New Space Vector Modulation Approach For Multilevel Converters

Akash Garg
Department of Computer Science and Engineering
Indian Institute of Technology Bombay
Mumbai, India
akash@cse.iitb.ac.in

Anshuman Shukla
Department of Electrical Engineering
Indian Institute of Technology Bombay
Mumbai, India
ashukla@ee.iitb.ac.in

***Abstract*— This paper presents an approach towards using Space Vector Modulation for multi-level converter based on pre-calculation of switching time for each voltage configuration in the converter using weighted time assignment to sectors. This algorithm minimizes runtime calculation of switching time and its simulation results are presented to validate the effectiveness of the proposed scheme. The concept of variable switching time and its importance for controlling converters have been presented.**

Keywords—trajectory; modulation; ripple; switching time;

I. INTRODUCTION

A large number of variable speed induction motors which are based on voltage inverters are being used today in a vast variety of devices like pumps, fans, tractions, machine spindles etc. This is mainly because of the development of fast switching methods in the recent years. This has led to a great amount of work being done on power converters. A good modulation strategy is the very first requirement for the getting good performance from any power converter. A lot of performance factors like output waveform, torque of induction machines depends to a great extent on the modulation strategy used [2].

Several voltage controlled Pulse Width Modulation(PWM) methods have been discussed extensively in literature e.g. sinusoidal PWM, sinusoidal PWM with third harmonic injection and Space Vector Modulation. The basic difference in all these methods is the time alloted and the order in which it is alloted to different switching states. This determines the output waveform of the converter and also determines range of loads which can be driven using the converter.

Space Vector PWM refers to a special switching sequence of voltage which is determined using reference vector. It has been shown to generate less third harmonic distortion in the output voltages and currents applied to the phases of an AC motor and it makes more efficient use of the source voltage. Space vector modulation is based on representing the three phase voltages as space vectors. The time for different nodes is determined using a space vector diagram in which the location of reference vector is used used to determine the time for different nodes surrounding it. The voltage is switched accordingly between different nodes [3].

In section II, we have presented the basic idea behind working of Space Vector Modulation. We have shown the time calculation for a two-level converter for any position of the reference vector and also summarized the reasons for failure of naïve algorithm in case of multilevel converters. Section III shows the application of conventional naïve algorithm in multilevel converters. Section IV presents the proposed variable switching time method, while section V presents its advantages over conventional methods. Section VI shows the simulation results for validating the effectiveness of the proposed algorithm.

II. BASIC APPROACH TOWARDS SVM

SVM is based on manipulating switching time for the possible voltage configurations in a converter to generate AC output from the converter. The basic design of a two level converter is shown in Fig. 1.

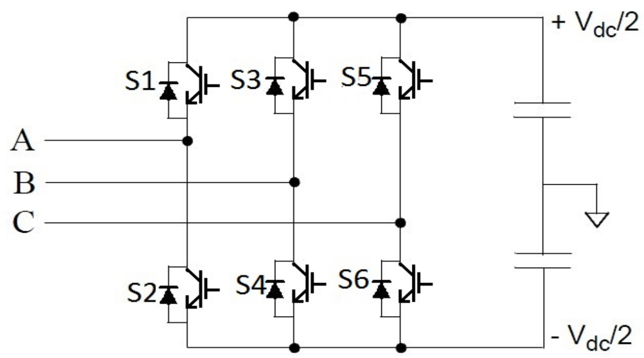

Fig. 1. Structure of a Two Level SVM Converter

In two level three phase converter there are two possible states for each phase, High or Low. 1 represents High state and 0 represents Low state for a phase. Thus a string of 3 bits can be used to represent all possible voltage configurations for the converter where first bit represents the state of first phase, second bit for second phase and third bit for third phase. Now each bit has either Low or High state so there are 2^3=8 possible states. The three switching states 100, 010, 001 forms the abc reference frame as shown in the Fig. 2. The intermediatory vector are formed with the combinations 110, 101, 011. The states 000 and 111 are represented by the origin. So the three phases represents three reference vectors each at 120 degree apart from other two. The intermediate states represents the angular bisector of the states. Now to decompose any reference vector it sufficient to take its component along the two vector surrounding the current position. The rest component can be taken along the origin i.e. along either 000 or 111. In Fig. 2, V_1(100), V_3(010), V_5(001) represent the reference frame(abc), V_2(110), V_4(011), V_6(101) represent the angular bisectors and V_0(000), V_7(111) represent the origin. V_{ref} is the reference vector which is to be decomposed in this frame. The angle of the reference vector with V_1 represented by α and the length of the vector is **r** [3].

