

Improvement of Commutation Time in Matrix Converter

Indrajit Sarkar, Sumanta Kumar Show, Prasad Syam

Abstract— Matrix Converter is a near ideal static frequency changer which provides solution to the problem of converting ac from one frequency and one magnitude to variable frequency and variable magnitude ac, without any bulky energy storing components like capacitors or inductors. One of the major obstacles towards commercial acceptance of this topology has been the commutation of the bidirectional switches. An attempt has been made here to find a very fast and simple but safe current commutation technique. It has been found that with simple modification of the Input Current Filtering circuit and Diode Clamp circuit; the Stepless current commutation can be achieved giving the fastest, safe and simplest commutation technique without any voltage & current sensors and complex commutation steps. The different aspects of this realization are verified through simulation in PSPICE and Hardware implementation. The challenges still unresolved are also mentioned.

Index Terms— Commutation Time, Current Commutation, Diode Clamp Circuit, Matrix Converter, Input Current Filter, Stepless Current Commutation, Undamped LC Filter

1 INTRODUCTION

POWER frequency changer is an integral part of ac drive applications. From power quality point of view, it is desirable to use a compact voltage source converter to provide sinusoidal output voltages with varying amplitude and frequency, while drawing sinusoidal input currents with unity power factor from the ac source. The Matrix Converter offers an almost all silicon solution for nearly ideal solid state power frequency changer [1].

The important features of Matrix Converter are -

- (a) Simple and compact power circuit
- (b) Generation of load voltage of variable amplitude and frequency
- (b) Sinusoidal input and output current waveforms with reduction of higher order harmonics
- (c) Control over input power factor irrespective of loads
- (d) Inherent bi-directional power flow
- (e) Minimum energy storage requirement

Although it can fulfil all of these ideal characteristics, there is however some practical issues in its implementation. Since there are no freewheeling paths, it is difficult to reliably commutate current from one bi-directional switch cell to other, without interrupting the load current and simultaneously not causing input short circuit. Thus commutations are usually carried out in different steps and commutation time thus depends on the switching time of the devices undergoing commutation, implying it limits the maximum switching fre-

quency.

Matrix Converter uses an array of self controlled bidirectional semiconductor switches and can give variable magnitude variable frequency output voltage without having any dc link bulky energy storing elements. Input filters consisting of shunt capacitors and line inductors are necessary to eliminate high frequency unwanted current components entering into the supply utility. A high speed diode bridge clamp circuit connecting input and output is required to reduce over voltages across the switches during fault or when input supply goes off.

2 CURRENT COMMUTATION

The process of turning off a conducting semiconductor switch and turning on a non-conducting semiconductor switch without interrupting the load current is known as Current Commutation [1]. As shown in figure 1 current commutation is taking place from switch cell-S1 to switch cell-S2 for output phase U and from switch cell-S3 to switch cell-S4 for output phase V. It is an integral part of a Matrix Converter realization where load current needs to be transferred in any one of the three input phases depending upon the modulation logic using one of the three different bi-directional switch cells connecting an output phase to the input phases. A switch cell is generally constructed using IGBTs and diodes in various configurations for medium power applications.

There are different schemes used for current commutation [1-5]. All schemes try to follow the switching constraints and also take into account the finite switching times of semiconductor devices and sensor delays. Some of these rely on output current direction, while others rely on relative magnitudes of input voltages to activate the commutation stages. Switching constraints are -

- 1) The input phases can never be shorted (short circuit may result large amount of currents through phases).

-
- Indrajit Sarkar is currently pursuing Masters in Electrical Engineering (Specialization - Power Electronics And Drives) at Bengal Engineering And Science University (BESU), Shibpur, India, PH-+918296327818. E-mail: jsr.indrajit@gmail.com
 - SumantaKumar Show is currently working at IIT Kharagpur, India as a Project Assistant, PH-+919932582375. E-mail: sumanta.show@gmail.com
 - Prasad Syam, Professor, Department of EE, BESU, Shibpur, India, PH-+919836893676. E-mail: prasidsyam@yahoo.co.uk, ps@ee.becs.ac.in

2) Assuming output current to be inductive in nature, the output phases must not be left open (open circuit may destroy switches due to switching voltage spikes).

2.1 Basic Current Commutation

In Overlap Current Commutation, the incoming cell is fired before the outgoing cell is switched off. This would normally cause a line-to-line short circuit. Extra line inductance slows down the rise of current so that safe commutation is achieved. This is not a desirable method since the inductors used are large. The switching time for each commutation is also greatly increased which may cause control problems.

