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Realization of Single Phase to Three Phase Matrix Converter using SVPWM Algorithm

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Original scientific paper

The direct AC to AC conversion techniques adopted in the implementation of the single phase to three phase converters do not yield the best output results due to the complexity of the segregation process and bidirectional nature of the input signal. Number of initiatives has been reported adopting a mid DC Link path for creating more appropriate results. However, none of them provides convincing results in producing the standard three phase output signals that are equal in magnitude and 120 degrees away from each other. This paper reports a novel attempt in implementing the space vector pulse width modulation based Matrix Converter system for direct single phase to three phase conversion using IGBT based bi-directional switches that produce convincing three phase output signals from a single phase voltage source.

Key words: Matrix Converters, Space Vector Algorithm, Single to Three Phase, Segregation method

Realizacija jednofazno-trofazne matrične transformacije koristeći SVPWM algoritam. Direktna AC/AC pretvorba preuzeta u implementaciji jednofazno-trofaznog konvertera ne daju najbolje rezultate zbog složenosti procesa segregacije i dvosmjerne prirode ulaznog signala. Mogu se pronaći mnoga rješenja koja koriste središnji DC link za dobivanje odgovarajućih rezultata. Međutim, niti jedno od postojećih rješenja ne daje dovoljno dobar rezultat koji se sastoji od standardne tri faze jednake amplitude koje su međusobno udaljene 120 stupnjeva. U ovome radu prikazana je nova metoda implementacije modulacije širine vektora temeljena na matričnoj transformaciji za jednofazno-trofaznu transformaciju koristeći IGBT dvosmjerne sklopke koje daju zadovoljavajući trofazni signal dobiven iz jednofaznog naponskog ulaznog signala.

Ključne riječi: matrične transformacije, vektorska modulacija, jednofazno u trofazno, metoda segregacije

1 INTRODUCTION

Conversion of single phase to three-phase is always an interesting task in the direct ac-ac converters sector. Having a converter that is capable of converting a single phase source voltage into a three phase balanced system has numerous advantages such as operating a three phase induction motor using a single phase source. Single phase to three-phase Matrix Converter system adopts the direct ac-ac conversion technique that converts the single phase alternating source voltage to three phase alternating voltages that are equal in magnitude and differ by 120° from each other. This type of converter has the high potential of applications where only single phase source is available such as at home, remote town, hill stations, mobile power source etc. The major difficulty in such converters is the alternating and bidirectional nature of the input signal. However, advance switching algorithm such as space vector modulation can be utilized to segregate the input signal along with the bidirectional IGBT Switches based Matrix Converter to produce the required three phase output waveforms. Matrix Converter enables the bidirectional power flow. Space Vector Pulse Width Modulation is a unique technique that makes the switching complexity of AC-AC converters much easier. Attempts are being made to utilize the space vector pulse width modulation techniques in the variable frequency drives. Due to this growth, newer topologies are being introduced with superior performance characteristics such as minimum harmonic content and unity power factor operation. This paper provides the details of the implementation of Space Vector PWM modulation scheme, IGBT based bidirectional switch design and the six switches Matrix Converter system in the realization. This paper also covers the related research initiatives, proposed simulation model and the hardware realization model. It also incorporates the results and findings of the proposed topology.

2 RELATED RESEARCH INITIATIVES

Many related research initiatives are being carried out by other researchers in the realization of single phase to three phase conversion. A separation and link approach using sinusoidal PWM modulation scheme has been reported [1]. However high vibration and low voltage transfer ratio issues were reported [1]. Lino.k et al suggested a compensation capacitor based Matrix Converter method in which the amplitude of the compensated capacitor is utilized to absorb the single phase power fluctuations. [2].In another approach, a power decoupling capacitor and a LC filter circuit are used to reduce the torque vibration and elimination of harmonic & pwm ripples respectively. [3]. Another research suggested using a full bridge rectifier – inverter combo circuits without dc filters are used to produce the three phase waveforms [4]. Relatively, in another research, an ac reactor with three additional bidirectional switches is used to compensate the fluctuations to obtain the pure sine wave [5].The major issue reported in the earlier research is the low voltage transfer ratio which can be defined as the ratio between the output phase voltage and the input supply voltage. It is reported that the maximum voltage transfer ratio achieved is 0.31 using sinusoidal pwm modulation [1]. This research reports a relatively new modulation technique called space vector pwm modulation in view of enhancing the voltage transfer ratio.

3 SINGLE PHASE TO THREE PHASE MATRIX CONVERTER SYSTEM

Matrix Converters are getting popularity in the three phase inverters and direct ac-ac three-phase to three-phase converters [6]. Using a single phase source as an input is a relatively challenging attempt. Fig. 1 shows the block diagram of the Single phase to three phase (SP2TP) Matrix converter system.