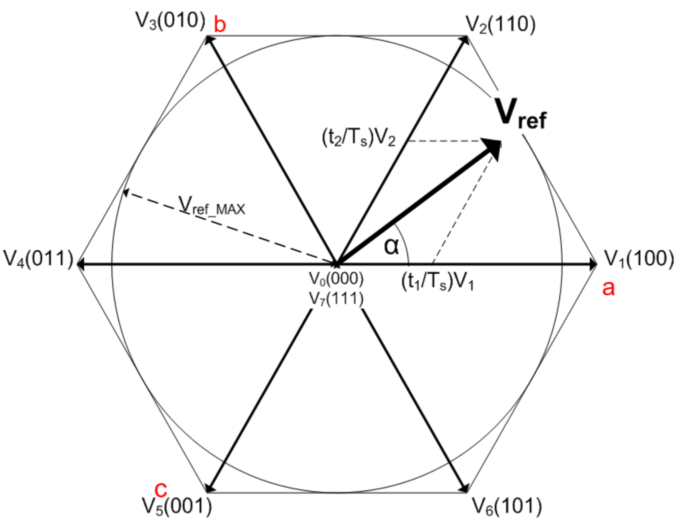

Fig. 2. Space Vector Diagram of two level converter

using simple geometry the times t_1 and t_2 comes out to be

$$t_1 = \mathbf{r}\sin(\alpha)T_s/V_1\sin(120^o) \quad (1)$$

$$t_2 = \mathbf{r}\cos(\alpha)T_s/V_2\sin(120^o) \quad (2)$$

$$t_3 = T_s - (t_1 + t_2) \quad (3)$$

here t_3 is the time spent at origin.

Multi-level converters hold a very important place in power conversion. They divide the source into many numbers of small steps which are then switched from time to time to produce sinusoidal waveform at the output. In multi-level converters, the modulation and control complexities are much more than two level converter. The increasing interest in multi-level motor drives in the recent years due to advantages like less torque ripple, less acoustic noises and losses, reduced current per phase or increased reliability have to greater interest in multi-phase converters. This makes multi-level converters suitable for high power applications [2]. A great deal of research has been done on the schemes used for pulse width modulation. At the center of all lies a proper modulation technique, which is crucial to ensure high performance of all types of converters.

As the number of voltage levels increases the working of the converter becomes very complex. The number of segments of the space vector diagram increases which makes it difficult to accurately determine the position of the reference vector at any arbitrary point of time. The switching of reference vector from one sector to another is very rapid so to calculate time for each node requires a nearly real time calculator which is very difficult to achieve at the present scale of use. This is one of the limiting factors for multilevel converters.

III. Modulation Strategies For Multilevel Converters

Applying the Space vector modulation scheme for a two level converter is much simpler than multi-level converter. For a two level converter there are just 8 switching states. Even when going from two to three levels the number of switching states increases from 8 to 27 [5], [2]. For N level converter the states increases as N^3.

The objective of PWM is to approximate the ideal circular trajectory of the reference vector by switching amongst the standard voltage configurations. The continously moving reference vector is sampled at a switching frequency f_s. During the interval $T_s = 1/f_s$ the reference vector is assumed to remain constant. For this assumption to be valid, f_s should be fairly higher than fundamental output frequency. Now in Fig. 3 at any instant the smallest triangular sector which entirely contains the reference vector is sector X and the nodes surrounding the sector are A, B, C [1]. Now the vector is decomposed in terms of A, B, C and voltage is switched between them with time alloted to them based on their contribution to reference vector. The total time for this switching is T_s [3]. The time calculation can be done using various algorithms which reduces the time required for it to some extent. After T_s reference vector is again sampled and the process is repeated again.