In Dead-Time Commutation there is a period where no devices are gated causing a momentary open circuit of the load. Snubbers or clamping devices are then needed across the switch cells to provide a path for the load current. This method is undesirable since energy is lost during every commutation. The bidirectional nature of the switch cells further complicates the snubber design. The clamping devices and the power loss associated with them also results in increased converter volume.

2.2 Safe and Reliable Current Commutation

Two different commutation strategies are:

- i) Relative input voltage magnitude based current commutation
- ii) Output current direction detection based current commutation

2.3 Output Current Based Commutation Strategy

Output current direction based we have Four Step, Three Step, Two Step and Single Step Current commutation strategies.

In contrast to the above mentioned current commutation strategies, where we need either current and/or voltage sensing circuits (relative magnitudes as well as directions) to commute switch cell currents, a Stepless Current commutation strategy [9,12] is proposed where such circuits are not required. In case of Stepless Current commutation strategy switching signals are provided to both of the switches in a single switch cell simultaneously and this is done irrespective of the magnitude and directions of voltage and current. The respective switch will "On" in accordance with the direction and magnitude of voltage and current, which implies that the switching loss will remain same as that of single step current commutation, neglecting extra losses due to short circuit for very small duration of time (200 ns) if any. Commutation interval will reduce significantly and limited only by the turn-off/turn-on time of the devices. But Stepless Current commutation results high input short circuit current, unless not limited by external circuits and high Ldi/dt voltage at the output (unless the inductive energy is not converted to capacitive stored energy) in case of output open circuit for inductive load. Input short circuit current can be limited by input cur-

rent filter circuit with appropriate modifications and output open circuit can be mitigated by Diode Clamp circuit, which normally exists for protection in Matrix Converter. In our simulation study and hardware implementation we have adopted Stepless Current commutation strategy with some modifications in the Input Filter circuit to limit input short circuit current and with some modifications of the Diode Clamp circuit to limit output voltage spikes.

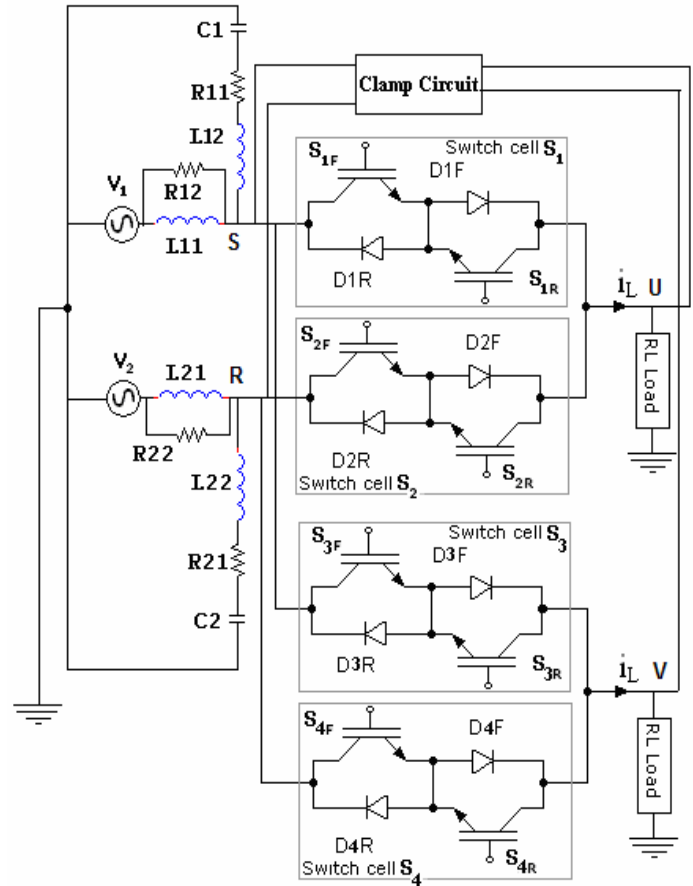


Fig. 1 Two phase to Two phase Matrix Converter with Input Current Filter Circuit and Clamp Capacitor Circuit

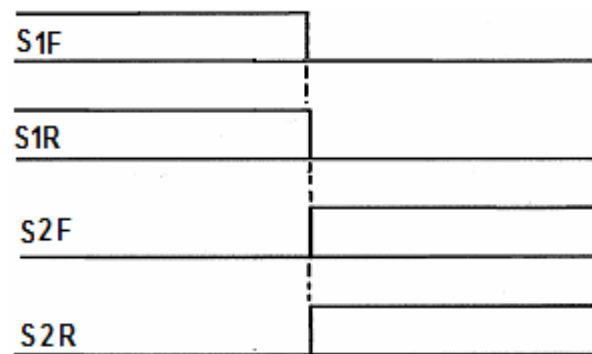


Fig. 2 Logic signal applied to the Gates of IGBT S1F, S1R, S2F and S2R in Stepless Current Commutation

3 INPUT CURRENT FILTER CIRCUIT

In Matrix Converter, Input Filter basically serves to mitigate near switching frequency current in the input supply lines. This filter circuit is also used for safe Stepless Current commutation. Preliminary idea for the filter design is taken from [5] and the analysis is extended to suit our purpose.

