ordinates for multilevel inverters is presented, which is based on the 3-Dimensional geometry of the vectors. This method calculates the on-state duration of switching vector without involving trigonometric functions, look-up tables or coordinate system transformation. Hence the computational complexity is very less compared to other algorithms. The proposed scheme is explained for a multilevel inverter and simulation results are presented with comparison of performance of a two level inverter and a three level inverter using this technique. The results shows that the algorithm can be applied for higher level inverter so that it operates at reduced Total Harmonic distortion.

Keywords: *Multilevel inverters, Space vector modulation (SVM), three-dimensional (3-D) space vector*

1.0 INTRODUCTION

Inverter is an inevitable part of electrical power system and utility in different applications. Inverter is required for power conditioning at source level, transmission, distribution and utility level. In the rising demand for Solar PV generation, the performance improvement of inveters is an area of constant research and development, since inverter is a key component of solar PV generation system. [1],[2].

Basic inverters give stepped waveforms which resembles sinusoidal waveforms which contains harmonics. Output waveform is obtained by controlling the switches with varying pulse width gate signals which is called Pulse width Modulation (PWM). Multilevel inverters were implemented to alleviate the stress on the power semiconductor devices, so that higher DC bus voltages could be employed [3]. Better sinusoidal waveforms are obtained in multilevel inverters. The most widely used Pulse Width Modulation (PWM) schemes for three-phase voltage source inverters are sinusoidal PWM (SPWM) and space vector PWM (SVPWM). SVPWM gives superior performance in terms of precision control and reduced harmonics. There are different modulation algorithms available for the implementation of SVPWM [5-7]. Most of the modulation algorithms use trigonometric functions or pre-computed look up tables.

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Here a three-dimensional (3-D) algorithm presented which is a generalization of the 2-D space vector technique. This can be used to give improved performance in Solar PV inverters without much complexity in the system. The space vectors will be in a plane if the system is balanced without triple harmonics. 3-D SVM is useful if the system is unbalanced or if there is a zero sequence or triple harmonics, because the reference vectors are not on a plane. [4],[9]. The proposed algorithm calculates the sequence of the nearest space vector for generating the reference voltage vector. This method provides the nearest switching vector sequence to the reference vector without involving trigonometric functions, look-up tables or coordinate system transformations which increase the computational load .The description of Multi level inverter is given in section 2. Section 3 gives the details of 3-D SVM followed by description of proposed method in section 4. The techniques verified using simulation and the discussion given in section 5.

2.0 MULTILEVEL INVERTERS FOR SOLAR PV APPLICATIONS

The main focus on the performance of an inverter is the purity of the output waveform obtained. It should operate with lesser harmonic contents so as to reduce the stress on the power system and on the equipment which uses the inverter output. Thus multilevel inverters where developed where the output sine wave is obtained by more number of steps so that the voltage is more sinusoidal in nature.

The operation of a cascaded multilevel inverter ahown in Figure 1 can be explained as below.

- The pole voltage of any phase for inverter-2 attains a voltage of $V_{dc}/2$, under the following conditions: when the top switch of that leg in inverter-2 is turned on and the bottom switch of the corresponding leg in inverter-1 is turned on.
- The pole voltage of any phase in inverter-2 attains a voltage of V_{dc}, when the top switch of that leg in inverter-2 is turned on and the top switch of the corresponding leg in inverter-1 is turned on.