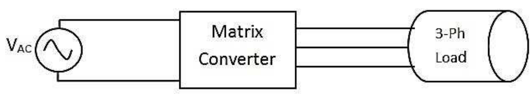

Fig. 1. SP2TP Matrix Converter System

The Matrix Converter system consists of six bi-directional switches with reverse blocking capabilities, in which two switches are allocated for each phase for forward and reverse flow of power. The six bi-directional switches are arranged in three limbs each carrying two switches as shown in Fig. 2. The midpoints between the switches in each limb are used as the output terminals of the converter. Due to this arrangement, there are eight possible states of Matrix Converters operations such as 100, 101, 110, 010, 011, 001, 000 and 111. Out of the eight available states, 000 and 111 are inactive states whereas the rest of the states are active states. Every half cycle of the source voltage is treated as a separate converter and thus the Matrix Converter operates as two equivalent converters in contrary series. The operations states have been obtained for the source positive and negative periods with rational states combinations. SPWM signals were used as the control signals. The proposed strategy was verified with a three phase balanced resistive load.

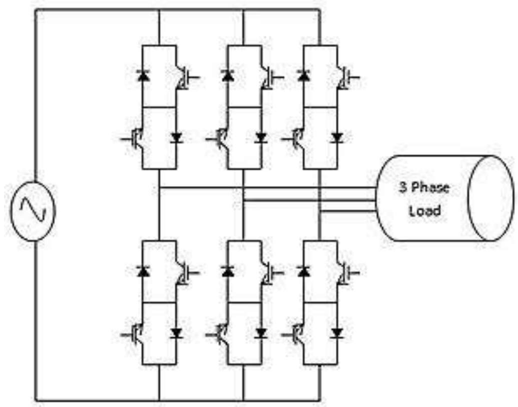

Fig. 2. Bidirectional IGBT Switches based Matrix Converter

Space Vector Pulse Width Modulation technique utilizes the magnitude and phase angle of the resultant vector of the three phase instantaneous voltages vectors to generate the PWM signals.The derived equivalent vector component is termed as Space Vector.

The objective of the SVM is to produce voltage and currents nearing unity power factor. However, due to a number of hardware limitations, attaining unity power factor has become more difficult. This paper attempts to describe the most stable and simplest space vector modulation technique for the single phase to three phase conversion using SP2TP Matrix Converters. The unique contribution in this research is to implement the space vector pwm modulation technique to control the matrix converter operation.

4 GENERALIZED THEORY OF SPACE VECTOR MODULATION

Space Vector Modulation technique adopts the Rotating Magnetic Field theory in which the instantaneous resultant flux of the three alternating fluxes that are 120° away produces the rotating magnetic field at synchronous speed.

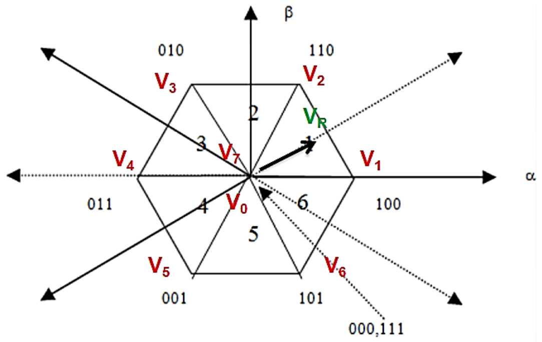

Fig. 3. Space Vector Sectors

Similarly, three phase voltages can be represented as a resultant voltage vector V_R whose loci of the tip travel in a circle. The circular path can be divided into six sectors based on the position of the phase angle variations. At any instant, the resultant voltage V_R can be transferred into α and β components using $\alpha\beta$-transform. The voltages $V_0, V_1, V_2 \ldots\ldots V_7$ represents the eight possible states between each sector as shown in Fig. 3.

At any particular moment, the resultant voltage vector V_R can be produced by appropriately firing the sector voltages at the given proportional time. Sampling Time T_S is the maximum time allocated to complete the switching of states to produce the equivalent resultant voltage vector. In Sector-1, the sequence of triggering would be $\boldsymbol{V_0 V_1 V_2 V_7 V_7 V_2 V_1 V_0}$, however, the sum of the time taken for this triggering sequence should be equal to the sampling time. The resultant voltage vector can be represented as α β components as shown below:

$$V_R = V_\propto + jV_\beta = \frac{2}{3}\left[V_a + a.V_b + a^2.V_c\right], \quad (1)$$

where $a = e^{j\frac{2\pi}{3}}$ and $a^2 = e^{j\frac{4\pi}{3}}$.

