Intelligent Commutation of Matrix Converter Bi-directional Switch Cells using Novel Gate Drive Techniques

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ABSTRACT

This paper deals with the problem of snubberless commutation in matrix converters. A novel method employs current detection within intelligent gate drive circuits for each bidirectional cell which communicate with the gate drives of other cells. The problems with other methods at low currents are overcome. Experimental results verifying the method are presented.

1. INTRODUCTION

The matrix converter offers an "all silicon" solution for AC-AC conversion, removing the need for reactive energy storage components used in conventional rectifier-inverter based systems [1]. A 3 phase to 3 phase matrix converter consists of nine bi-directional switches that are used to connect the input

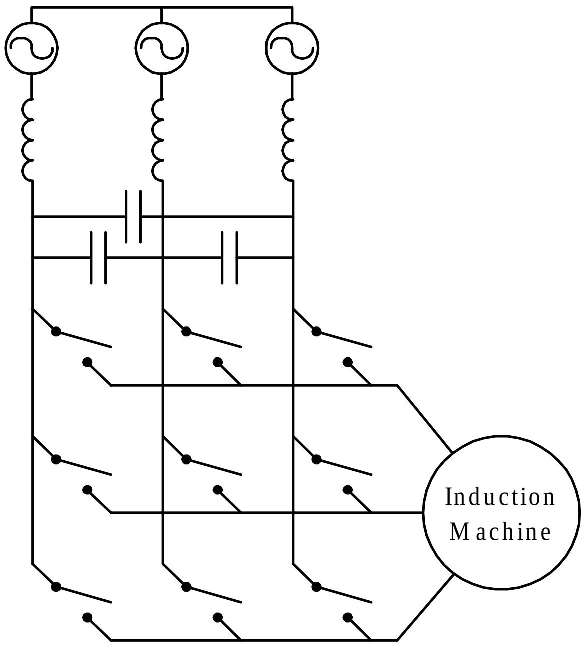

Figure 1. 3 phase to 3 phase matrix converter

phases directly to the output phases of the converter(figure 1). The switching of these bi-directional switches is then modulated to produce the desired output voltage and frequency. Matrix converters offer many advantages over traditional topologies such as the ability to regenerate energy back to the utility, sinusoidal input and output currents and controllable input current displacement factor [2]. The size of the converter can also be reduced since there are no large reactive components for energy storage. There are however some important practical issues to be considered with the matrix converter. Since there are no freewheel paths, it is difficult to reliably commutate current from one switch to another [3]. This paper will review existing approaches to this problem and present a new method which removes many of the difficulties with existing methods.

2. CURRENT COMMUTATION

When considering commutation strategies for matrix converters two general rules must be adhered to [1]. The incoming and outgoing switches should not be switched on together at any point in time since this will result in an input line to line short circuit leading to switch over currents. Also these switches should not both be off at the same time since there is then no path for the inductive load current and large overvoltages would destroy the switches.

These two considerations cause a conflict since semiconductor switches cannot be switched instantaneously. Various methods have been proposed to avoid this difficulty and to ensure successful commutation.

The first method is termed "overlap" current commutation where the incoming switch is fired before the outgoing switch is turned off. This causes a momentary short circuit between two of the phases of the supply. Extra supply inductance must be included to stop the current rising to destructive levels during the short circuit. This method is rarely used since the inductors used are large and expensive [4].

Another method is "dead time current commutation" in which the outgoing switch is turned off before the incoming switch is fired. This produces a "dead time" in which there is no path for the load current to take. Snubber networks must then be used to provide a path for the current[5,6]. This method is poor since energy is lost during every "dead time" period and the snubber networks occupy a large volume compared to the semiconductor devices. The bi-directional nature of the switches also complicates the snubber design.

The third method is the most reliable to date and was first proposed in [3] and later named the "semi-soft commutation method"[5]. It relies on the use of a bi-directional switch cell where the direction of the current can be controlled. Figure 2 shows an elementary two phase to single phase matrix converter comprising two such cells. Each cell is composed of two IGBTs and two diodes in anti parallel. In steady state operation SA1 and SA2 are gated so as to accommodate both current directions. A timing diagram for he commutation process is shown in figure 3 and is as follows, assuming the load current is in the direction shown and initially cell A is

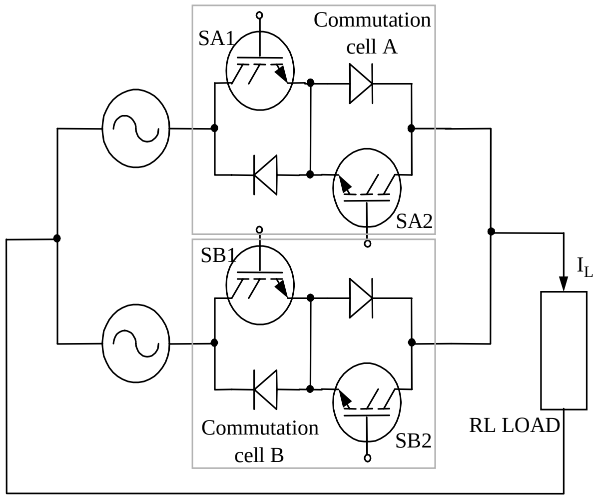

Figure 2. 2 phase to single phase matrix converter

conducting. When a commutation is required the non-conducting device in cell A (SA2) is switched off. The direction of the current I_L must be known so that the non-conducting