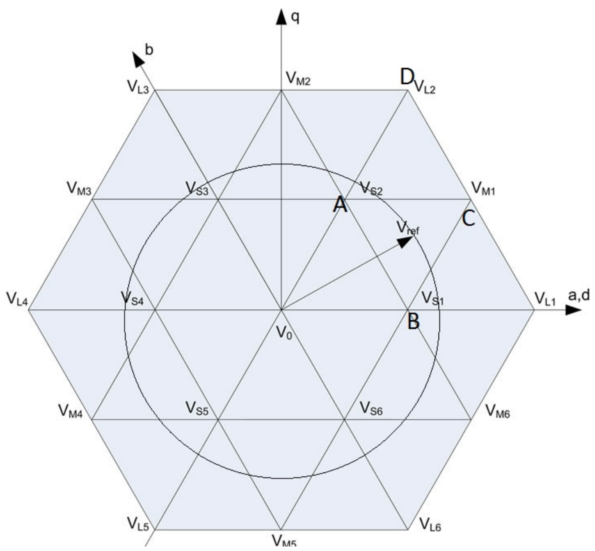

Fig. 3. Space Vector Diagram for three-level converter

For a two level converter using a uniform switching time serves the purpose as it is easier to find out the position of the space vector after T_s. In the space vector diagram all the triangular sectors are equivalent in a two level converter and in ideal case the space vector spends equal time in all the sectors during rotation. It is also assumed that there are very minor (negligible) changes in the location of space vector during the switching. In a two level converter this effect turns out to be negligible [1].

But in case of a multi-level converter the smaller triangular sectors are not all equivalent. Clearly from Fig. 3 the time spent in each one is different as the portion of the path of reference vector is different in different sectors. Therefore switching time used should depend on the time spent in the sector. Further during the switching time, the effective change in location also affects the output as the angle subtended by each triangle is very small. Therefore even a slight change in angular position leads change in the sector in which space vector is present. The large number of switching states creates additional problems as all the switching states can't be accounted in sequence therefore sequential switching becomes a problem. Even after determining the position of space vector the times for each node have to be calculated on a real time basis which in case of multi-level converter in difficult as time spent in each sector is very small. Various methods have been presented to make calculations faster but it is highly difficult to achieve real time calculation with a converter of more levels which limits the performance of all such methods.

IV. Variable Switching Time Method

By pulse width modulation of voltages we try to make the trajectory of the space vector as close as possible to a circular loop. The better is the resemblance to a circular loop the better is the output. Most of the above problems can be accounted for by using variable switching time i.e. using a different switching time for the each sector whenever the times for the nodes are to be calculated. This also reduces the problem of determination of the position of the space vector. Let us have a track of all the sectors through which space vector passes in one rotation. Allot a switching time to each sector based on the portion occupied by the sector in the reference vector trajectory. The diagram Fig. 5 schematically represents the scheme and the method used for time calculation in the algorithm. Let θ be the angle subtended by A and B at the center in the diagram then the total time for switching of the three nodes represented by the vertices is given by

$$T_s = (\theta/360)*T \qquad (4)$$

where T is the total Time of one rotation. Now the time for each node is calculated using the usual method described in the previous section. The equations governing the time distribution are as follows.

Let a, b and c denote the three nodes of a sector for which time has to be distributed. Let T_s be the total time alloted to this sector and f_a, f_b and f_c be the fraction of the total time of the sector for the nodes a, b and c . Let E denote the angle bisector of the entry and exit of the reference vector in the sector. Then

$$f_a + f_b + f_c = 1 \qquad (5)$$

$$f_a*(a.x) + f_b*(b.x) + f_c*(c.x) = E.x \qquad (6)$$

$$f_a*(a.y) + f_b*(b.y) + f_c*(c.y) = E.y \qquad (7)$$

where a.x and a.y denote the x and y coordinate of the node a in xy plane and similarly for b, c and node E. The three equations in three variables can be easily solved and the time for each node can be calculated from f_a, f_b and f_c as follows:

$$f_a = t_a/T_s \qquad (8)$$

$$f_b = t_b/T_s \qquad (9)$$

$$f_c = t_c/T_s \qquad (10)$$

But the time is calculated only once and it is used for each loop. So the need for any calculation of switching time during runtime has been eliminated. Consider a 5 level converter with following schematic diagram shown in Fig. 4.