The orthogonal two phase components can be expressed as

$$\begin{aligned} V_\propto + jV_\beta = & (0.667V_a - 0.33\,(V_b + V_c)) \\ & + j\,(0.577\,(V_b - V_c)) \end{aligned} \quad (2)$$

The tip of the resultant space vector traces in the loci of a circle. At any instant, the resultant space vector can be equated to the average values of the voltages produced by operating the converter in the corresponding sector active states.

At any particular instant, the output phase voltages of any two windings that are shared carry a voltage of $0.333V_S$ and the other winding carries $0.667V_S$. In general, all the active vectors carry a voltage of $0.667V_S$.

If T_S represents the Sampling period, then the average value of the resultant voltage vector can be represented as follows:

The average voltage of the zero vectors V_0 and V_7 is Zero. Thus the fictitious time of the reference voltage vector can be represented as:

$$(V_R T_S) = (V_n T_n) + (V_{n+1} T_{n+1}) \quad (3)$$

$$\int_0^{\frac{T_S}{2}} V_R\, dt = \int_0^{\frac{T_O}{2}} V_O\, dt + \int_{\frac{T_O}{2}}^{\frac{T_O}{2}+T_n} V_n\, dt + \int_{\frac{T_O}{2}+T_n}^{\frac{T_O}{2}+T_n+T_{n+1}} V_n\, dt + \int_{\frac{T_O}{2}+T_n+T_{n+1}}^{\frac{T_S}{2}} V_7\, dt$$

The Sampling Time T_s can be written as

$$T_S = 2\,(T_O + T_n + T_{n+1}) \quad (4)$$

By substituting the values of the V_n and V_{n+1}, the reference voltage vector can be obtained in the $\alpha\beta$ components as

$$\begin{vmatrix} V \\ V \end{vmatrix} \frac{T_S}{2} = \frac{2}{3}V_S \left[\begin{vmatrix} cos\frac{(n-1)}{3} \\ sin\frac{(n-1)}{3} \end{vmatrix} T_n + \begin{vmatrix} cos\frac{(n)}{3} \\ sin\frac{(n)}{3} \end{vmatrix} T_{n+1}\right] \quad (5)$$

$$\begin{vmatrix} V \\ V \end{vmatrix} \frac{T_S}{2} = \frac{2}{3}V_S \begin{bmatrix} cos\frac{(n-1)}{3} & cos\frac{(n)}{3} \\ sin\frac{(n-1)}{3} & sin\frac{(n)}{3} \end{bmatrix} \begin{vmatrix} T_n \\ T_{n+1} \end{vmatrix} \quad (6)$$

The triggering times for the various sectors can be expressed in terms of $\alpha\beta$ components as

$$\begin{vmatrix} T_n \\ T_{n+1} \end{vmatrix} = \frac{\sqrt{3}}{2}\frac{T_S}{V_{RMS}} \begin{bmatrix} sin\frac{(n)}{3} & -cos\frac{(n)}{3} \\ -sin\frac{(n-1)}{3} & cos\frac{(n-1)}{3} \end{bmatrix} \cdot \begin{vmatrix} V_\alpha \\ V_\beta \end{vmatrix} \quad (7)$$

Using the above expression, the triggering time for various sector voltages can be estimated to produce the resultant space vector at any particular instant.

5 GENERATION OF THREE PHASE VOLTAGES

One of the possible ways to produce the three phase voltages that are 120 degrees away from each other from a single phase alternating sourceis to segregate the Single Phase Input Signal at appropriate angles and share the available power across the three phases. Based on the