3.1 Undamped LC Filter as Input Filter

The undamped L-C passive filter is a second order filter provides 12dB per octave of attenuation after the cutoff frequency f_n . Gain = Current through filter Capacitor/ Source Current (I_{in}). Taking source as a current source it has no gain after f_n and presents a peaking at resonant frequency f_n .

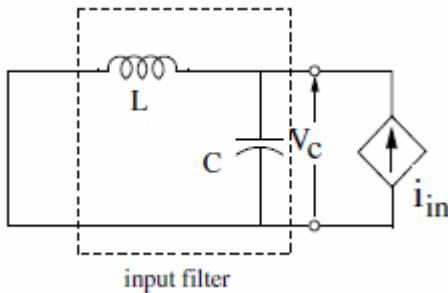


Fig. 3 Input Current Filter

$$\text{Where } f_n = \frac{1}{2\pi\sqrt{LC}} \text{ Hz}$$

In case of damped input filter -

$$S^2 + \frac{R}{L}S + \frac{1}{LC} = 0$$

Where R = Damping resistance.

Comparing it with second order equation -

$$S^2 + 2\xi\omega_n S + \omega_n^2 = 0$$

$$2\xi\omega_n = \frac{R}{L}, \omega_n^2 = \frac{1}{LC}, \xi = \left(\frac{R}{2}\right)\sqrt{\frac{C}{L}}$$

Where ξ = Damping co-efficient and ω_n = Natural frequency of oscillation.

In our study switching frequency taken as 7.8 KHz and f_n to be 1/3rd of it = $7.8/3 = 2.6$ KHz. The value of filter inductor and filter capacitor [10] taken as 0.78mH (as available in the lab), 6 μ F (Two capacitors in parallel 3 μ F each) and the corresponding cutoff frequency $f_n = 2.326$ KHz. Damping resistance used as 1 Ω and an additional resistance of 0.1 Ω is provided by the filter inductor, hence damping resistance becomes 1.1 Ω and damping coefficient is .048.

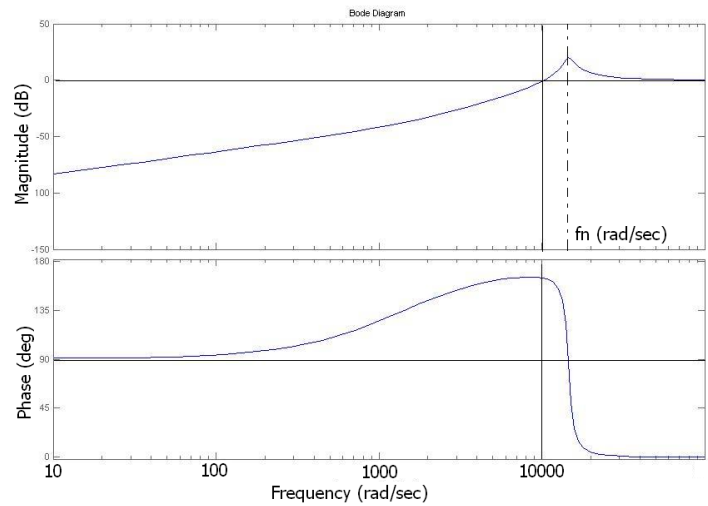


Fig. 4 Gain and Phase Plots

From above MATLAB Gain and Phase plots for the LC Current filter used, the gain becomes positive and phase becomes zero after f_n .

Introduction of an extra resistance in series with filter capacitor reduces the magnitude of input short circuit current for stepless current commutation. But this will introduce further loss in the filter circuit and increase the impedance of the branch which will reduce the share of the input high frequency current. Therefore to meet both ends the input filter is modified as follows.