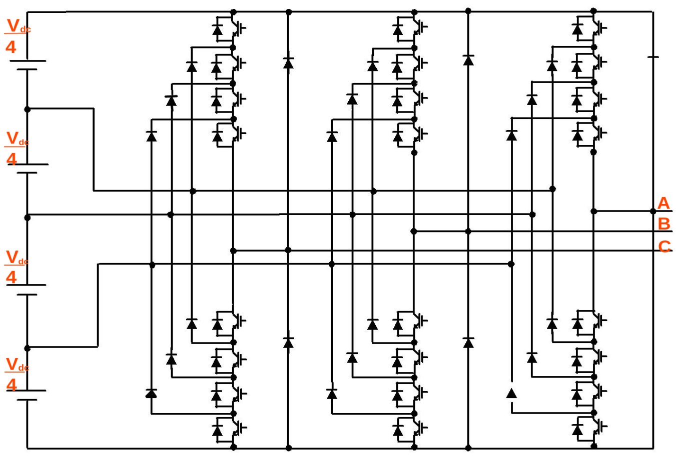

Fig. 4. Schematic of a 5 level converter

The space vector diagram for the above converter is shown in Fig. 5.

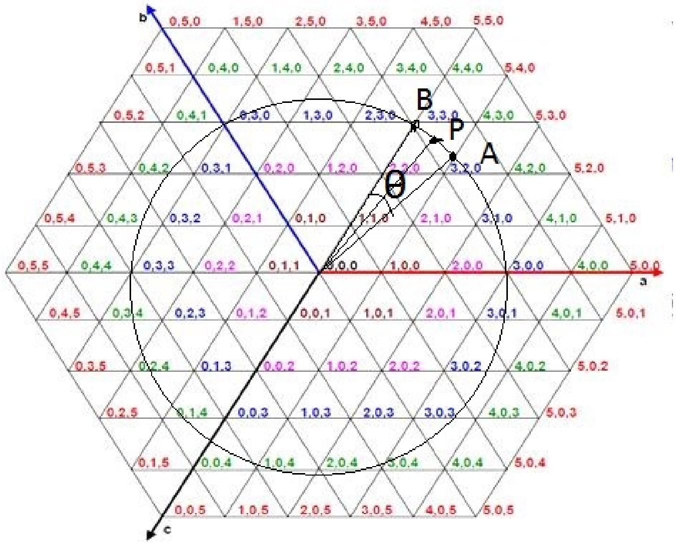

Fig. 5. Space Vector Diagram of 5 level Converter showing angle of entry and exit of reference vector in a sector in its path

In the Fig. 5, A and B are the entry and exit points in the trajectory of reference vector in that particular sector and P is the angle bisecting vector which is the position of the vector in that sector which will be approximated using nodes. The angle subtended by A, B at centre is θ which decides the switching time for that sector.

Thus in each of the sector the voltages will be switched at all nodes irrespective of the determined position of the reference vector. To calculate the times for the nodes the location of the space vector is assumed to be the angle bisector of the angle θ. Thus a track of the all the position of the space vector has been obtained at once and all the calculation for the switching times can be done at once. The times for any nodes in any sector can be calculated by simple geometry as shown for the two level converter as all calculations are required to be done only once. Further during the switching even if the position of the reference vector changes then it does not affect the result as the switching time is according to the time spent in the sector and the location at the next time of determination of position of the reference vector will be in next sector. Once all the calculations have been done for one rotation no further calculation is required. In case of constant switching time method each loop of sinusoidal curve is differs a bit in from others and the average of a large number of them turns out to be very close to sinusoidal loop as in the average almost all nodes have been accounted for and the time for each node turns out to be very close to the one calculated above. Thus this scheme has inherited advantage of producing the long time average wave form of the constant time algorithm. Further the switching is not random and no calculations are required for running the converter for a long. A schematic diagram of the proposed method is presented in the Fig. 6.

