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A SHEPWM Technique With Constant v/f for Multilevel Inverters

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ABSTRACT

This paper concern on a new application of selected harmonic elimination pulse width modulation technique (SHEPWM) for multilevel inverters. In this paper, first, the switching angles are calculated using constrained optimization technique. With these switching angles both the fundamental harmonic can be controlled and the selected harmonics can be eliminated. Then, using these calculated switching angles, a set of equation is formed which calculates the switching angles with respect to modulation index. Using this technique three-phase voltage has been obtained from a five-level cascade inverter. This voltage is applied to an induction motor. The dynamic behaviour of the induction motor has been examined for constant v/f operation and the simulation results have been given.

Keywords: Multilevel inverter, SHEPWM technique, optimization theory, induction motor, v/f operation.

Çok Seviyeli İnverterler için Sabit v/f Özellikli Bir SHEPWM Tekniği

ÖZET

Bu makale, çok seviyeli inverterler için seçilmiş harmonikleri yok eden darbe genişlik modülasyon (SHEPWM) tekniğinin yeni bir uygulamasını açıklamaktadır. Makalede ilk olarak, sınırlayıcılı optimizasyon tekniği kullanılarak anahtarlama açıları hesaplanır. Bu anahtarlama açıları ile hem temel harmonik kontrol edilebilir ve hem de seçilen harmonikler yok edilebilir. Sonra, bu hesaplanmış anahtarlama açıları kullanılarak; modülasyon indeksi değişkenine göre anahtarlama açılarını hesaplayan denklem kümesi elde edilmiştir. Bu denklemler kullanılarak 5-seviyeli kaskad inverterden üç-fazlı gerilim Elde edilmiştir. Bu gerilim bir asenkron motora uygulanmıştır. Sabit v/f çalışma için asenkron motorun dinamik davranışı incelenmiş ve simülasyon sonuçları verilmiştir.

Anahtar Kelimeler: Çok seviyeli inverter, Seçilmiş harmonikleri yok eden darbe genişlik modülasyon tekniği, Optimizasyon teorisi, asenkron motor, v/f çalışma.

1. INTRODUCTION

Multilevel inverters have become an effective and practical solution for increasing power and reducing harmonics of ac waveforms. The main advantages of multilevel PWM inverters are the following: 1) The series connection allows high voltage without increasing voltage stress on switches. 2) Multilevel waveforms reduce the dv/dt at the output of an inverter. 3) At the same switching frequency, a multilevel inverter can achieve lower harmonic distortion due to more levels of the output waveform in comparison to a two level inverter (1). Various multilevel inverter topologies have been proposed and implemented (1-7). There are three reported basic topologies of multilevel inverters: Diode-clamped, Capacitor-clamped, and Cascade multilevel inverters (7,9).

The concept of diode-clamped multilevel inverters was first introduced by Nabae in 1981. The general structure of the multilevel inverter is to synthesize a sinusoidal voltage from several levels of voltages, typically obtained from capacitor voltage sources. Unfortunately this structure is quite limited not only due to voltage unbalance problems but also due to voltage clamping requirements (2).

In order to eliminate the clamping diodes the capacitor-clamped topology has been developed and used in many applications. The voltage level of the capacitor-clamped multilevel inverter is similar to that of the diode-clamped multilevel inverter. However, the advantage of the capacitor-clamped inverter is to have two or more switching combinations at the mid levels of the output voltage (7).

The cascade multilevel inverter topology which is formed by series connections of one phase bridge type inverters (H-bridge) is simpler than the other two types of topology and packaging is possible. The number of output voltage levels can be easily adjusted by adding or removing the full bridge cells. The output voltage of cascade multilevel inverters is determined by the synthesation of the voltage of the isolated dc sources.

If the three multilevel inverters mentioned above are compared each other all require the same number of main switches per phase leg. The diode-clamped multilevel inverters require extra clamping diodes, the capacitor-clamped topology require extra balancing capacitor and the cascade multilevel inverter topology needs additional isolated dc sources.

Each phase of the multilevel inverters is formed by series or parallel connection of the switching devices. This topology decreases the power ratings of the switching device and increase the output voltage and output power.