3.2 Modified Input Filter

Figure 1 shows a Two phase to Two phase Matrix Converter. In our simulation study two phases are taken as 110 Volts 0° and 110 Volts 120° (50 Hz). Two outputs loads are Load1 as 48.6 Ω and 1.829 mH, Load2 59.6 Ω and 0.676 mH. Switching frequency is taken as 7.8 KHz. Inductors L12 and L22 of 70 μ H are introduced in series with R-C in order to limit short circuit current as well as to reduce watt loss in R11 and R21. In this case damping co-efficient reduces a bit.

Inductor in series with R-C may block high frequency currents through L-R-C branch resulting voltage spikes at the converter input, hence a path is provided for high frequency current components with reduced magnitude by using another resistor R12 and R22 in parallel with L11 and L21 of L-C filter respectively.

The Input Filter arrangement is shown in the figure 1. The L-C filter components are $L11 = L21 = 0.78$ mH and $C1 = C2 = 6$ μ F. These values of inductors and capacitors are taken as only these were available in the laboratory. Damping resistance in series with filter capacitor $R11 = R21 = 1$ Ω and in parallel with filter inductor $R12 = R22 = 120$ Ω . Watt loss in R11 and R21

becomes 0.5 Watt (from 4 Watt) and watt loss in R12 and R22 is 0.2 Watt. Total watt loss in input filter is 0.7 watt.

4 DIODE CLAMP CIRCUIT

The overvoltage protection scheme proposed is a Clamp circuit [6] made up of capacitor connected to all input and all output lines through two diodes bridges as shown in figure 5. It is operative for all of the 18 IGBTs and protects the switches from the surge coming from input AC line as well as from the surge on the output side that would be otherwise produced whenever an emergency shut-down of the converter is required or commutation of the switches taking place. When the output inductive currents of the motor are interrupted, the energy stored in the load is transferred to the Clamp capacitor and no critical overvoltage is caused if the capacitor is large enough.

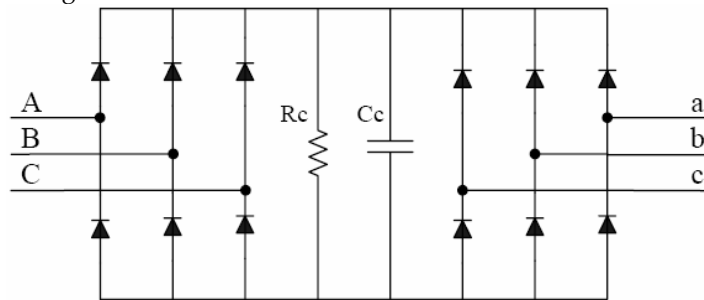


Fig. 5 Diode Clamp Circuit

Furthermore, the Clamp circuit prevents output voltage spikes caused during current commutation by the line inductance of the power switch matrix and by the unavoidable timing inaccuracies.

Since the capacitor voltage increases at each switching operation, some means to discharge the capacitor is required. An efficient energy removal method is to pump back the clamp energy to power system, but with Diode Bridge circuit it is not possible. Here we have used a resistor known as bleeder resistor in parallel with the Clamp capacitor to dissipate the clamp energy.

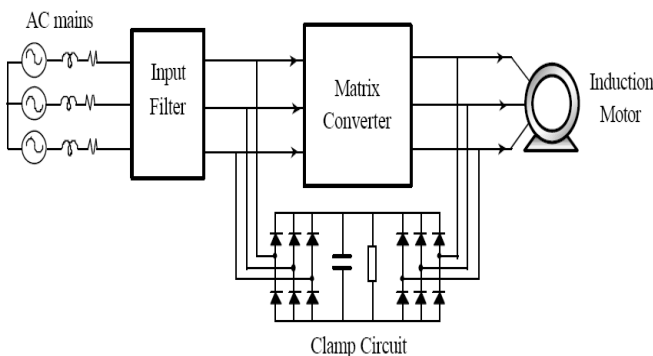


Fig. 6 Clamp circuit arrangement for three phase to three phase Matrix

Converter

5 CLAMP CIRCUIT CALCULATIONS

During fault condition the induction machine's rotor and stator inductance stored energy will act as current source and will charge the Clamp capacitor.

Equivalent circuit of Diode Clamp circuit (per phase) in conjunction with the induction machine is shown in figure 7 [6]. I_s , I_r and I_m are the motor's per phase stator current, rotor current and magnetizing current respectively. V_c is the voltage across Clamp capacitor.