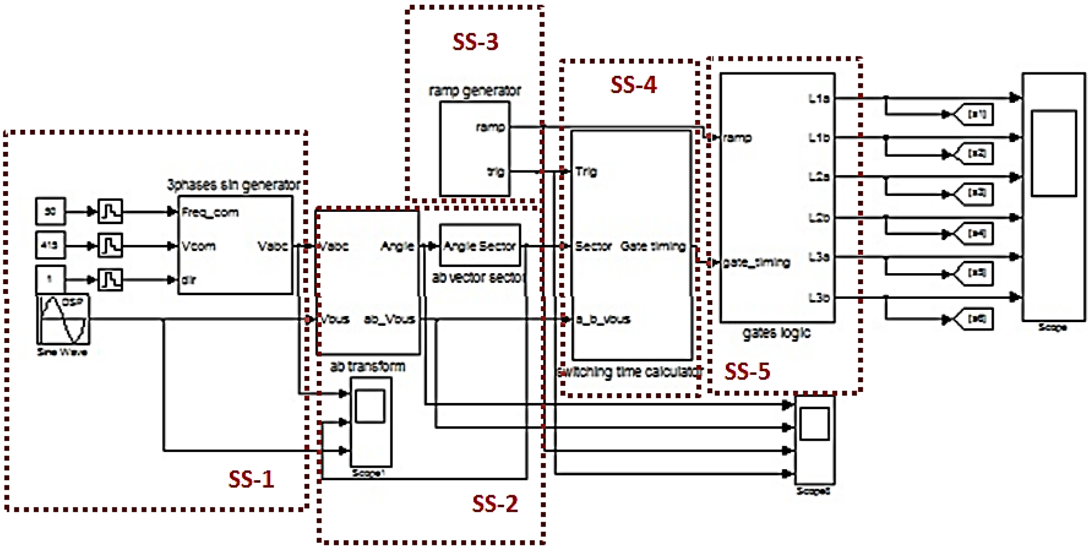

Fig. 4. Matlab Simulation of Space Vector PWM of Matrix Converter

Table 1. States of Firing Sequence

Sectors	Phase Angle of Input Signal	State of Firing Sequences
1	(0 – 60)	101
2	(60 – 120)	100
3	(120 – 180)	110
4	(180 – 240)	010
5	(240 – 300)	011
6	(300 – 360)	001

Space vector six sectors theory, the desired output can be obtained at any instant by switching the respective sector voltages for the pre calculated time. This segregation technique simplifies the firing sequence in such a way that one of the output phase voltages will be at peak value when the other two phases act as a return path.

Table 1 provides the comparison between sectors proportional to states of firing with the range of Phase-A angle distribution.

The $\alpha\beta$ component of the resultant voltage vector has a factor of 2/3. This factor limits the maximum possible peak voltage to 0.667 of the Input Peak Voltage (Vm). Thus the voltage transfer ratio of the system is 0.667. Further, at the midpoint of each sector of 60 degrees, two of the waveforms have half of its maximum magnitude and the third one will be at its peak value in the opposite direction. Thus the available input signal during the 60 degree duration should be utilized for the corresponding state of firing and the other two phases have to be treated as reverse path with half of the available magnitude.

In order to segregate the Phase-A waveform, during the first 60 degree, the Phase-A shares the input signal with Phase-C and both carry 33.33% of the input magnitude. Phase-B has the Peak amplitude of 66.67% but in the negative direction. The corresponding state to this condition is 101. During the second 60 degree range, the Phase-A will carry the available peak amplitude at positive direction where Phase-B and Phase-C carries half of the available magnitude in reverse direction. The state corresponding to this condition is 100.

Table 2 shows the specification of the proposed model of the single phase to three phase matrix converter system.

6 SIMULATION OF MATRIX CONVERTER SYSTEM

Matlab /Simulink application is used for the simulation of the proposed space vector PWM based single phase to three phase direct ac-ac Matrix Converter system. The proposed simulation circuit can be classified into two sections. The first section is the control system where the Space Vector Modulation PWM signals are generated taking sinusoidal fundamental frequency as a reference signal and the second section of the simulation circuit is the IGBT Bidirectional switches based Matrix Converter system for direct ac-ac conversion.

Figure 4 shows the Space Vector PWM based control circuit. It consists of five subsections. The first section is the Three phase sine wave generator module where the reference three phase voltages that are 120 degrees away from each other. The second subsection is the AB Transform

Table 2. Matrix Converter Specification

Specification of the proposed model	
Input Source	Single Phase, 240V, 50Hz
Output	Three Phase, (200V-400V), 50 Hz (12.5 Hz to 200 Hz)
Type of Converter	Direct AC-AC Converter
Adopted Converter	IGBT Based Matrix Converter
Adopted Modulation Scheme	Space Vector PWM
Design & Simulation	Matlab / Simulink
Inductive Load	30-Ph Induction Motor, Squirrel Cage Type, 0.75 kW, 220-240 / 380-415 V, 4 Poles, 1500 rpm, 50 Hz

module where the three phase voltages are transformed to two phase system based on Clarke Transformation. The second section also produces the sector signals for the six sectors adopted in the space vector algorithm. The third section is the Ramp Generator module where the high frequency carrier signal is produced. It also generates the high frequency pulse signals at carrier frequency. The fourth subsection is the Switching Time Calculator module where the timing signals are produced based on the sector reference voltages. The fifth module is the Gate Logic modules where the PWM signals are produced based on the switching time signals from the Switching Time Calculator modulator.

Figure 5 shows the simulink model of the Matrix Converter Circuit. Matrix converter is designed based on (3x2) switch arrangement with a total of six bidirectional swtichesthat were used for three limbs of the converter. Each limb of the Matrix Converter is designed using two Bidirectional switches for the forward and the other one for the reverse power flow.

Table 3 shows the simulation parameters of the proposed model of the Matrix Converter system.