It is generally accepted that the performance of an inverter with any switching strategies, can be related to the harmonic contents of its output voltage. As the number of input voltage levels increases the output waveform approaches the sinusoidal wave with minimum harmonic distortion (8). Power electronic researchers have always studied many novel control techniques to reduce harmonics in such waveforms. In multilevel topology several well-known modulation techniques are used. These modulation techniques are Subharmonic Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM), and Selected Harmonic Elimination Pulse Width Modulation (SHEPWM) (3,6,9,10).

SPWM strategies for multilevel inverters employ extensions of carrier based techniques used for two level inverters. The control principle of the SPWM method is to use several triangular carrier signals with only one modulation wave per phase. It has been shown that the spectral performance of a multilevel waveform can be significantly improved by employing alternative dispositions and phase shifts in the carrier signals, however, the side band harmonics occur at the carrier frequency. As the carrier frequency is much higher than the fundamental, those harmonics in the output voltage are not so important and can be eliminated using filter circuits (3,13)

In the SVPWM technique; any three-phase quantities e.g. three-phase voltages and currents can be represented by a space vector in a d-q plane via Park's transformation. The vector starts from the origin and ends at the certain point so that the length and the phase angle of the vector together represent the instantaneous values of the particular three-phase quantities [8]. In the SVPWM technique, the calculation of dwell-time and selection of sectors are similar to that of the two level inverters. The hardware implementation of the technique is simple and the current ripples are very low. Therefore SVPWM technique is suitable for high power/voltage applications (9).

Selected harmonic elimination PWM technique is introduced by Patel and Hoft (11). The idea of the technique is that the basic square-wave output is " chopped " a number of times, which are obtained by proper off-line calculations. The results are then either directly stored in look-up tables or interpolated by simple functions for real time operation. The SHEPWM based methods can theoretically provide the highest quality output among all the PWM methods. The disadvantage of this technique is that if the number of switching angles are increased then the look up table requires much memory space.

In this paper, a new application of the SHEPWM technique used in the multilevel inverters is introduced. The simple algebraic equations which calculates the switching angles according to given modulation index are formed. These algebraic equations use pre-calculated switching angles according to predefined criteria's. As these equations can be easily solved by the microprocessors or DSP's the use of look-up table is, thus, eliminated.

Using this technique, the three-phase voltage are obtained from a five-level cascade inverter and applied to an induction motor. The dynamic behaviour of the induction motor is examined and the simulation results are given.

2. MULTILEVEL SHEPWM TECHNIQUE

SHEPWM technique is first introduced by Patel and Hoft and it is an effective technique for the elimination of low order harmonics in two and three-level inverters (11). This technique is further extended to be used in multilevel inverters.

Figure 1 shows three-phase structure of a five-level cascade inverter. As can be seen in the figure, each phase consist of two series connected H-bridge inverters H_1 and H_2. Each H bridge cell is fed by an isolated separate dc source. The output phase voltage of the inverter is the sum of the output voltage of these cells.

The switching angles for each cell of the five-level cascade inverter are calculated by using SHEPWM technique for only a quarter of a period. Figure 2 illustrates the general quarter wave symmetric five-level SHEPWM switching pattern. α_i and β_i's are the switching angles of the cells H_1 and H_2 respectively. Each cell of such a single-phase inverter switches m times per quarter cycle. Owing to the symmetries in the PWM waveforms, only the odd harmonics exist.

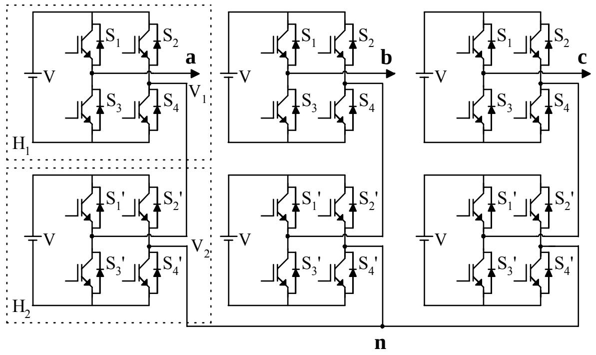


Figure 1. Three-phase structure of a five-level cascade inverter.