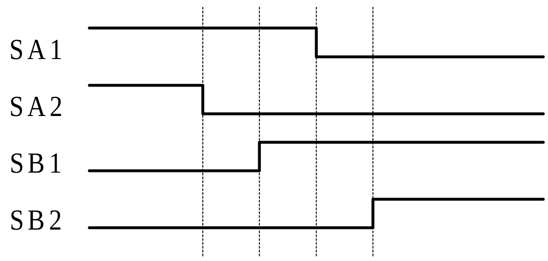

Figure 3. Timing diagram for 4 step commutation strategy

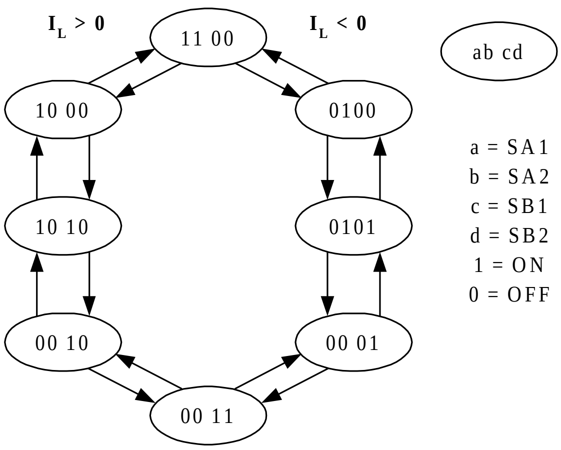

Figure 4. State diagram for 4 step commutation strategy

device can be determined. The device in cell B that will carry the current after commutation (SB1) is then switched on. This allows both cells to be on without short circuiting the input phases and provides a path for the load current. A short time later SA1 is turned off and SB2 is turned on. This completes the commutation process. Problems occur however at low current levels when the direction of the current is not certain and incorrect decisions as to which switches to fire can occur causing shoot through conditions. There are ways of making this method more reliable but they too involve the addition of snubber networks. A state diagram for the commutation process is shown in figure 4.

A further method as described in [7] can also be used. In this method only the correct device in the conducting cell is gated. This simplifies the commutation to a 2 step process since only the correct device in the incoming cell is switched on and the outgoing device is switched off. Current reversal is catered for by gating both devices in the conducting cell when the current level falls below a threshold level. The non-conducting device is then turned off when the current has risen sufficiently in the opposite direction. A timing diagram for the current reversal in commutation cell A is shown in figure 5. The problem with this method is that a commutation between cells cannot occur during a current reversal. Since the direction of current is unknown, the correct outgoing device cannot be determined. The threshold level may also be relatively large in large converters, which may the output waveform quality. This method would also be unsuitable if the target output current was to be within the threshold level. A state diagram of the 2 step commutation strategy can is shown in figure 6.

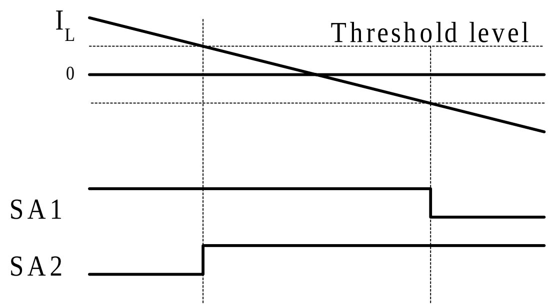

Figure 5. current reversal using threshold detection

For a commutation strategy to be fully reliable in practical applications accurate current direction information must be obtained. If there is any uncertainty, errors may occur. The following section describes a commutation strategy and current direction detection technique that enables reliable commutation at any point in time without the use of snubbers or clamping circuits across the commutation cells.

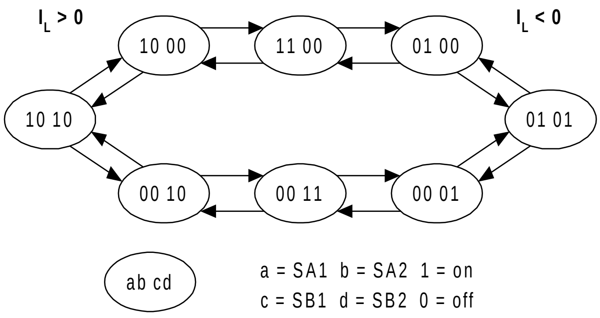

Figure 6. State diagram for 2 step commutation strategy

3. IMPROVED COMMUTATION METHOD

This method is similar in concept but only the conducting device is gated at any one time. Correct operation relies on an intelligent gate driver circuit for each cell which determines current direction and is also co-ordinated with the gate drivers of the other cells. A block diagram of the gate driver can be seen in figure 7.