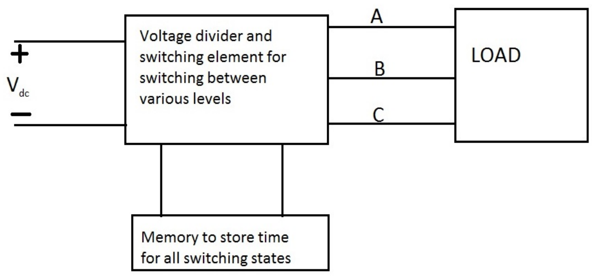

Fig. 6. Schematic diagram for the proposed method

V. Comparison with the Conventional Scheme and Advantages Over it

This scheme has various advantages over the traditional scheme in terms THD and has a different approach towards switching frequency. As explained earlier, this scheme has a pure repetition of the waveform in every loop i.e in each loop the pulses used are same as that of earlier loop. This implies that the current waveform in the load also follows the same pattern. For decomposition of the waveform across the load, it is sufficient to decompose one loop of it. In this scheme there is lesser distortion in the waveform across due to uniformity of the current in each loop weighted distribution of pulse width where weightage is based not on the the current position of the space vector but on the overall contribution of the node to the trajectory of the reference vector. Therefore this scheme has a THD advantage close to that of a sinusoidal waveform [2].

Further the pre-calculated switching time allows the redistribution of time easier and thus further makes it easier to reduce THD. One of the main advantage is that in this scheme it is easier to broaden the waveform which reduces the harmonics present in the waveform and thus impacts the THD directly.

This scheme has a completely different approach towards switching frequency. The switching frequency is based of the number of sectors crossed by reference vector. The number of sector depends on the number of levels of the converter and the maximum line to line voltage used by the load. In the traditional approach there multiple switching possible in a single sector if position of the reference vector is found in the same sector multiple time. This usually occurs when the angle subtended by the sector at the origin per 360° is higher than the time between consecutive detection of the space vector position. But in the present case there is no such possibility as the position for each sector has been fixed at the angle bisector of the angle subtended by entry and exit of the reference vector in the sector. On comparing at less number of levels the switching frequency is less as compared to traditional approach.

This scheme has a disadvantage in terms of the range of converters for which it can be used. This scheme is designed for the usage in converters with many levels. In case of converters with less number of levels, the switching time alloted to a sector increases which distorts of the quality of the waveform as the switching time alloted to a node increases and all the time being used in one state thus creates distortion in output waveform. The main usage of this scheme is with converters with more number of levels where the portion occupied by a sector of the space vector trajectory is very small.

It makes implementation of the space vector modulation much easier for a converter with more number of levels. It has repetition of switching time for the nodes, and therefore exact repetition of the waveform, thus it reduces the third harmonic distortion. In case of Space Vector Modulation, one basic requirement is that while switching from one node to another position of only switch should be changed which is inherent to this method as all the nodes have been accounted and switching between adjacent nodes required only one switch to be changes. Switching times are predetermined for all nodes and waveform produced is closer to the sinusoidal loop. No time is used for calculating nodal times thus improves the performance.

VI. Simulation Results

The simulation of a seven level converter based on the above algorithm was done in Matlab. A schematic diagram of the 7 level converter for which the simulation was done is given in Fig. 7-