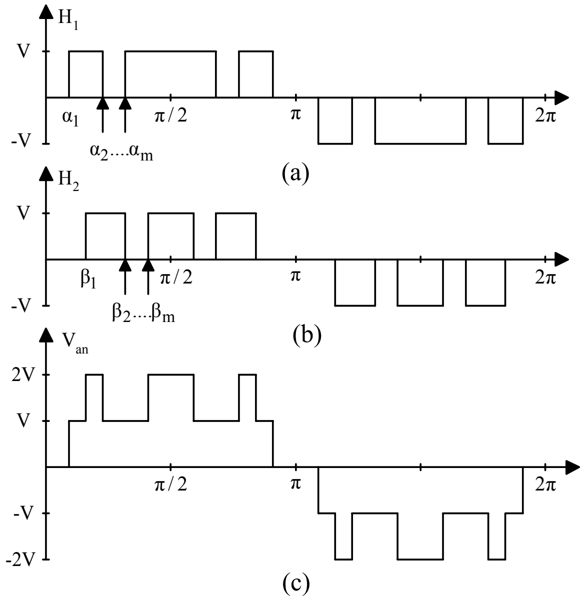


Figure 2. Waveform of five-level SHEPWM.
(a) Output voltage of H_1 bridge.
(b) Output voltage of H_2 bridge.
(c) Phase voltage.

The amplitude of the nth harmonic of the inverter phase voltage can be written from the sum of the output voltages of the cells H_1 and H_2 as (6).

$$V_n = \frac{4V}{n\pi}(\cos n\alpha_1 - \cos n\alpha_2 + ... \pm \cos n\alpha_m + \cos n\beta_1 - \cos n\beta_2 + ... \pm \cos n\beta_m) \quad (1)$$

Where n is the order of the harmonics, and V is the input dc voltages of the cells H_1 and H_2 respectively.

Theoretically, 2m-2 odd harmonics can be eliminated by solving 2m-1 nonlinear equation. This is achieved by equating the amplitudes of the selected harmonics to zero and setting the fundamental to a desired value.

It is very difficult to solve such a set of equations numerically due to the convergence problem and it also requires considerable computation. For such problems, in order to overcome the computational problems a constrained optimization approach has been proposed (4,6). For the full solution of this optimization scheme, the cost function and the constraints for α and β switching angles can be written as,

Cost function:

$$F = (V_1 - 2M)^2 + V_5{}^2 + V_7{}^2 + ... \quad (2)$$

Constraints:

$$0 < \alpha_1 < \alpha_2 < ..... < \alpha_m < \pi/2$$
$$0 < \beta_1 < \beta_2 < ..... < \beta_m < \pi/2 \quad (3)$$

Where F is the cost function, M is the modulation index, V_1 is the amplitude of the fundamental, and, V_5, V_7,... are the amplitudes of the 5th and 7th selected harmonics which are going to be eliminated.

Matlab/Optimization toolbox is a very useful software package for the solution of multi-variable constrained optimization problems. In this paper, “fmincon” function is used in the algorithm for the determination of α and β values. The figure 3 shows the variation of switching angles as a function of modulation index. These results have been obtained by taking 3 switching angles for each bridge cell and using equations (1-3) the 5th, 7th, 11th and 13th harmonics are eliminated in the range between 0.05-1.15 of modulation index. The figure 4 shows the results for the elimination of 5th, 7th, 11th, 13th, 17th, 19th, 23rd and 25th harmonics in the same range of modulation index. This time 5 switching angles are used.

As there are no triplen harmonics in three-phase star connected isolated-neutral systems, there is no need to extend the algorithm to eliminate the triplen harmonics in the solution of the nonlinear equation set (14). In general, the most significant low-frequency harmonics are chosen for elimination by properly selecting angles among different level inverters, and high frequency harmonic components can be readily removed by using additional filter circuits.

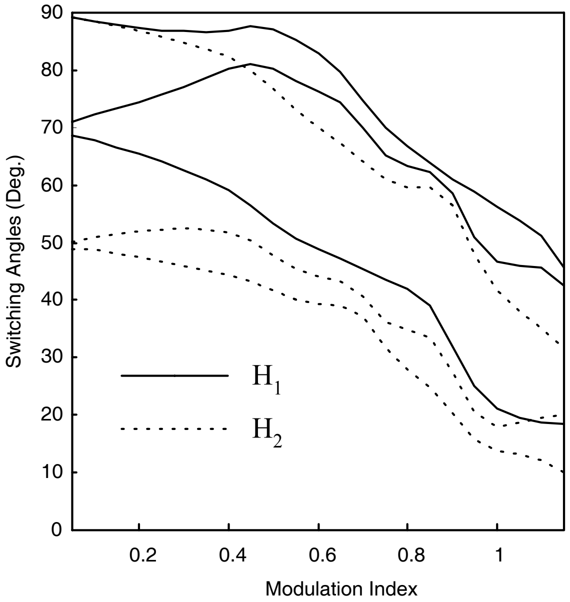


Figure 3. Switching angles as a function of modulation index (m=3).