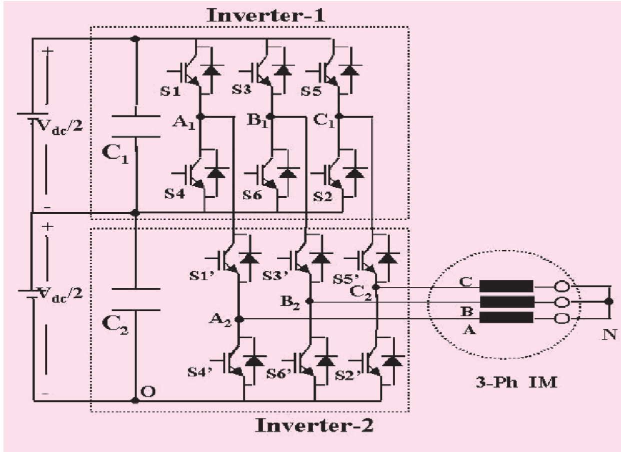

FIG. 1 3 LEVEL INVERTER BY CASCADING 2 LEVEL INVERTERS

- The pole voltage of a given phase in inverter-2 attains a voltage of zero, if the bottom switch of the corresponding leg in inverter-2 is turned on. Thus, the pole voltage of a given phase for inverter-2 is capable of assuming one of the three possible values- 0, $V_{dc}/2$ and V_{dc} , which is the characteristic of a three level inverter.

In the case of stand-alone solar PV inverters, use of multilevel inverters will improve the performance of the connected load. It also improves the efficiency of the system in case of grid connected systems. But it involves more number of switches which adds to the losses and complexity of switching calculation [1],[2].

3.0 3D SPACE VECTOR MODULATION SCHEME

The mail concept of 3-D space vector modulation is that, one reference vector is obtained by using 3-D co-ordinates as shown in Figure 2. Here the point 0 represents ground, 1 is the lower DC level and 2 represents higher DC level. Using these the other points are to be calculated to obtain the rotating vector. Most of the modulation algorithm for this involve trigonometric functions, look-up tables or coordinate system transformations which increase the computational load. Here a simpler modulation algorithm is followed as explained below which does not involve trigonometric functions

3.1 Calculation of reference Vector

Here, four vectors u_1, u_2, u_3 and u_4 are used to approximate the desired voltage vector in a control cycle. Thus during each subcycle, a vector is generated which is a combination of four switching state vectors $u_{1(t1)}$, $u_{2(t2)}$, $u_{3(t3)}$ and $u_{4(t4)}$, where t_1, t_2, t_3, and t_4 are the on-state durations of the active switching state vectors. The four vectors nearest to the reference vector must be identified. This algorithm is proposed for for identifying this vector, by using subcubes within the vector space.

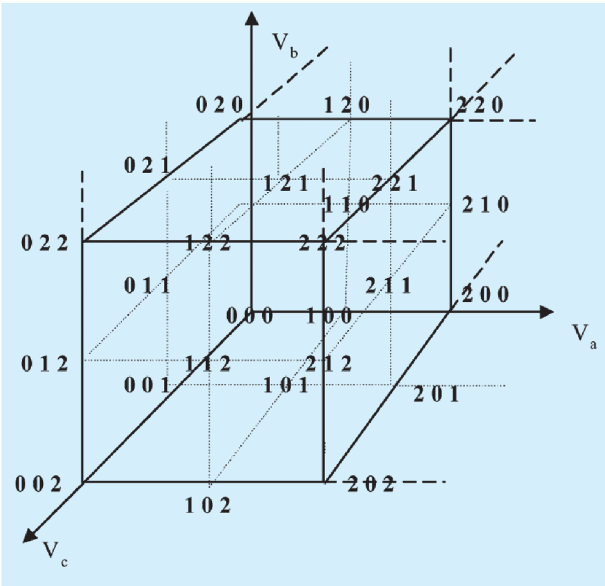

FIG. 2 3D SPACE VECTORS OF A THREE LEVEL INVERTER

Here and easy method for calculating the reference vector is followed. Here a tetrahedron is located in the vector space, the 4 vertices of which represents 4 vectors which together forms the required reference vector. The modulation algorithm operates on normalized input voltage vector. This method works satisfactorily for unbalanced systems and systems with harmonics where the reference vector cannot be placed on a 2-D plane.