Figure 6 shows the bidirectional switch of the Matrix Converter.Each switch is designed using two back to back common emitter IGBT modules with parallel diodes and snubber circuit for reverse voltage blocking. A sinusoidal single phase alternating voltage source is used as the power input to the converter. The three outputs are taken from the midpoints of each limb between the two bidirectional switches.

The proposed model was tested under different load conditions by varying the mechanical torque of the motor. The characteristics of the matrix converter were studied under different operating frequencies of the space vector algorithm for performance efficiencies.

Table 3. Specification of Simulation Model

Simulation Parameters	
Modulation Scheme	Space Vector PWM
Carrier wave	Saw tooth
Carrier Amplitude (Vcm)	1V
Carrier Frequency (fc)	4500 Hz
Carrier Wave Ratio =(fc) / (fr)	90
Modulation Index = (Vrm)/ (Vcm)	1.0
Vref Amplitude(Vrm)	Sinusoidal, 1V
Vref Frequency (fr) and Angle	50 Hz, zero
3-Ph Ref Amplitude	415 V
3-Ph Ref Frequency & angle	50 Hz, zero
No. of Samples per cycle	90
Sampling Time period (Ts)	222.2 μ s
Seconds per Degree	0.617 μ s
No. of degrees per sample	4
Sampling time per sector	3.33 ms

7 HARDWARE IMPLEMENTATION OF THE MATRIX CONVERTER SYSTEM

The proposed space vector PWM based Matrix Converter system can be realized practically using the state of

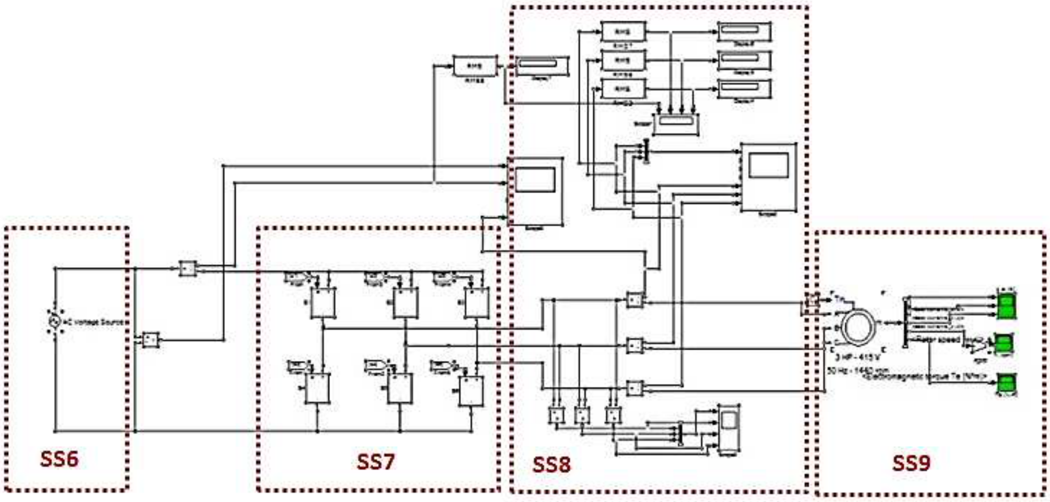

Fig. 5. Matlab Modeling of SP2TP IGBT based Matrix Converter Circuit

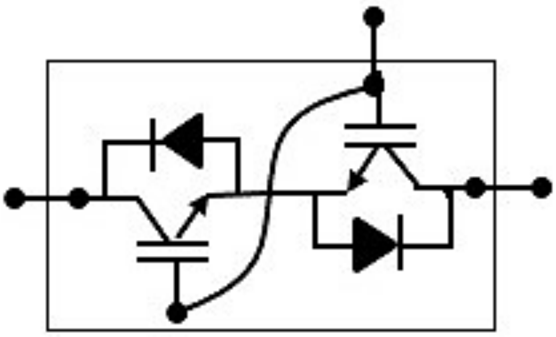

Fig. 6. Bidirectional Switch

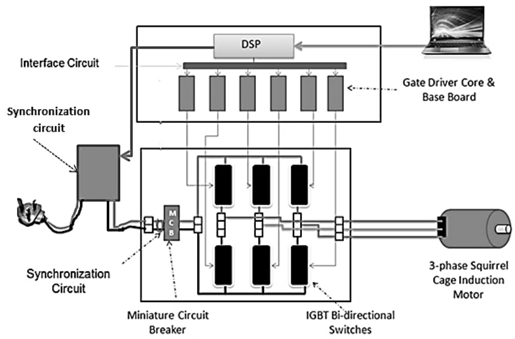

Fig. 7. Hardware Implementation of Matrix Converter System

the art hardware circuitry. Figure 7 provides the block diagram representation of the hardware implementation.