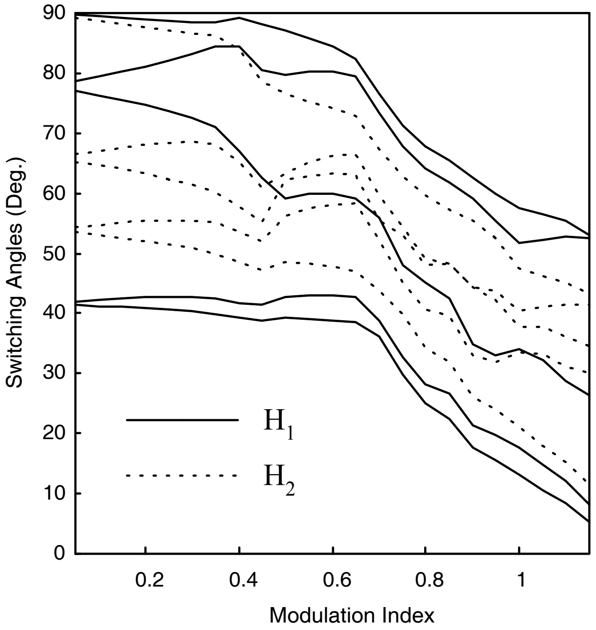


Figure 4. Switching angles as a function of modulation index (m=5).

3. EQUATIONS FOR THE DETERMINATION OF SWITCHING ANGLES

Due to the high complexity, the determination of switching angles on-line during real-time operation is considered to be impractical. Hence, firstly the equations are solved off-line. The results are then stored in look-up tables for real-time operations. The switching angles corresponding to any modulation index can be easily determined using this look up table. The look-up table stores the switching angles, which correspond to modulation index. For this, the modulation index increased with steps starting from an initial value and for every step of modulation index, the corresponding switching angles are determined and stored in the look-up table. In order to find the switching angles for any modulation index the step must be kept very small. This makes look-up table to occupy much memory space and making the algorithm very long.

In this study, a new technique is used for the computation of the switching angle during real-time operation. This technique avoids the use of look-up tables for the computation of the switching angles. The technique is based on the simple functions, which represent the off-line calculated solution trajectories and obtained by a suitable curve fitting technique. Thus, the output of the optimal SHEPWM switching strategy is represented as a set of curves which define the switching angles for any given modulation index. The modulation index between the values of 0.05 and 1.15 is divided into five regions. Third order polynomial curve fitting is applied to every region. “Polyval” function of the Matlab has been used for the construction of the polynomial functions. Figure 5 shows these regions. As the switching angles vary approximately linear with low values of modulation index, the first region is kept larger than the others.

In the analysis, the number of region is kept the same both for m=3 and m=5. If the number of region is decreased then the order of polynomial should be increased. However, this would increase computation time. Equations (4) show the variation of switching angles as a function of M in the second region for m=3.

$$\alpha_1 = 431.7357\ M^3 - 724.9738\ M^2 + 360.8806\ M + 0.0001$$

$$\alpha_2 = 263.4361\ M^3 - 614.4191\ M^2 + 401.2735\ M + 0.0002$$

$$\alpha_3 = 196.1671\ M^3 - 569.5637\ M^2 + 409.3648\ M + 0.0001$$

$$\beta_1 = 211.5309\ M^3 - 399.5012\ M^2 + 229.5341\ M + 0.0002 \quad (4)$$

$$\beta_2 = 291.2417\ M^3 - 530.5984\ M^2 + 287.3848\ M + 0.0003$$

$$\beta_3 = 559.3158\ M^3 - 977.3094\ M^2 + 501.9763\ M + 0.0001$$

The switching angles obtained from 3rd order polynomials and that obtained from optimization technique are very close to each other. This is shown in Tables 1 and 2 for M=0.6.