4.0 ALGORITHM FOR CALCULATING THE SWITCHING TIME

The steps for calculating the switching time is described below

4.1 Obtaining Reference vector

- The space vectors of a multilevel converter form a cube in a 3-D space as shown in Figure 2.
- This space can be split up into six tetrahedrons which generate the cube's total volume.
- For a certain reference vector in three-phase coordinates (ua, ub, uc), the integer part of each component(a ,b, c) is given as

$$a=\text{int}(u_a) \quad ....(1)$$

$$b=\text{int}(u_b) \quad ....(2)$$

$$c=\text{int}(u_c) \quad ....(3)$$

- Obtain the sub-cube where the reference vector is pointing.
- The 3-D space is formed by a certain number of sub-cubes depending on the number of the levels of the inverter.
- One sub-cube for two-level, eight sub-cubes for three-level inverters, etc. The coordinates (a, b, c) are the origin coordinates corresponding to the reference system of the sub cube where the reference vector is pointing. This is shown in Figure 3.

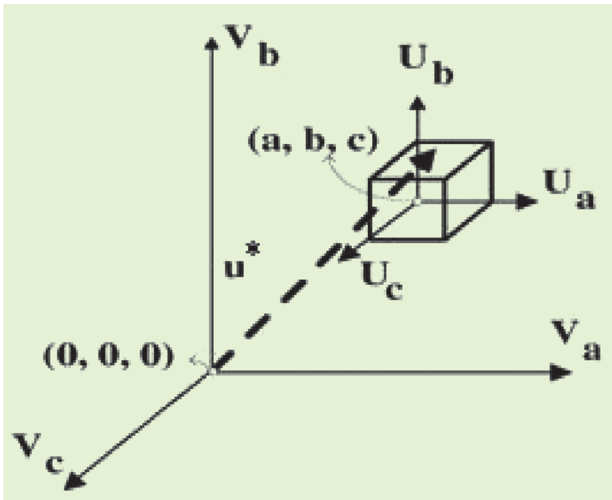

FIG. 3 ORIGIN OF THE SUB CUBE WHERE THE REFERENCE VECTOR IS SUPPOSED TO BE FOUND.

- Find the tetrahedron where the reference vector is pointing out of the 6 tetrahedrons in each subcube.
- After finding the tetrahedron with centroid close to the vector, the four space vectors corresponding to the four vertices of a tetrahedron will generate the reference vector.

4.2 Calculation of Duty-Cycles

The state vectors are the vertexes of the corresponding tetrahedron generates the reference vector as shown in Figure 4.