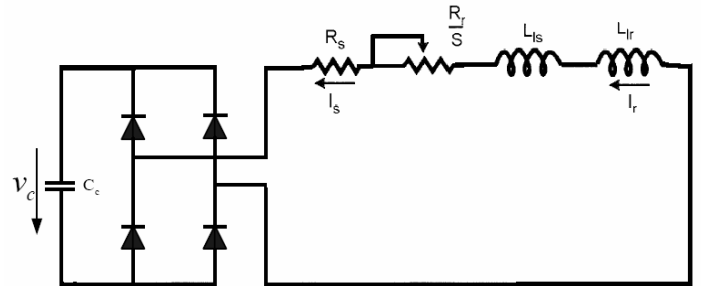


Fig. 7 Per phase equivalent circuit of Diode Clamp circuit eliminating Induction M/C's shunt branch

It is assumed that the motor speed remains constant during Clamp capacitor charging.

Induction Machine Parameters- Slip Ring Induction Motor, 1 KW, 230 Volts/Phase, 50 Hz, 3 phase, 6.5 Amps, 1400 RPM, Rotor Volts- 40 Volts/Phase, Rotor Amps - 10 Amps, Cold resistance of stator = 1.3 Ω /Phase, $L_s = L_r = 5.88$ mH.

Total magnetic energy stored in a three phase inductor carrying balanced three phase currents i_a, i_b, i_c is (RMS values)-

$$Q = L (i_a^2 + i_b^2 + i_c^2) / 2 = 3LI^2 / 4$$

Where I is the peak value of phase currents. Applying the same for a three phase induction motor and neglecting magnetizing branch we have-

$$\Delta Q = 3(L_s + L_r) I^2 / 4 = 3LI^2 / 2$$

Where $I_s = I_r = I$ and $L_s = L_r = L$. Taking a safety factor of 1.5 for current, we have -

$$\Delta Q = (3/2)^3 LI^2$$

Applying energy balance equation -

$$\frac{1}{2} C_c V_c^2 = \frac{1}{2} C_c V_{c0}^2 + \Delta Q$$

$$\frac{1}{2} C_c V_c^2 = \frac{1}{2} C_c V_{c0}^2 + (3/2)^3 LI^2$$

Where V_{C0} is the initial voltage of the capacitor C_c is the capacitance value of the Clamp capacitor V_c is the final voltage of C_c . Now $V_{C0} = 3 \times 400 \sqrt{2} / \pi = 540.2$ Volts and allowing V_c to be maximum of 700 Volts, $L = 5.88$ mH, $I = 1.5 \times 6.5$ Amps C_c becomes $8.46 \mu\text{F}$. Clamp capacitor taken as $24 \mu\text{F} / 1000$ Volts [11].

Bleeder resistance is used to maintain a steady value of voltage across the capacitor depending on the input supply voltage. The capacitor voltage may rise above this steady value during output open circuit or input open circuit condition. Bleeder resistance gives a path to discharge capacitance up to the steady value after fault condition subsides. It is important to note that diode bridges of both sides of the capacitor do not allow capacitor to pump back his stored energy. In our case the value of Bleeder resistor taken as $5.5 \text{ K}\Omega$ corresponding to Clamp Capacitor discharging time 0.13 seconds. The Clamp circuit capacitor current and the voltage across it during commutation are observed and are within limit.

The same capacitance value and bleeder resistance is sufficient to keep the output voltage spikes within limit if output open circuit condition arises during Stepless Current commutation. No further modification is needed.

6 CURRENT AND VOLTAGE WAVEFORMS

In our study two input voltage sources are taken as 110 Volts and 110 Volts 120° at 50 Hz and two phase loads as Load1 48.6Ω and 1.829 mH, Load2 59.6Ω and 0.676 mH. Switching Frequency 7.8 KHz. The ratio of Voltage Transducer is = 69 and that of Current Transducer is = 2.56.

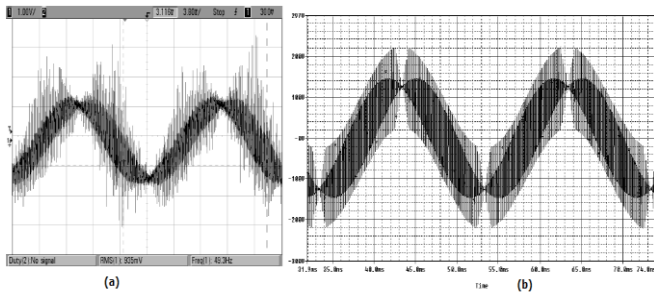


Fig. 8 U phase load voltage (a) Experimental result (b) Simulated result in Orcad PSpice