Table 1. Comparison of switching angles for m=3 and M=0.6

Switching Angles	Calculated value (Deg.)	The value obtained by curve fitting (Deg.)	Error (%)
α_1	48.7536	48.7928	0.080
α_2	76.2644	76.4756	0.276
α_3	82.8297	82.9481	0.143
β_1	39.4305	39.5909	0.406
β_2	44.1449	44.3240	0.405

β_3	70.0633	70.1667	0.147

Table 2. Comparison of switching angles for m=5 and M=0.6

Switching Angles	Calculated value (Deg.)	The value obtained by curve fitting (Deg.)	Error (%)
α_1	38.7802	38.9778	0.509
α_2	42.9010	43.2317	0.770
α_3	59.8143	60.0605	0.411
α_4	80.2979	80.6724	0.466
α_5	84.5050	84.7412	0.279
β_1	47.7368	47.9793	0.507
β_2	58.1824	58.7566	0.986
β_3	63.2534	63.9352	1.000
β_4	66.3079	66.9324	0.941
β_5	74.2243	74.5528	0.442

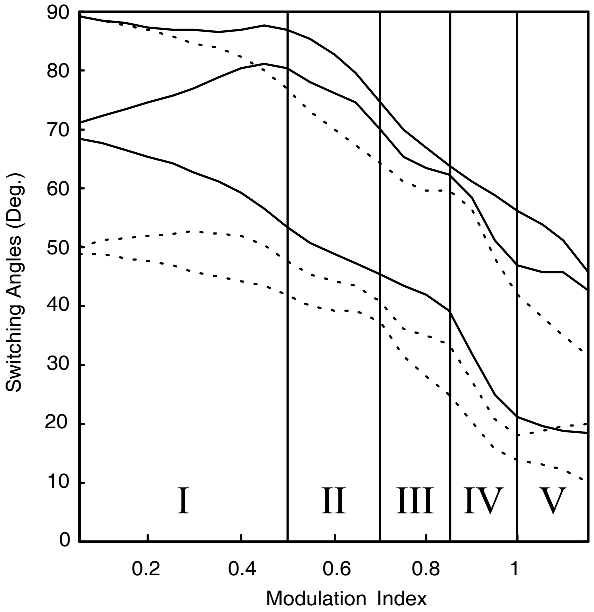


Figure 5. Constructed regions for m=3

Using the equations for every region shown in figure 5, both the amplitude and the frequency of the inverter output voltage can be controlled. It has been chosen that the modulation index M=1 to be occur at 50 Hz fundamental frequency. Thus the frequency range of 2.5-57.5Hz is obtained which corresponds to 0.05-1.15 modulation index range. The accuracy of the on-line generated switching angles depend on the proximity of functions and could be increased using higher order polynomials.

In this technique only the coefficients of the polynomial have to be saved in the memory. The flow chart of the algorithm is shown in figure 6.

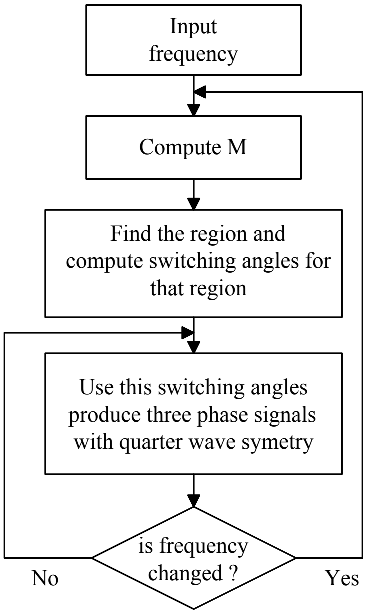


Figure 6. Flowchart for PWM waveform

4. ANALYSIS OF THREE-PHASE AC MOTOR FED BY FIVE-LEVEL CASCADE INVERTER

The simulation of an ac motor fed by a five-level cascade inverter has been carried out using the SHEPWM waveform as explained in the previous sections. For the simulation, the equations for the switching angles for each region shown in figure 5 in the range of 0.05-1.15 modulation index have been constructed. For any frequency, the one of the region in figure 5, which corresponds to the value of M maintaining constant v/f, is determined. The switching angles are calculated from the algebraic equations of the determined region. Using these switching angles, three-phase PWM waveforms with quarter wave symmetry is obtained. These three-phase voltage is applied to d-q model of an induction motor. Matlab/Power System Blockset has been used for the simulation and the block diagram is given in figure 7.

A s-function has been used for the calculation of switching angles. A time varying input frequency is used during the acceleration to maintain constant V/f ratio. The PWM waveforms for each H-bridge are then constructed according to the flowchart given in figure 6. 5 Nm load torque has been applied to the motor during the simulation. The other parameters are tabulated in Table 3.

