Comparative Analysis of Modulation Techniques in Frequency Converter

A. Agarwal [1], P. Sanjeevikumar [2,*], V. Agarwal [3], S. Rajasekar [4], M. Pastor [5], M. Cernat [6]

[1] Department of Electrical Engineering, National Institute of Technology, Delhi, India.
[2] Department of Electrical & Electronics Engineering, University of Johannesburg, Auckland Park, South Africa.
[3] Department of Electrical Engineering, M.N. National Institute of Technology, Allahabad, India.
[4] Technology and Development, Power Grid Corporation of India Limited, Gurgaon, India.
[5] Department of Electrical Engineering & Mechatronics, Technical University of Košice, Košice, Slovak Republic.
[6] Department of Electrical Engineering, Transilvania University of Brasov, Brasov, Romania.
* Corresponding Author Email: sanjeevi_12@yahoo.co.in

***Abstract*–A generalized frequency converter has been realized which makes use of a cyclo-converter in newer form AC-AC converter. An attempt has been made to operate this converter both in a conventional low frequency AC-AC converter and a new high frequency AC-AC converter. The ability to directly affect the frequency conversion of power without any intermediate stage involving DC power is a huge advantage of the system. The output of this converter has a frequency either $f_o = f_i \times N_r$ or $f_o = f_i / N_r$. where N_r is an integer and f_i is the source frequency. A methodology is developed to generate the required trigger signal for any integer multiple/sub multiple of the output frequency. The undesirable harmonic components in the output of the frequency converter have been minimized using four modulation techniques namely; sinusoidal pulse width modulation (SPWM), delta modulation (DM), trapezoidal modulation (TM) and space vector modulation (SVM) technique. The converter is simulated using well known software package MATLAB. Comparative simulation analysis is presented for a single phase frequency converter (SPFC) topology with all these modulation techniques when the converter is operating both step up as well as for step down mode.**

***Index Terms*-- Frequency Converter (FC), Total Harmonic Distortion (THD), Modulation Techniques.**

I. Introduction

Cyclo-converters are static frequency changers (SFCs) designed to convert constant voltage and constant frequency AC power to adjustable voltage and adjustable frequency AC power without any intermediate conversion to DC. The well-known advantage of natural commutation in thyristor controlled cyclo-converters give the cyclo-converter an edge over many competing systems, mainly in application of: 1) variable frequency control of ac machines and 2) variable speed and constant frequency (VSCF) power supplies for air craft, space vehicles, and mobile systems [1].

Developments in the field of AC to AC converter and cyclo-converter circuit are a subject of investigation [2]. A wide variety of converter circuits are possible depending upon the output frequency and voltage. One of the main disadvantages of the thyristor-controlled cyclo-converter circuit is that the output frequency cannot be increased to that of input frequency due to the need of an external commutation circuit [3]. However, if the self-commutated devices are used in place of SCRs, a need of external commutation circuit is eliminated. Then the same cyclo-converter circuit with self-commutated devices will result a direct AC to AC converter or generalized frequency converter, capable of converting power at the main frequency to a variable frequency that may be higher or lower to the input frequency. This converter is ideal for large AC motor drives, VSCF (variable speed constant frequency) systems, high frequency induction heating, arc welding and plasma generation, power factor correction, industrial laser drivers and so on [4]. Eventual applications could range from power grid stabilizers to ion rocket drives.

Most application requires a sine wave rather than a square wave or any other kind of waveforms [5]. For the applications of frequency converter, where the system frequency is variable one, like induction heating, the output of a frequency converter contains a lot of harmonics, which affects in the process like quenching, where the need is to heat the element to a predetermined depth. In this case the depth of penetration is going to depend on the frequency of the supply. So, if there is a lot of harmonics in the supply, depth of penetration is going to be out of control which in turn will lead to undesirable performance and may create the product to perform badly [6]. Because of this problem it becomes necessary to get rid of the harmonics from frequency converter output. Different modulation techniques or conventional filter system could be employed to reduce the harmonics [7]. However, the conventional filters are generally not used for reduction of harmonics because the output frequency is varying and using tuned filter for each harmonic is not feasible. Hence, the solution lies in the use of modulation techniques [8].