Based on the implementation of the space vector algorithm in the Matlab/Simulink tool, PWM signal codes can be generated using appropriate application and downloaded to the Digital Signal Processor (DSP). The digital signal processor generates the required PWM signals based on PWM codes and supplies to the Interface Circuit. The Interface circuit converts the low voltage PWM signals to an appropriate level that is suitable to drive the IGBT Core drivers. A separate IGBT core driver/ base board assembly has to be designed for individual bidirectional switches of the matrix converter.Appropriate gate resistors have to be used based on the selected IGBT characteristics. Six separate IGBT Core drivers are used to control the operation of the six switches of the matrix converter. IGBT Core circuits provided the necessary PWM pulses to the respective gate terminals of the bidirectional switches.Six modules of common emitter dual IGBTbased bidirectional switches are to be used to construct the Matrix Converters. Matrix Converter hardware can be designed using three legs with two bidirectional switches in each leg. It should be noted that the two switches connected in the same leg should not be operated at the same time in order to avoid direct short circuiting across the input source. The input single phase source is applied across the legs. The Three phase outputs are extracted from each leg between the two bidirectional switches. A Squirrel cage induction motor is used as a lagging power factor load. A Synchronization circuit is required in order to synchronize the PWM signals with the bidirectional sinusoidal input source. Additional coding has to be added to the DSP programming to provide the synchronizing pulse to trigger the closure of the input main circuit breakers. A miniature circuit breaker can be used as overload protection device to protect the equipment.

8 RESULTS AND OBSERVATIONS

Figure 8 shows the output line currents of the matrix converter. The output currents are found to be sinusoidal with the phase angle difference of 120° from each other. The combined waveform resembles the three phase system and produces three alternating fluxes which in turn produces the rotating magnetic field.

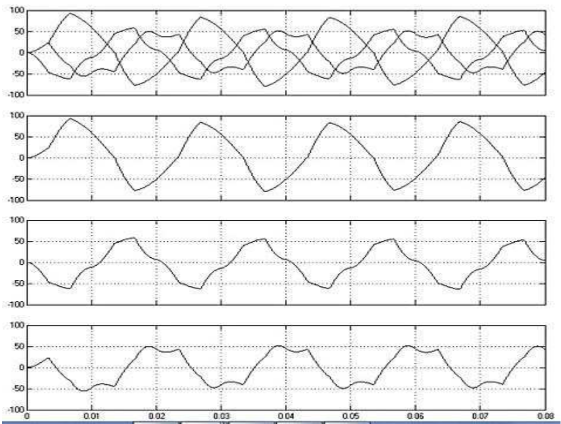

Fig. 8. Output Line Currents under Lagging Power Factor Load

The induction motor stator windings are connected in star, thus the line currents equals the phase currents of the motor.

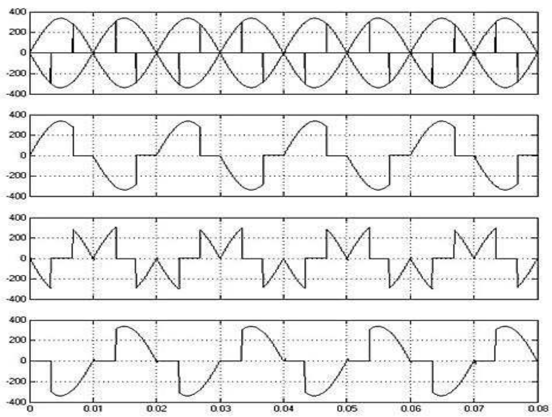

Fig. 9. Output Line Voltages under Lagging Power Factor Load

The line to line output voltages of the Matrix Converter are found to be uniformly alternating with the phase difference of120 degrees from each other. The converter output line voltages resembles the three phase system voltages, thus the induction motor achieves the required starting torque due to relative fluxes in the air gap. Fig.9 above shows the line to line output voltages of Matrix Converter.

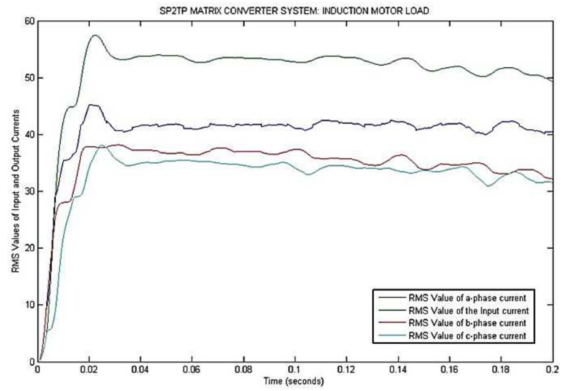

Fig. 10. RMS Values of Input & Output Currents

Figure 10 shows the rmsvalues of the input and output currents.The starting current of the induction motor is found to be 2% to 3% higher than the normal load current. But the currents are found to be unbalanced due to the presence of high harmonic content.