Table 3. Motor parameters

Nominal Power	3 Hp
Line-line voltage	220V
Frequency, f	50Hz
Stator resistance, R_s	0.435 Ω
Rotor resistance, R_r	0.816 Ω
Stator inductance, L_s	2mH
Rotor inductance, L_r	2mH
Mutual inductance, Lm	69.31mH

Inertia, j	0.089 kgm^2
Pairs of poles, p	2

The simulation results have been presented in figure 8-11. The simulations have been done for m=3, m=5 and for f=25 and f=50 Hz fundamental frequencies. As can be seen from the simulation results, both selected harmonics are eliminated and a variable amplitude and frequency ac voltages are obtained.

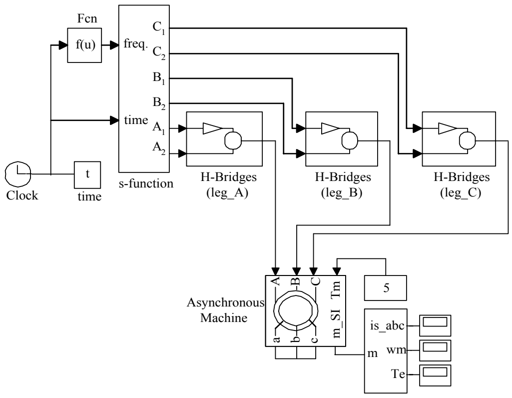
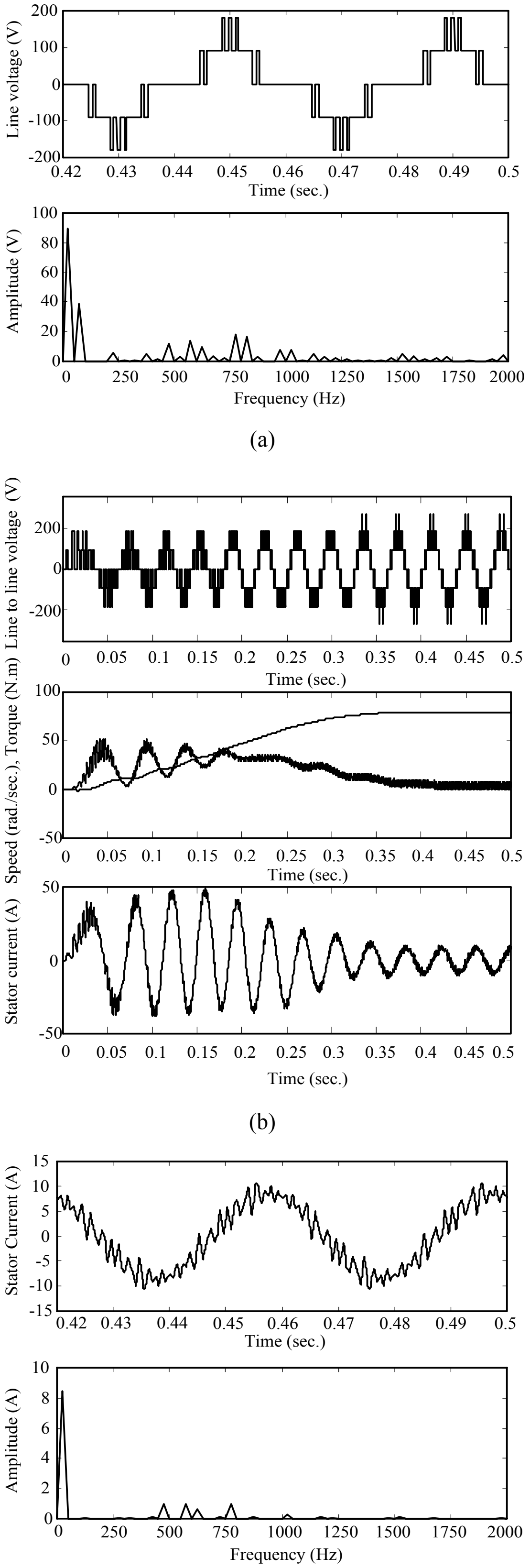


Figure 7. Block Diagram of the system.