In this work a direct single stage frequency converter has been proposed where four modulation techniques, namely sinusoidal PWM, space vector modulation, trapezoidal modulation and delta modulation are proposed to minimize the undesirable harmonic components. The modulation techniques so far available are used in converters and in matrix converters [9]. There are no mature techniques which are in use in the application field of frequency converters [10]. So, the aim is to modify these modulation techniques which are in use in the other areas and apply them in a frequency converter. The simulation of modified modulation techniques is done using MATLAB SIMULINK software with the aim of reducing harmonic contents and their performance is evaluated in terms of total harmonic distortion (THD).

II. Frequency Converter

Fig. 1 shows the detailed power circuit of the proposed frequency converter. A 220 V (50 Hz) single phase supply is used as input V_i. The power circuit is made up of eight IGBTs (BUP 314D) with common emitter configuration [11]. The inductive load used has a value of R = 2 kΩ and L = 100 mH.

978-1-5090-1797-3/16/$31.00 ©2016 IEEE

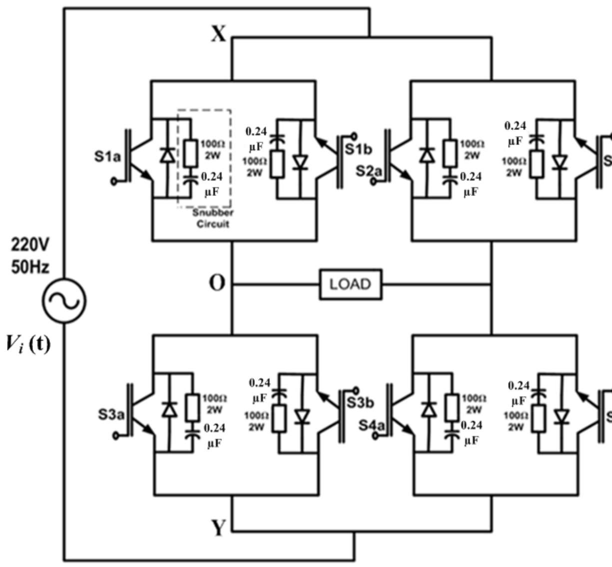


Fig. 1. Frequency converter circuit.

To protect against over voltages each IGBT is provided with a parallel RC snubber circuit. The equations that proved useful in selecting the value of C required for keeping the voltage transients within the device rating is [12]:

$$C = \left(\frac{10\ VA}{V_i^2}\right) \times \frac{60}{f_i} \quad (1)$$

Here C is the minimum value of capacitance in µF. With full load volt-amp rating of power circuit of 1 kVA, voltage applied to the circuit, V_i of 220 V and operating frequency f_i of 50 Hz, C has been selected as 0.24 µF. The resistance required to ensure adequate damping is calculated from (2):

$$R = 2\sigma (L_e C)^{0.5} \quad (2)$$

where σ is the damping factor normally taken to about 0.65 and L_e is the effective commutating circuit inductance. Selecting the value of $L_e = 2$ mH, R comes out approximately 100 Ω. Special high speed current limiting fuses capable of interrupting the short circuit current within few ms are also used to protect the IGBT.

III. Software Simulation

Sinusoidal PWM, delta modulation, trapezoidal modulation and space vector modulation techniques are implemented in the frequency converter to reduce the harmonic distortions at the output. The converter is simulated using MATLAB/SIMULINK software and its facilities with resistive-inductive load taking R = 2 kΩ and L = 100 mH.

With increase in carrier wave frequency, the switching frequency increases, but the total harmonic distortion of the converter output does not reduce significantly and switching losses increase proportionally with the carrier frequency. THD is minimum at unity modulation index for constant carrier frequency [13-16]. All the results are depicted for m = 1, f_c = 2 kHz. The performance of the converter is accomplished at different output frequency and simulations results are shown for each case.