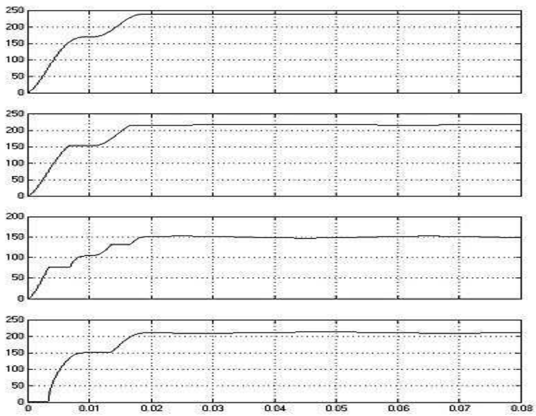

Fig. 11. RMS Values of Input & Output Voltages

Figure 11 shows the rms values of the input and output voltages. The difference in magnitude is caused due to the segregation of the input sinusoidal voltage. Irrespective of the inequalities, the performance of the induction motor is found to be smooth with appropriate slip corresponding to the applied mechanical load.

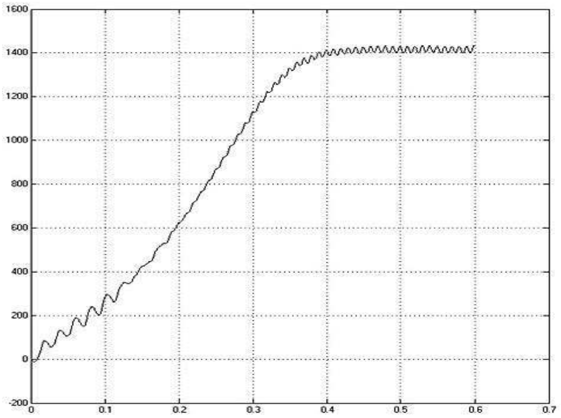

Fig. 12. Speed Characteristics under Induction Motor Load

Figure 12 shows the speed characteristics of the induction motor. In comparison with the standard speed characteristics of the motor, the speed characteristics of Matix Converter operated induction motor resembles closely to its standard three phase induction motor characteristics.howeverit suffers from minute vibrations. The vibration of the motor is caused due to the unbalanced variation in the phase voltages.

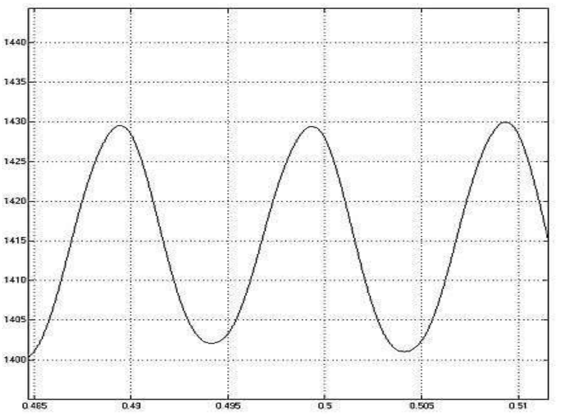

Fig. 13. Speed Fluctuation Characteristics

Figure 13 shows the speed fluctuation characteristics of the induction motor. The per unit slip fluctuation is found to be 0.02 of the synchronous speed. This 2% slip fluctuation doesn't have a significant effect in the overall performance of the induction motor.

9 TOTAL HARMONIC DISTORTION HD OF MATRIX CONVERTER SYSTEM

Based on the Fast Fourier Transform (FFT) analysis with the fundamental frequency of 50Hz, the Total Harmonic Distortion (THD) of various signals were studied. It is noticed that the THD of the three line parameters differ significantly due to the presence of high harmonic content;however it lies within the acceptable range.

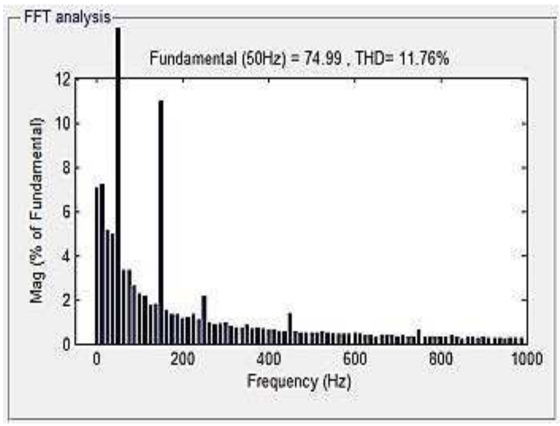

Fig. 14. THD Characteristics of 'a' phase current

Figure 14 shows the THD characteristics of phase 'a' current. The percentage THD of the phase 'a' current is found to be at 11.76% with 75% of the signal resides at fundamental frequency. It is noted that the old frequencies has the higher content compared to its equivalent even frequencies.