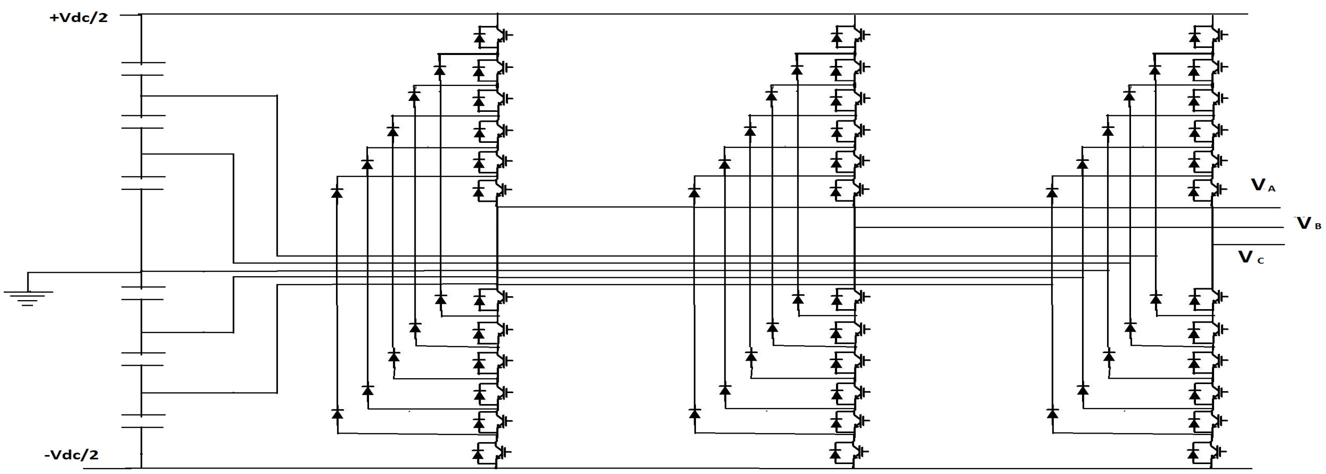

Fig. 7. A schematic view of the converter simulated

The following parameters were used in simulation. The maximum line-to-line voltage was kept limited to 5 volts and a 3 phase load was used with a resistance value of 5 ohm and inductance value 5 Henry. The calculations were done for a standard frequency of 60 Hz.The switching time for each node was pre-calculated and stored and voltages were switched at each node according to the calculated time. This was done with the help of a simple program which had pre-stored time for each node and it just sequentially reads the time from memory and voltage corresponding to it and applies the voltage to the load. The following phase current graph was obtained in the process.

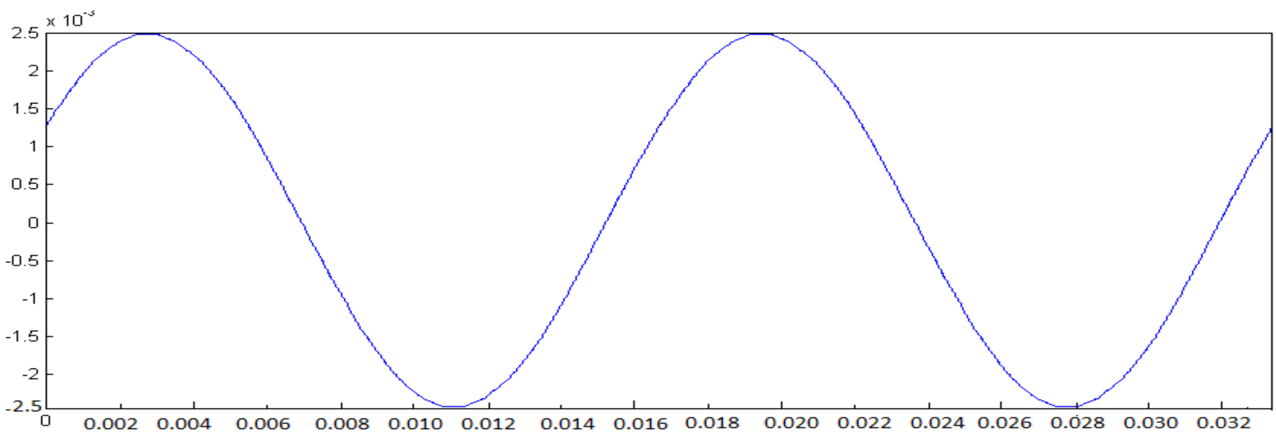

Fig. 8. Current output of the converter in simulation

For the next loop no further calculations were done and the same values were used and a completely identical loop is obtained. In terms of values this graph turns out to be a very good approximation of the average values obtained over many loops in conventional algorithm.

In the current graph shown in Fig. 8, the current waveform comes to be of completely symmetrical shape. The shape of the upper half is completely identical as that of lower half. The values of the current comes out to be completely symmetric.

The voltage output waveform graph is presented Fig. 9.