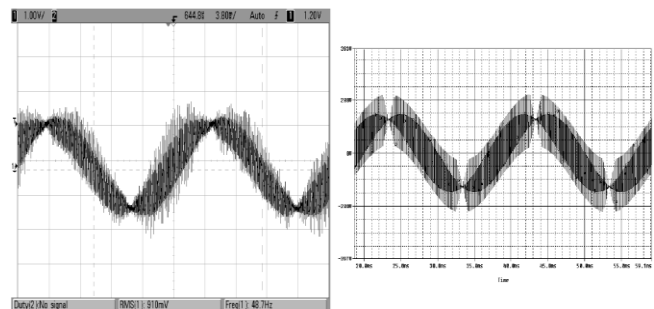


Fig. 9 V phase load voltage (a) Experimental result (b) Simulated result in Orcad PSpice

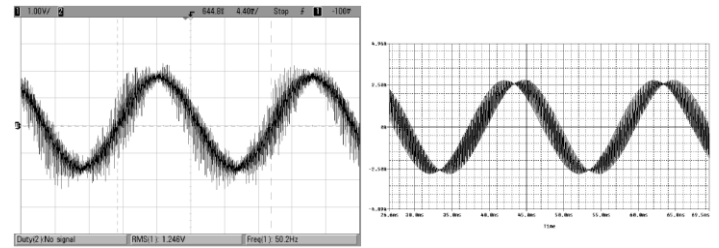


Fig. 10 U phase load current (a) Experimental result (b) Simulated result in Orcad PSpice

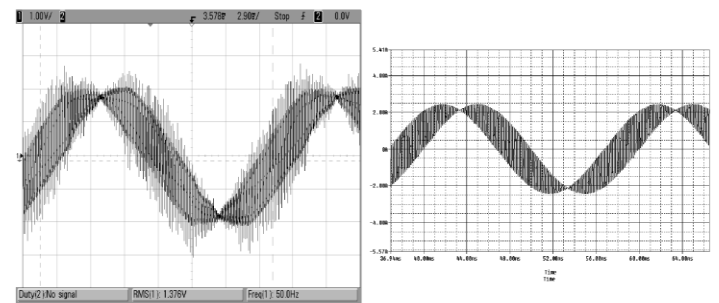


Fig. 11 V phase load current (a) Experimental result (b) Simulated result in Orcad PSpice

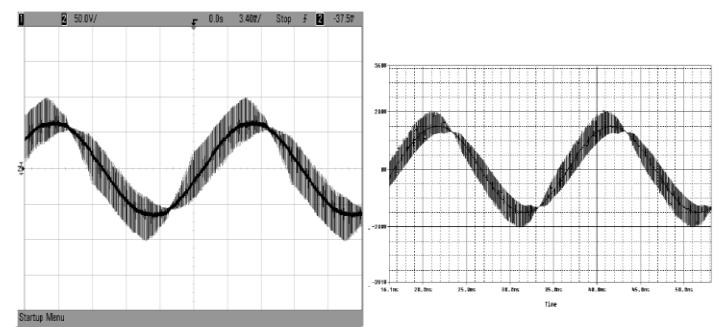


Fig. 12 R phase source voltage (a) Experimental result (b) Simulated result in Orcad PSpice

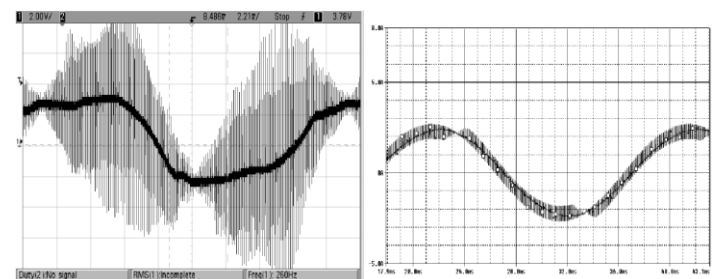


Fig. 13 R phase source current (a) Experimental result (b) Simulated result in Orcad PSpice

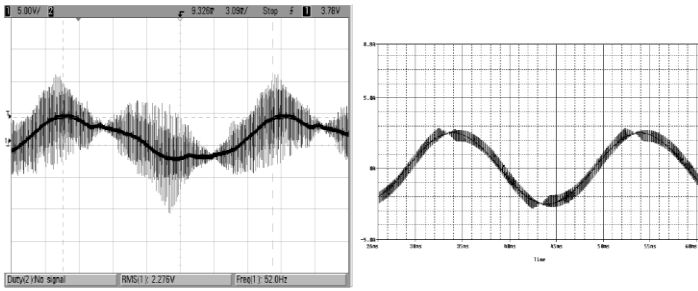


Fig. 14 S phase source current (a) Experimental result (b) Simulated result in Orcad PSpice