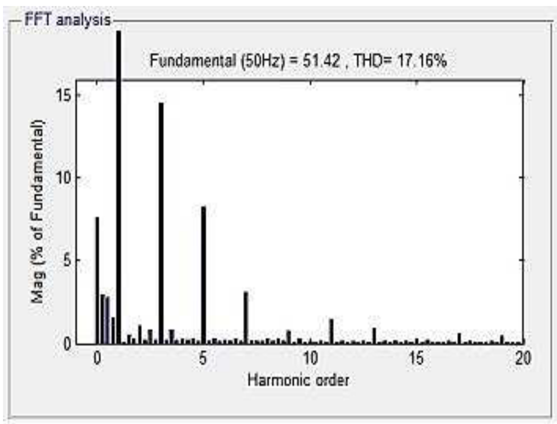

Fig. 15. THD Characteristics of 'b' phase current

Figure 15 shows the THD characteristics of phase 'b' current. The percentage THD of the phase 'b' current is found to be at 17.16% with 51.42% of the signal resides at fundamental frequency.

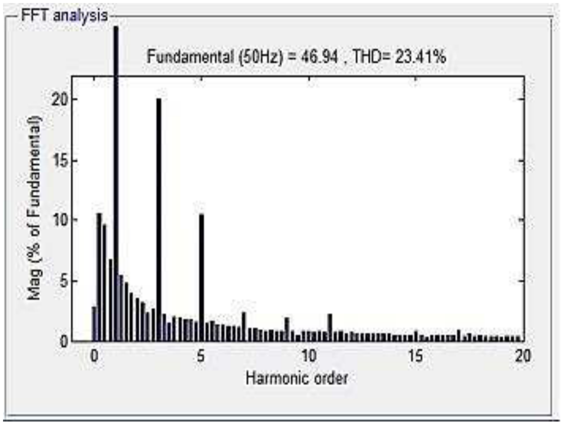

Fig. 16. THD Characteristics of 'c' current

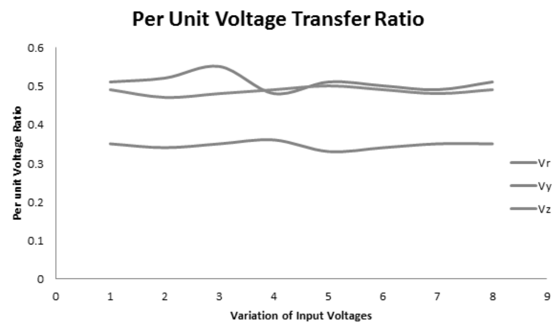

Fig. 17. Per unit VTR characteristics

Figure 16 shows the THD characteristics of phase 'c' current. The percentage THD of the phase 'b' current is found to be at 23.41% with 46.94% of the signal resides at fundamental frequency.

The efficacy of the proposed model is tested by applying varying input voltages and estimating its voltage transfer ratio (VTR)s. By using the sinusoidal pwm scheme a voltage transfer ratio of 0.31 has been achieved [1]. The voltage transfer ratio of the matrix converter is measured as the ratio of the output phase voltage to that of the input source voltage. Due to the adaptation of space vector pwm modulation, the voltage transfer ratio is found to be much higher than the other topologies.However, due to the unbalanced nature of the output waveforms, each phase has a different voltage transfer ratio. Fig. 17 shows the per unit voltage transfer ratio characteristics of the proposed Matrix Converter system. R-phase is noticeably high with the ratio of 0.51, whereasthe ratio of the Y-phase is 0.35 and the B-phase is 0.49. Compared to the related research finding, the ratio of all the phases are higher compared to 0.31 reported in Sinusoidal pwm modulation based topology/improvement to current technologies

The proposed space vector PWM based Matrix Converteris an unique system that has a potential to explore more research initiatives in the realizationof single phase to three phase direct ac-ac converters.The proposed methodology and the obtained results provide the fundamental concept of the implementation of using space vector PWM for single phase to three phase matrix converter system.The obtained results shall be used as grounds for further enhancement and improvements.

10 CONCLUSION

The SP2TP Matrix Converters is regarded as the next generation direct ac-ac converter which has promising features such as high reliability, efficient and stability operation. Its role in the power conversion of single phase to three phase system is commendable; however there is a huge avenue for improvements and to meet the expected standards. Besides, there is a promising hope that the proposed system can be further enhanced and that it could be commercialized through various applications for the betterment of human kind.

ACKNOWLEDGMENT

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