A. Sinusoidal Pulse Width Modulation

The steady state performance curves of the frequency converter are obtained for various output frequencies as shown in Fig. 2 to Fig. 4. Fig. 2 demonstrates the output voltage along with THD at modulation index, m = 1 and carrier frequency, f_c = 2 kHz at output frequency f_o = 500 Hz (50 × 10). THD in the output is found to be approximately 18 %. With further increase in the output frequency, say for N_r = 40 (f_o = 2 kHz), THD turns up to be 14 % as shown in Fig. 3. After 2 kHz output frequency, THD remains constant there afterwards. When the output frequency is reduced, f_o = 16.6 Hz, THD turns up to be 1.6 % as shown in Fig. 4. When the output frequency is further reduced, f_o = 10 Hz, THD remains same as 1.6 %.

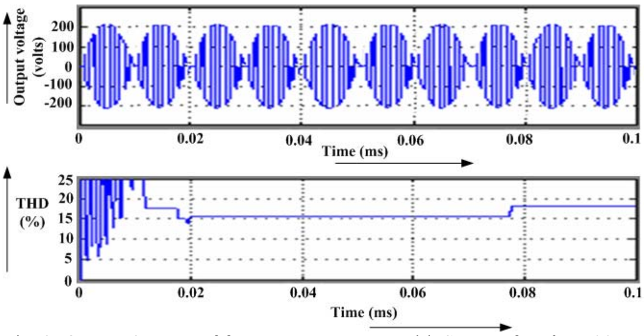


Fig. 2. Output & THD of frequency converter with SPWM for f_o = 500 Hz.

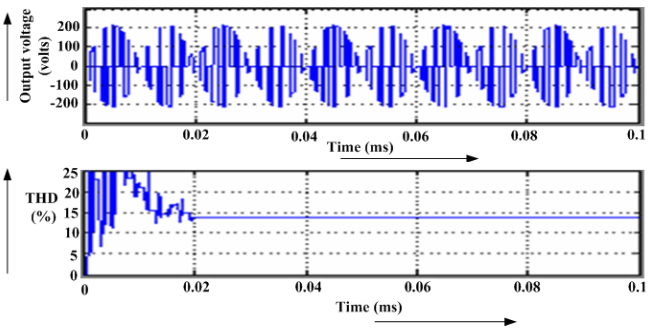


Fig. 3. Output & THD of frequency converter with SPWM for f_o = 2 kHz.

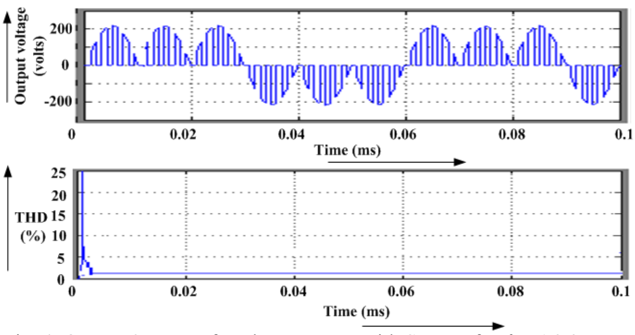
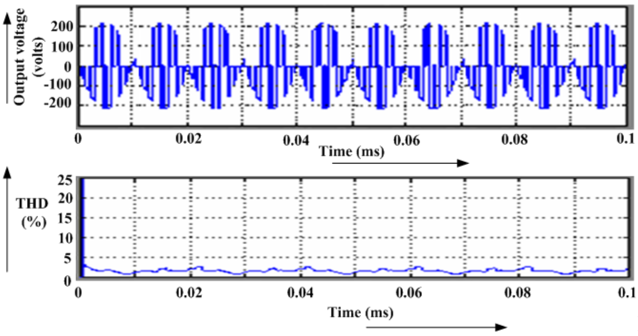


Fig. 4. Output & THD of cyclo-converter with SPWM for f_o = 16.6 Hz.