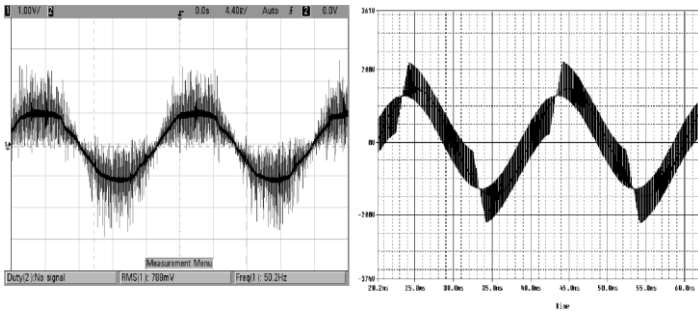


Fig. 15 R phase Voltage waveform at the converter input (a) Experimental (b) Simulated in Orcad PSpice

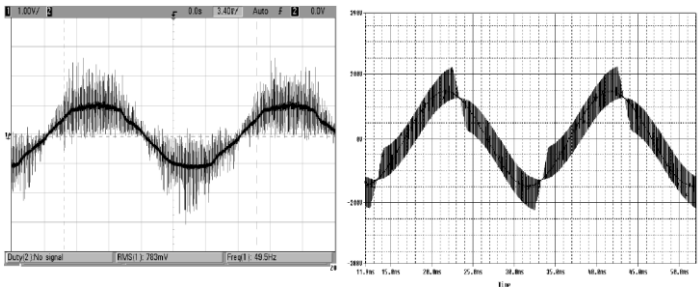


Fig. 16 S phase Voltage waveform at the converter input (a) Experimental (b) Simulated in Orcad PSpice

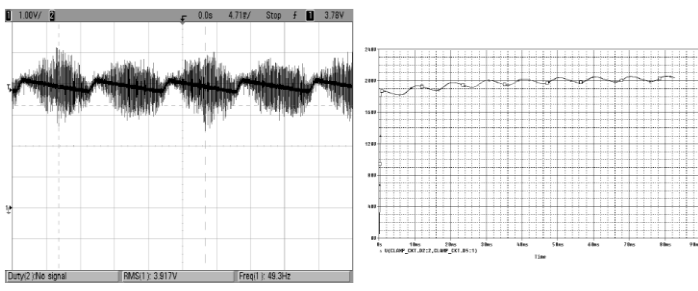


Fig. 17 Voltage across Clamp capacitor (a) Experimental (b) Simulated in Orcad PSpice