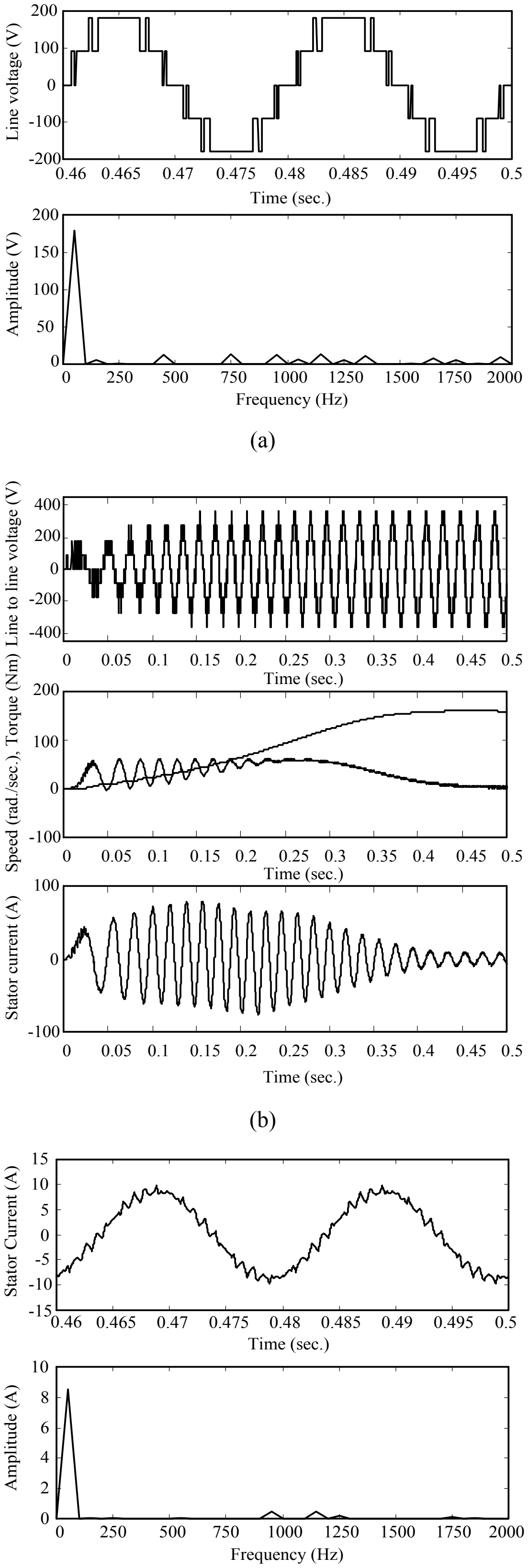


(a)

(b)

(c)

Figure 8.Waveforms for m=3 and f=25Hz.



(a)

(b)

(c)

Figure 9.Waveforms for m=3 and f=50Hz.

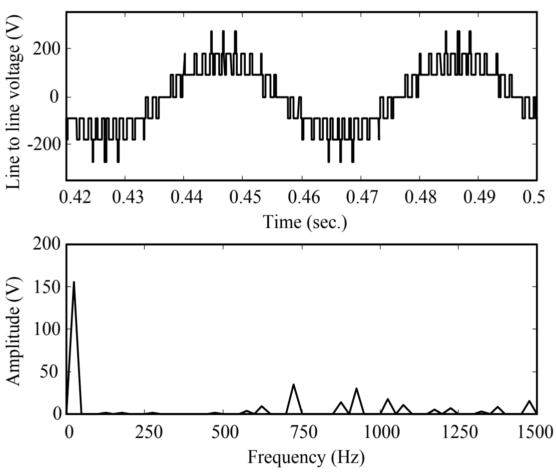


Figure 10.Waveforms for m=5 and f=25Hz.

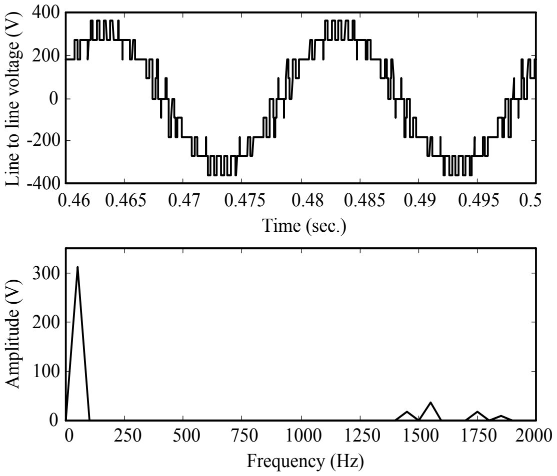


Figure 11.Waveforms for m=5 and f=50Hz.