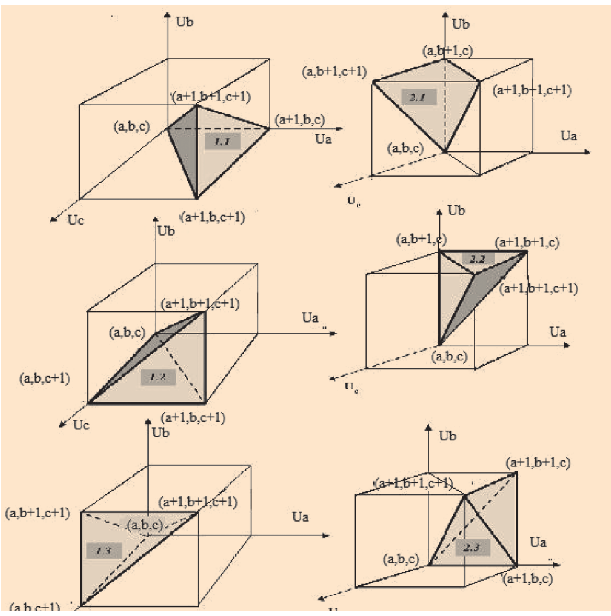

FIG. 4 TETRAHEDRONS IN TO THE CUBE WITH THE CORRESPONDING STATE VECTORS

The switching cycles can be calculated using the following equations

$$U_a=S_{a1}\ d_1+Sa_2\ \ d_2+S_{a3}\ d_3+S_{a4}\ d_4 \qquad ...(4)$$

$$U_b=S_{b1}\ d_1+S_{b2}\ \ d_2+S_{b3}\ d_3+S_{b4}\ d_4 \qquad ...(5)$$

$$U_c=S_{c1}\ d_1+S_{c2}\ \ d_2+S_{c3}\ d_3+S_{c4}\ d_4 \qquad ...(6)$$

$$d_1+d_2+d_3+d_4=1 \qquad ...(7)$$

Where U represents the voltage level, S represents the switching gate signals and d represents the duty cycle. The coordinates (a, b, c) represent the different voltage levels of the dc link. They take values between zero and n-1, where n is the number of levels of the multilevel converter. The duty cycles are only functions of the reference vector components and the integer part of reference vector coordinates. Thus the switching signals are obtained without involving trigonometric functions

5.0 SIMULATION RESULT

The algorithm explained in the previous section is implemented using MATLAB/Simulink™. In order to compare the performance, simulation is done for both 2 level and 3 level inverters [10-13]. The simulation diagrams are shown in Figure 5 and 6 respectively.

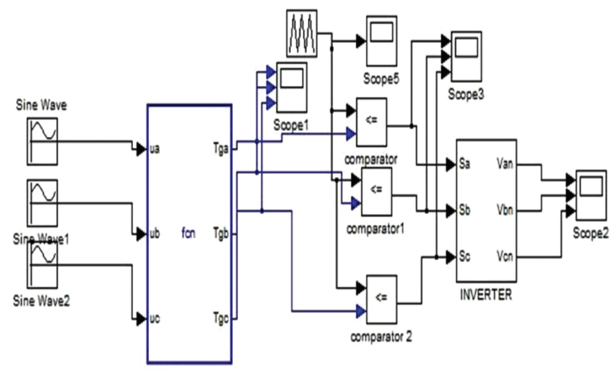

FIG. 5 SIMULATION DIAGRAM OF TWO LEVEL INVERTER WITH 3D SVM

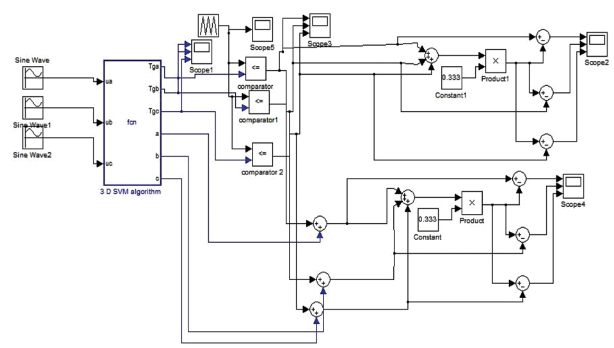

FIG. 6 SIMULATION DIAGRAM OF THREE LEVEL INVERTER WITH 3D SVM

The simulation is initially done for a constant DC supply voltage to analyze the operation. The behavior will be almost same for standalone Solar PV inverters since the input is regulated by the battery voltage. The proposed technique is also analysed by using solar PV input with a DC to DC controller [10]. The PV source is modeled using single diode model as shown in Figure 7. The voltage and current levels at various solar insolation is shown in Figure 8.