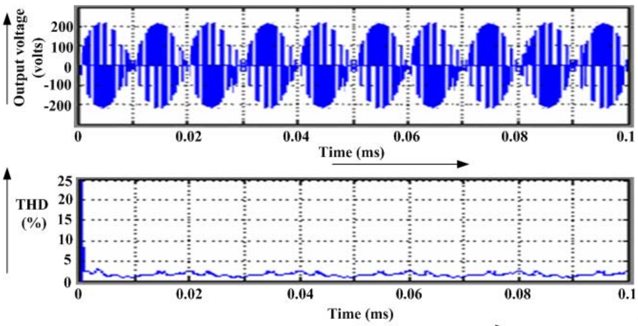
B. Delta Modulation

For delta modulation technique, the performance of the converter is evaluated with variation in the output frequency. When the output frequency is 10 times the input frequency i.e., f_o = 500 Hz, THD results approximately 2.8 % as shown in Fig. 5. With further increase in output frequency, f_o = 2 kHz, THD is located approximately 2.5 % as shown in Fig. 6. With further increase in the output frequency, THD evaluated is approximately the same. This shows that for delta modulation with an increase in frequency the THD remains almost constant and it is less as compared to SPWM. Fig. 7 shows the result of delta modulated cyclo-converter at output frequency, f_o = 16.6 Hz, THD obtained is very high, i.e., 23.2 %. With further reduction in output frequency, f_o = 10 Hz, THD resulted out to be in the range of 25.4 %.



F

Fig. 5. Output & THD of frequency converter with DM for f_o = 500 Hz.



F

Fig. 6. Output & THD of frequency converter with DM for f_o = 2 kHz.

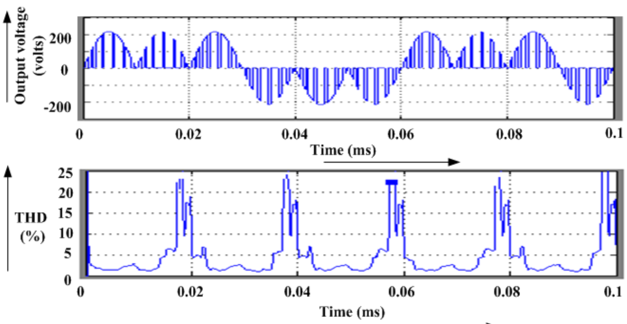


Fig. 7. Output & THD of frequency converter with DM for f_o = 16.6 Hz.

C. Trapezoidal Modulation

The performance of frequency converter with trapezoidal modulation technique is discussed as below. Fig. 8 presents the output waveform of the frequency converter along with THD for an output frequency f_o = 500 Hz. Obtained THD is approximately equal to 11.8 %. When the frequency is increased to forty times the input frequency, $f_o = 40 \times f_i$, i.e. 2 kHz, THD further reduces and now it is only 5 % which is quite low as shown in Fig. 9 which remains constant there afterwards. At output frequency of f_o = 16.6 Hz, the resulted THD is 1.2 % as shown in Fig. 10. With further reduction in the output frequency, i.e. when N_r = 1/5 times of input frequency or at an output frequency of f_o = 10 Hz, THD remain same as 1.2 %.

D. Space Vector Modulation

Fig. 11 to Fig. 13 illustrate the output of the frequency converter with space vector modulation technique at various values of output frequency. When the output frequency becomes ten times of input frequency, f_o = 500 Hz, THD acquired is 1.8 % as shown in Fig. 11. With further increase in the output frequency, f_o = 2 kHz, THD slightly reduces and appears to be 1.2 % as shown in Fig. 12, respectively and it remains the same with further increase in the output frequency. When the output frequency is one third of the input frequency, f_o = 16.6 Hz, THD comes out to be 1.01 % as shown in Fig. 13. With further reduction in the output frequency, f_o = 10 Hz, THD slightly increases and appears to be 1.1 %. After this if there is further reduction in the output frequency, THD does not change.