5. CONCLUSION

In this paper, a new application of SHEPWM technique which both eliminates the selected harmonics and controls the fundamental component of the line voltage has been studied. Three-phase voltage has been obtained from a five-level cascade inverter using the switching angles determined from algebraic equations. The three- phase voltage is applied to an induction motor and dynamic behaviour of the induction motor has been examined under v/f control.

In the proposed SHEPWM application, there is no need to save all the switching angles which correspond to modulation index values as in the conventional SHEPWM technique. Here, only the coefficients of the algebraic equations are saved in the memory. Hence, less space has been used in the memory, which makes it suitable to implement practically using microprocessors and DSP's.

The simulation results show that using the proposed technique of the voltage can be controlled in a wide range. If the number of selected harmonics which are going to be eliminated from the line voltage are increased either the level of the inverter or the number of switching angle in a quarter period needs to be increased.

6. REFERENCES

1. Li L.., Czarkowski D., Liu Y., and Pillay P.,:Multilevel Space Vector PWM Technique Based on Phase-Shift Harmonic Suppression. Applied Power Electronics Conference and Exposition, 2000. APEC 2000. Fifteenth Annual IEEE, Vol.1, pp. 535-541, February 2000
2. Nabae A., Takahashi I., Akagi H., A new Neutral-Point-Clamped PWM Inverter, IEEE Trans. Industry Applications, Vol. 19, No 6, pp. 1057-1069, Nov/Dec. 1983.
3. Sirisukpraset S., Lai J.S., Liu T.H., Optimum Harmonic Reduction with a Wide Range of Modulation Indexes for Multilevel Converters. Annual Power Electronics Seminar, September 19-21, 1999.
4. Lund R., Manjrekar M.D., Steimer P. and Lipo T.A. Control Strategies for a Hybrid Seven-Level Inverter, European Power Electronics Conference, pp. 1-10, Sept. 1999, Lausanne Switzerland.
5. Tolbert L.M., Peng P.Z, Habetler T.G., Multilevel Converters for Large Electric Drives, IEEE Transactions on Industry Applications, Vol. 35, No. 1, pp. 36-44, Nov/Dec. 1983.
6. Li L.., Czarkowski D., Liu Y., and Pillay P., Multilevel Selective Harmonic Elimination PWM Technique in Series-Connected Voltage Inverters, IEEE Trans. Ind. App. Vol. 36, No. 1, pp. 160-170, January/February 2000.
7. Lai J.S., and Peng F.Z., Multilevel Converters - A New Breed of Power Converters, IEEE Transactions on Industry Applications, pp.509-517, May/June 1996.
8. Zhang H., Jouanne A.V., and Wallace A, Multilevel Inverter Modulation Schemes to Eliminate Common Mode Voltages, IEEE Industry Applications Conference, Thirty-Third IAS Annual Meeting. Vol.1, pp. 752 –758, 1998.
9. Celanovic N., Space Vector Modulation and Control of Multilevel Converters, Doctor of Philosophy, Faculty of the Virginia Polytechnic Institute and State University, 20 September 2000.
10. Quin J., Lipo T.A., Switching Angles and DC Link Voltages Optimization for Multilevel Cascade Inverters. Electric Machines and Power Systems Conference, 1999.
11. Patel H.S. and Hoft R.G, Generalized technique of harmonic elimination and voltage control in thyristor inverters, Part I: harmonic elimination, IEEE Trans. Ind. App., Vol. IA-9, pp. 310-317, May/June 1973.
12. Sun J., Beineke S., Optimal PWM Based on Real-Time Solution of Harmonic Elimination Equations, IEEE Transactions on Power Electronics, Vol.11, No.4, pp.612-621, July 1996.

13. Carrara G., Gardella S., Marchesoni M., Salutari R., Sciutto G., A New Multilevel PWM Method: A Theoretical Analysis, IEEE Transactions on Power Electronics, Vol.7, No.3, pp. 497-505, July 1992.

14. Tuncer S., Tatar Y., Harmonic Optimization Method for Cascade Multilevel Inverters, 2nd FAE International Symposium, pp. 457-460, November 2002.