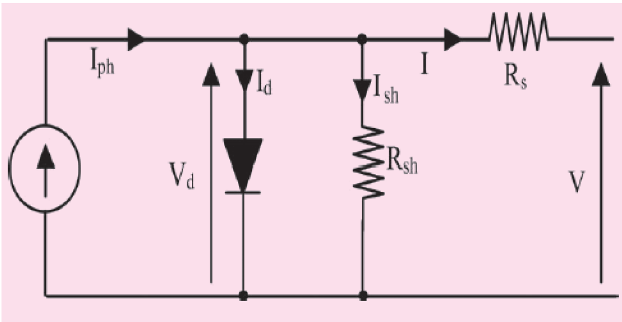

FIG. 7 PV CELL MODELLING

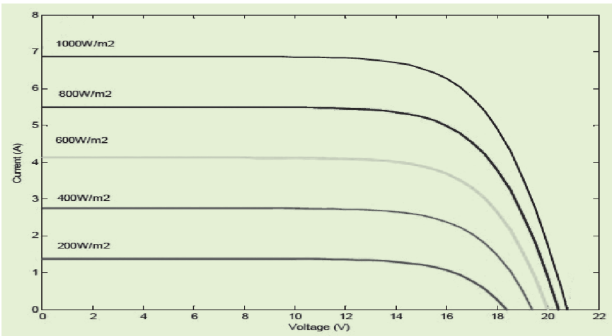

FIG. 8 VARIATION OF VOLTAGE AND CURRENT OF SOLAR PV OUTPUT WITH VARIATION IN INSOLATION

Figure 9 shows the output waveform obtained using the proposed 3D space vector modulation technique. Compared to the 2 level model, the waveform is more sinusoidal and it can be substantiated by analyzing the THD in the waveform [11], [12], [13].

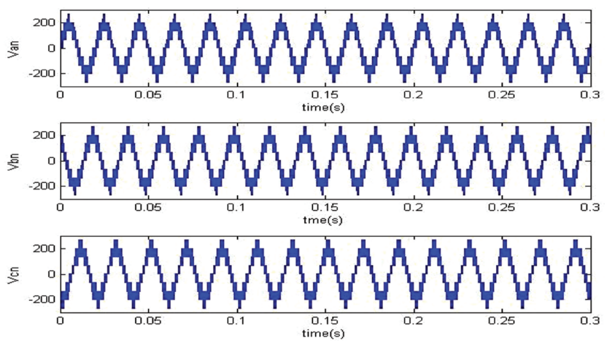

FIG. 9 OUTPUT AC WAVEFORM OF MULTI LEVEL INVERTER USING THE PROPOSED TECHNIQUE

Figure 10 shows the comparison of harmonics in the output voltage of 2 level inverter and 3 level inverter with 3 D space vector modulation. Percentage of magnitude of different frequency components with respect to magnitude of fundamental component are show. It can be seen that while going from two level to three level inverter, the THD has reduced considerably from 89% to 38%.