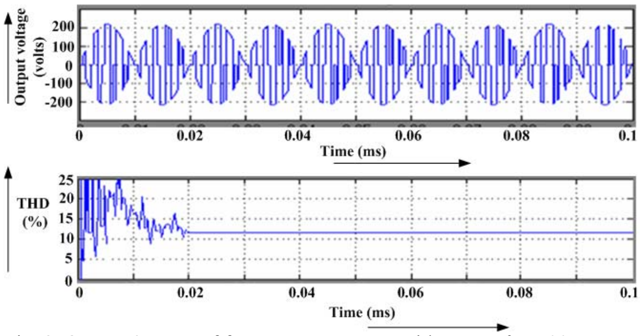


Fig. 8. Output & THD of frequency converter with TM at f_o = 500 Hz.

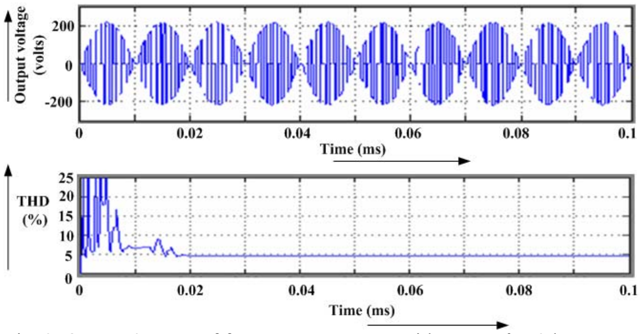


Fig. 9. Output & THD of frequency converter with TM at f_o = 2 kHz.

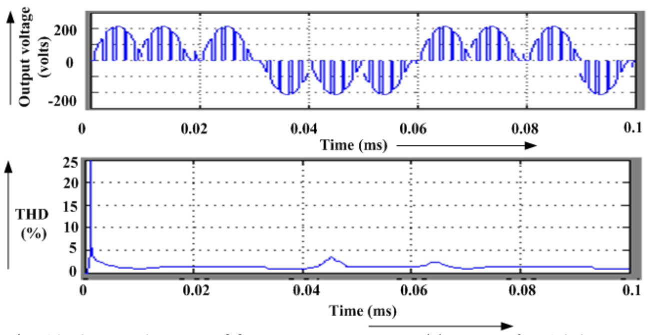


Fig. 10. Output & THD of frequency converter with TM at f_o = 16.6 Hz.

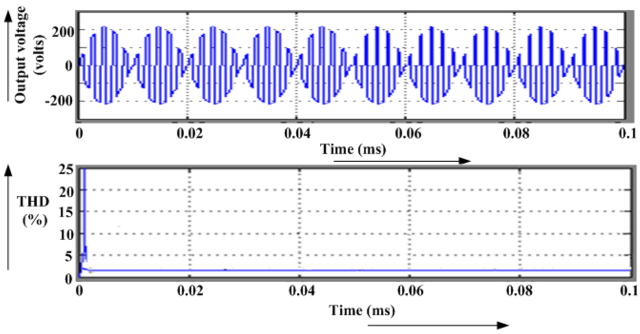


Fig. 11. Output & THD of frequency converter for SVM with f_o = 500 Hz.

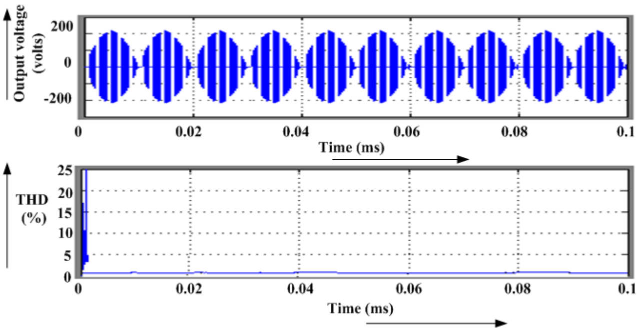


Fig. 12. Output & THD of frequency converter for SVM with f_o = 2 kHz.