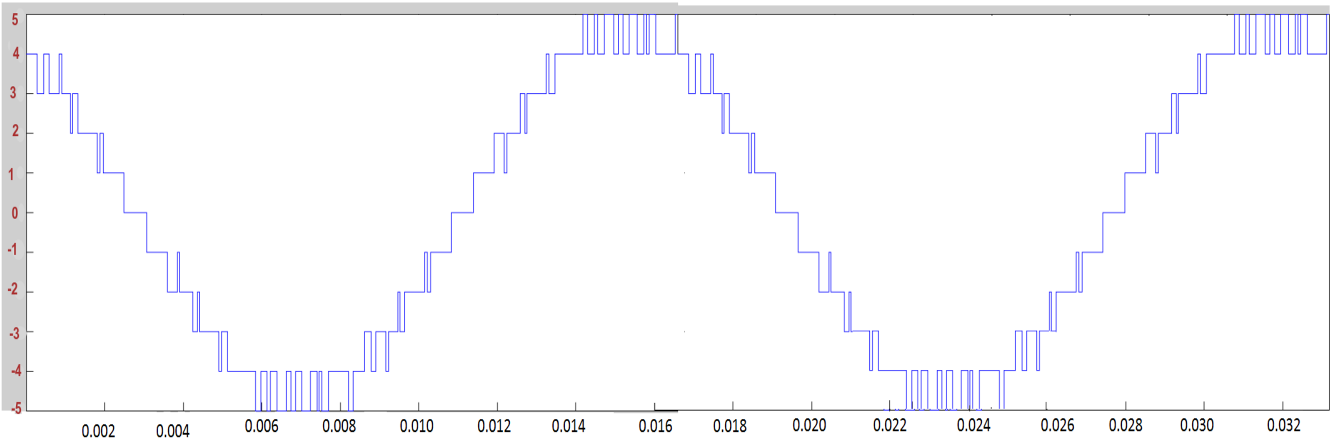

Fig. 9. Line Voltage across the converter in simulation

The voltage waveform again shows symmetry in the upper and lower half of the voltage. This occurs because of the symmetry of the times calculated for positive and negative voltages. The voltages can be applied in the same manner with same pulsewidth without any further calculation.

Thus these results have shown the functioning of the converter without any run time calculations. The output waveform obtained with the new scheme is good and can be easily modified by just changing the proportionality factor of switching time for certain sectors which improve the spread of the loop and can give better matching for sinusoidal waveform.

VII. Conclusions

In this paper the space vector modulation scheme for a two and multi-level converter has been analyzed. The basic driving forces for using a multi-level converter over a two level converter has been discussed. A novel algorithm for implementing space vector modulation for multi-level converter has been described. The concept of variable switching time and its advantages has been described. The simulation results have been presented to show that the new scheme works properly for the inverter and gives better output without any runtime calculations. Further it has been shown that the new scheme tends to produce lesser THD in the waveform than conventional algorithm due to higher symmetry of switching time.

References

[1] V T Ranganathan, “Space vector pulse width modulation – a status review,” Sadhana, vol. 22 part 6, pp. 675-688, December 1997.

[2] Bengi Tolunay, Space vector modulation for three-level converters, Upasala University, 2012, pp.26-34.

[3] Jin woo jung, “project#2 Space vector pwm inverter,” The ohio state university, 20-Feb-2005.

[4] J.Rodriguez, S.Lai, and F. Z. Peng, “Multilevel inverters: survey of topologies, controls and applications,” IEEE Transactions on industry applications, vol. 49. no. 4, Aug 2002, pp. 724-738.

[5] Kai CAI and Shanmei CHENG “A general SVM strategy for n-level m-phase converter,” Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE..

[6] Dhana Prasad Duggapu and Swathi Nulakajodu “Comparison between diode clamped and H-bridge Multilevel converter,” VSRD -IJEECE, Vol. 2(5), 2012, 228-256

[7] Sule Ozdemir, Engin Ozdemir, Leon M. Tolbert and Surin Khomfoi “Elimination of Harmonics in a Five-Level Diode-Clamped Multilevel Inverter Using Fundamental Modulation,”IEEE PEDS pp. Vol. 2007