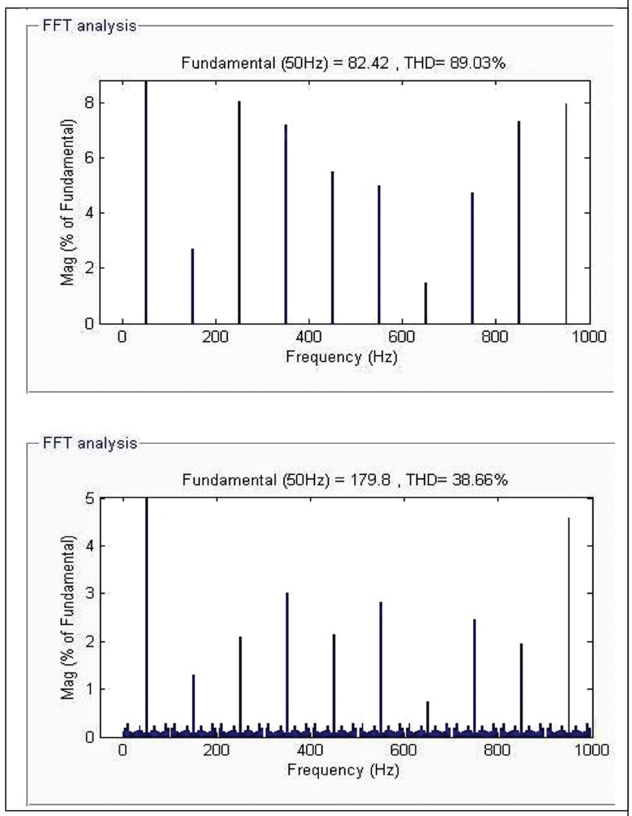

FIG. 7 PV CELL MODELLING

6.0 CONCLUSIONS

The 3-D space vector modulation algorithm without using trigonometric functions is presented here. It can be seen that the computational complexity is much less compared to the other methods. The method is very useful to readily calculate the switching sequence and the on-state durations of the respective switching state vectors for multilevel inverter . This algorithm can be extended to n-level inverter easily and implemented using simpler controllers. This method can be applied for Solar PV inverters without much complication and difference in cost.

7.0 REFERENCES

[1] C J Hatziadoniu, F E. Chalkiadakis, V K Feiste and, "A power conditioner for a grid-connected photovoltaic generator based on the 3-level inverter," IEEE Transactions on Energy Conversion, Vol.14, No.4, pp. 1605-1610, December 1999.

[2] S Jain and V Agarwal, "A Single-Stage Grid Connected Inverter Topology for Solar PV Systems With Maximum Power Point Tracking," IEEE Transactions on Power Electronics, Vol.22, No. 5, pp. 1928-1940, September 2007.

[3] J Rodriguez, J S Lai, and F Z Peng, “Multilevel inverters: A survey of topologies, controls, and applications,” IEEE Transaction on Industrial Electronics, Vol. 49, No. 4, pp. 724–738, August 2002.

[4] M Mohan Renge and M S Hiralal” Three dimensional space vector modulation to reduce common mode voltage for multilevel inverter ”IEEE Transaction on Industrial Electronics, Vol 57, No.7, pp. 2324-2331, July 2010.

[5] G Carrara, S Gardella, M Marchesoni, R Salutary, and G Sciutto, “Anew multilevel PWM method: A theoretical analysis,” IEEE Transaction on Power Electronics, Vol. 7, No. 3, pp. 497–505, July 1992.

[6] A S Aneesh Mohamed., Anish Gopinath, M R Baiju,”A simple space vector PWM generation scheme for any general n-level inverter” IEEE Transaction on Industrial Electronics, Vol 56, No.5, pp.1649 -1656, May 2009.

[7] Anish Gopinath, A S Aneesh Mohamed and M R Baiju,”Fractal based space vector PWM for multilevel inverters –a novel approach” IEEE Transaction on Industrial Electronics, Vol 56, No.5, pp.1230 -1237, April 2009.

[8] N Celanovic and D Boroyevich, “A fast space vector modulation algorithm for multilevel three phase converters,” IEEE Transaction on Industrial Applications, Vol. 37, No. 2, pp. 637–641, March/April 2001.

[9] M Angeles Martin Prats, L. G. Franquelo, J M Carrasco and J I Leon, ”A 3D space vector modulation algorithm for multilevel converters” IEEE Power Electron Lett., Vol 1, No.4,December 2004.

[10] K K Prajapat, A Katariya, A Kumar and S Shukla., "Simulation and Testing of Photovoltaic with Grid Connected System," International Conference on Computational Intelligence and Communication Networks (CICN), pp.692-697, 7-9 October 2010.

[11] Ned Mohan, Tore M Undeland, “Power electronics: converters, applications, and design”, John Wiley & Sons, 01-Jan-2007.

[12] Muhammad H Rashid, “Power Electronics: Circuits, Devices, and Applications”, Pearson Education India, New Delhi, 2004.

[13] Shihong Wu, Yi Wang, Shengcun Gao, Jianwei , Rui Huang and Dan Guo, "Simulation on Harmonic Spectrum of Inverter Output Voltage Based on MATLAB," International Conference on Computational Intelligence and Software Engineering (CiSE), pp.1-3, 10-12 December 2010.