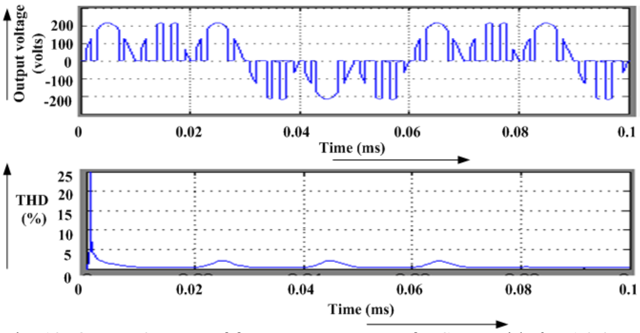


Fig. 13. Output & THD of frequency converter for SVM with f_o = 16.6 Hz.

When the output frequency is increased, then THD has been found to decrease with increase in the output frequency as shown in Fig. 14. After the output frequency of 2 kHz, THD appears to be constant with further increase in the output frequency. There is no specific pattern for the value of THD for different value of frequencies but still space vector modulation (SVM) is better as compared to delta modulation (DM), sin PWM (SPWM) & trapezoidal modulation (TM).

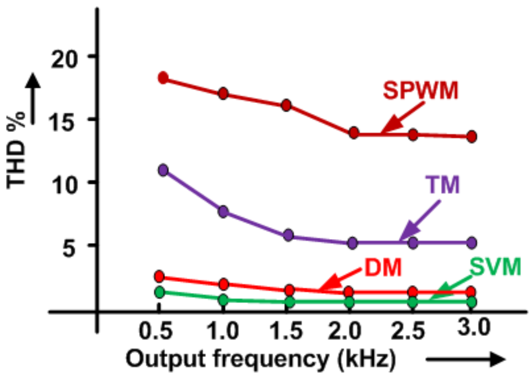


Fig. 14. Performance at higher frequency for frequency converter.

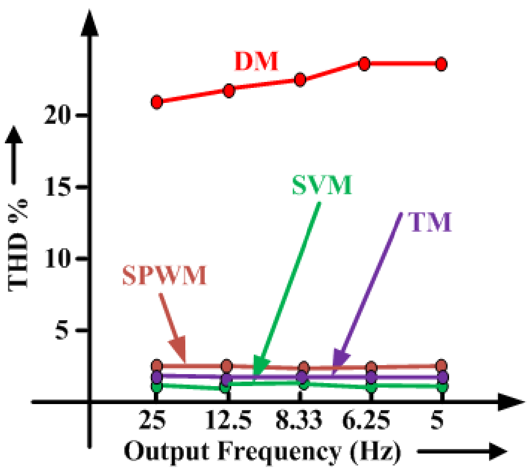


Fig. 15. Performance at lower frequency for frequency converter.

Thus for lower frequency operation the performance deteriorates with delta modulation. But for other modulation techniques the performance gets better as shown in Fig. 15. The lowest THD in SPWM comes out to be 1.6 %, for trapezoidal modulation it is 1.2 %. The space vector modulation technique provides the minimum THD equal to 1.01 % as compared to other modulation techniques.

IV. Conclusions

Four modulation schemes have been implemented in order to improve the output of the frequency converter. Space vector modulation techniques work well for step up and step down mode for all frequencies ranging from 10 Hz to 2 kHz and THD has been found minimum equal to 1.2% for step up operation and 1.01% for step down operation. Where as in case of SPWM, minimum THD obtained is 14 % for step up and 1.6 % for step down mode. In case of delta modulation, minimum THD obtained is 2.5 % for step up mode and for step down mode; THD comes out very high, in the range of 17.5 % ~ 28 %. In the trapezoidal modulation THD at the output it has been found minimum equal to 5 % for step up operation and for step down operation THD has been found minimum equal to 1.2 %.

Acknowledgment

This work was supported by the Scientific Grant Agency of the Slovak Republic under the Contract no. VEGA 1/0464/15 and by the project no. FEI-2015-3.

V. References

[1] R. Y. Sarakhanova, S. A. Kharitonov, "Cycloconverter based on bridge circuit for power supply systems of autonomous objects", *Micro/Nanotechnologies and Electron Devices (EDM), 2015 16th International Conference of Young Specialists on*, Erlagol, 2015, pp. 472-476.