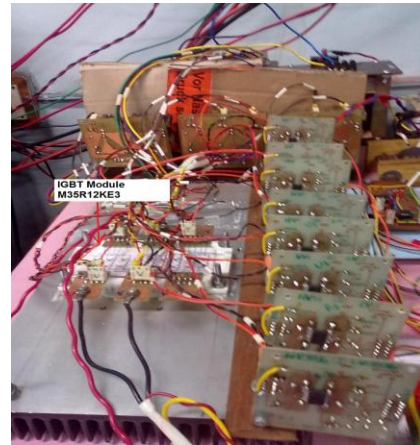


Fig. 18 IGBT Module and Driver Circuits

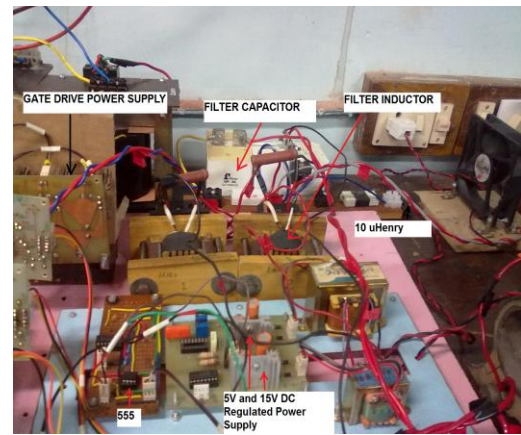


Fig. 19 Filter Circuit and Logic Circuit

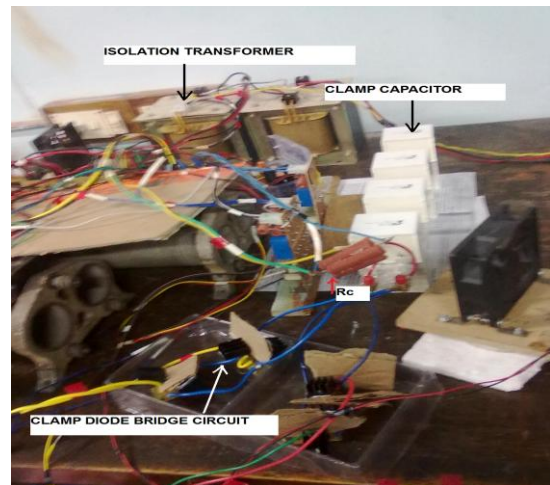


Fig. 20 Diode Clamp Capacitor Circuit



Fig. 21 Two phase R-L Loads

7 CONCLUSION

Stepless Current commutation techniques are studied in depth. The reductions of input short circuit current, overshoot of voltages and commutation intervals are the major objectives of any commutation techniques.

The commutation time can be reduced to minimum possible in Stepless Current commutation technique but may cause severe input short circuit current. To reduce this short circuit current, the input filter is modified accordingly. It limits the input short circuit current to an acceptable level and presence of resistor in parallel with filter inductor eliminates any voltage spikes to appear just after series filter inductor. The additional Clamp circuit with two phase to two phase converters further improves the output voltage and current waveforms with reduction in the commutation time.

It is interesting to note that most of these passive elements are usually present in a Matrix Converter circuit for filter and protection requirements. Addition of the resistance will add to the commutation losses but its advantages will outweigh this disadvantage.

Any voltage overshoot in input and output of the converter is further reduced by the presence of Diode Clamp circuit.

ACKNOWLEDGMENTS

Authors are thankful to department of Electrical Engineering, Bengal Engineering and Science University Shibpur for the encouragement and support in this work.

REFERENCES

- [1] P. Wheeler, J. Rodriguez, J. Clare, L. Empringham, A. Weinstein, "Matrix Converters: A Technology Review," *IEEE Trans. Ind. Electron.*, vol. 49, pp. 276-289, Apr. 2002.
- [2] P. Wheeler, J. Clare, L. Empringham, "Enhancement of matrix converter Output Waveform Quality Using Minimized Commutation Times" *IEEE Trans. Ind. Electron.*, vol. 51, pp. 240-244, Feb. 2004.

- [3] P. Wheeler, J. Clare, L. Empringham, M. Bland, M. Apap, "Gate Drive level Intelligence and Current Sensing for Matrix Converter current Commutation" *IEEE Trans. Ind. Electron.*, vol. 49, pp. 382-389, Apr. 2002.
- [4] L. Empringham, P. W. Wheeler, and J. C. Clare, "Intelligent commutation of matrix Converter Bidirectional switch cells using novel gate drive techniques" in *Proc. IEEE PESC'98*, 1998, pp. 721-726
- [5] P. Wheeler and D. Grant, "Optimization input filter design and low-loss switching technique for a practical matrix converter" *IEEE Proceedings of Electric Power Applications*, vol. 144, no. 1, pp 53-60, Jan. 1997
- [6] Peter Nielsen, Frede Blaabjerg, Senior Member, IEEE, and John K. Pedersen, Member, IEEE "New Protection Issues of a Matrix Converter: Design Considerations for Adjustable-Speed Drives" *IEEE Transactions on Industry Applications*, Vol 35, No. 5, September/October 1999
- [7] A. Dasgupta, S. Mukherjee, M. Sengupta, P. Syam and A. K. Chattopadhyay "Implementation of Universal Logic System of Generating Commutating Pulses in Matrix Converters using FPGAs", *IEEE-ICIT06*, Mumbai, December 2006 (Proceedings in CDROM), pp 1436-1441
- [8] Ned Mohan, William Robbins and Tore Undeland, "Power Electronics converters, Applications and Design" Media Enhanced third edition, WILEY INDIA EDITION, 2007
- [9] Sumanta Kumar Show, Indrajit Sarkar, Prasad Syam, "Exploring the possibility of Single Step Current Commutation in a Matrix Converter" *NPEC-2011*, BESU, Shibpur, December 2011
- [10] Indrajit Sarkar, Sumanta Kumar Show, Prasad Syam, "Role of Input Current Filter to Facilitate Single Step Commutation in Matrix Converter" *NPEC-2011*, BESU, Shibpur, December 2011
- [11] Indrajit Sarkar, Sumanta Kumar Show, Prasad Syam, "Role of Diode Clamp Circuit to Facilitate Single Step Commutation in Matrix Converter" *NPEC-2011*, BESU, Shibpur, December 2011
- [12] Sumanta Kumar Show, "Single Step current commutation technique in a Matrix Converter" *ME Thesis*, Dept. of EE BESU Shibpur, 2011