[2] A. Azam, "Three to single-phase high-power quality switch-mode cycloconverter", *IET Power Electronics*, vol. 7, no. 6, pp. 1603-1617, June 2014.

[3] M. Basirifar, A. Shoulaie, "Impact of different control strategies on cycloconverter harmonic behavior", *Power Electronics, Drive Systems and Technologies Conference (PEDSTC), 2011 2nd*, Tehran, 2011, pp. 385-391.

[4] A. Symonds, M. Laylabadi, "Large cycloconverter drives in mining applications", *Industry Applications Society Annual Meeting, 2013 IEEE*, Lake Buena Vista, FL, 2013, pp. 1-12.

[5] C. A. F. Ferreira, B. V. Borges, "Sine-Wave Amplitude-Modulation Concept for Linear Behavior of Phase-Modulated Resonant Converters", in *IEEE Transactions on Industrial Electronics*, vol. 60, no. 5, pp. 2074-2083, May 2013.

[6] H. Wang *et al.*, "Two-Stage Matrix Converter Based on Third-Harmonic Injection Technique", in *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 533-547, Jan. 2016.

[7] J. R. Wells, X. Geng, P. L. Chapman, P. T. Krein, B. M. Nee, "Modulation-Based Harmonic Elimination", in *IEEE Transactions on Power Electronics*, vol. 22, no. 1, pp. 336-340, Jan. 2007.

[8] K. Georgaka, A. Safacas, "Modified sinusoidal pulse-width modulation operation technique of an AC-AC single-phase converter to optimise the power factor", *IET Power Electronics*, vol.3, no.3, pp.454-464, May 2010.

[9] M Raghuram, R. K. Jarial, Anshul Agarwal, "Implementation of symmetrical angle PWM in matrix converter topology as a multi-converter", *3rd Student's Conference on Engineering and Systems* (SCES 2014), May 28-30, 2014 at MNNIT Allahabad, India.

[10] F. Yahyaie, P. W. Lehn, "Using Frequency Coupling Matrix Techniques for the Analysis of Harmonic Interactions", *IEEE Transactions on Power Delivery*, vol. 31, no. 1, pp. 112-121, Feb. 2016

[11] L. Zarri, M. Mengoni, A. Tani, G. Serra, D. Casadei "Minimization of the Power Losses in IGBT Multiphase Inverters with Carrier-Based Pulsewidth Modulation", *IEEE Transactions on Industrial Electronics,* vol.57, no.11, pp.3695-3706, Nov. 2010.

[12] T. Shimizu, S. Iyasu, "A Practical Iron Loss Calculation for AC Filter Inductors Used in PWM Inverters", *IEEE Trans. on Industrial Electronics*, vol. 56, no. 7, pp. 2600-2609, Jul. 2009.

[13] Anshul Agarwal, Vineeta Agarwal, "A Study of Modulation Schemes for Frequency Converter" in *IEEE sponsored International Conference on Electrical Energy Systems & power electronics In Emerging Economics (ICEESPEEE 2009)* , pp. 1298-1303 , 16-17 April 2009, Chennai.

[14] M Raghuram, Anshul Agarwal, "Simulation of Single Phase Matrix converter as All in One Converter" in *3rd International Conference on Power, Control, Signals and Computation (EPSCICON-2014)*, 8-10 January, 2014 at Vidya Acdemy of Science and Technology, Karela, India.

[15] P.Sanjeevikumar, B.Geethalakshmi, P.Dananjayan, "Performance analysis of AC-DC-AC converter as a matrix converter", *Conf. Proc. IEEE India Intl. Conf. on Power Engg., IEEE-IICPE'06,* Chennai (India), pp. 57–61, 19–21 Dec. 2006.

[16] P. Sanjeevikumar, B. Geethalakshmi, P. Dananjayan, "A PWM current source rectifier with leading power factor", *Conf. Proc. IEEE Intl. Conf. on Power Electron., Drives and Energy Systems for Industrial Growth, IEEE-PEDES'06,* pp. 1–5, 12–15 Dec. 2006, Delhi (India), 2006.