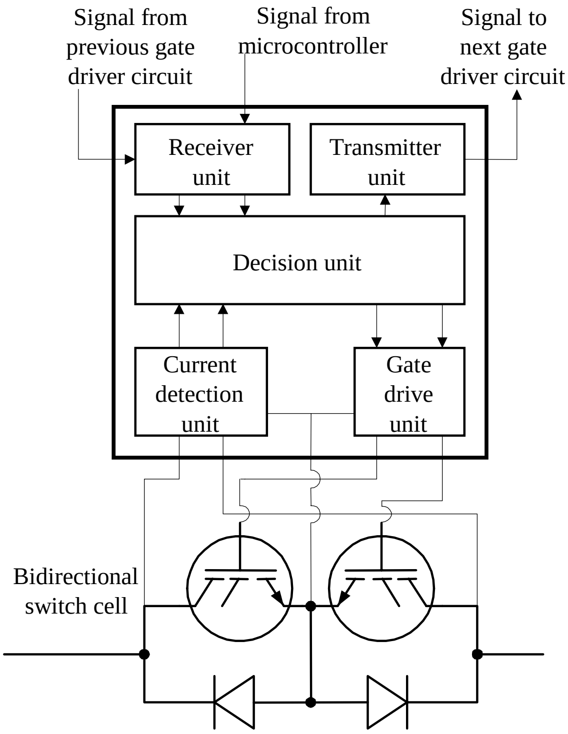

Figure 7. Gate driver block diagram

3.1 Current direction detection

This method uses the voltages across each of the devices in the commutation cell to determine the direction of current flow. The voltages V_A and V_B (Figure 8) are measured. Assuming current I_L is in the direction shown, S1 will be conducting and S2 will be reversed

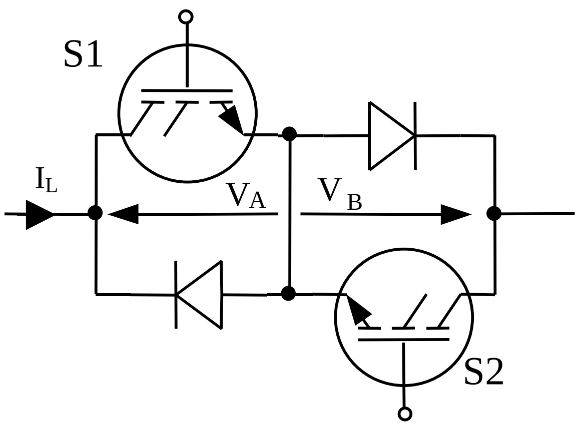

Figure 8. Bi-directional switch cell.

biased. This results in V_A being around 1.2V (depending on devices used) and V_B being around -0.7V. When current is in the opposite direction the reverse situation exists. Assuming that the correct device is gated, the direction of current in the cell can be deduced. This detection circuit and associated control logic are integrated into the gate drive for each cell. To make the current direction information reliable only one of the devices in a cell is gated at any one time. This means that the current is either zero or flows in the designated direction.

3.2 Commutation method

This is explained with regards to figure 2 and is illustrated in figure 9, assuming that initially cell A is conducting and the load current is in the direction shown. Under these conditions SA1 will be gated and conducting. The current direction information from the

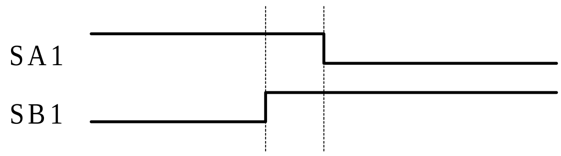

Figure 9. 2 step commutation

cell A gate drive is passed to the gate drive for cell B. When the modulation strategy demands commutation to cell B, SB1 is gated on the basis of the current direction information passed from cell A and SA1 is subsequently turned off. After a short interval (typically 5 μs) the current direction information is taken from the detection circuit in cell B rather than cell A. The commutation is now complete. This mechanism ensures a continuous path for the load current with no possibility of input short circuits. To provide for both load current directions in between commutations, the active cell drive circuit automatically transfers the drive between the devices within the cell if the detection circuit determines that the current has fallen to zero. This control of the direction of current within the bidirectional switch ensures that the current direction is known. A special case arises when the converter is switched on for the first time since the current direction information is not established. The first cell in the commutation sequence gates either one of the two devices. If this is the correct device, current flows and the circuit continues working as described above. If no current is detected the drive is transferred to the correct device automatically. A state diagram of the 2 step commutation strategy is shown in figure 10.

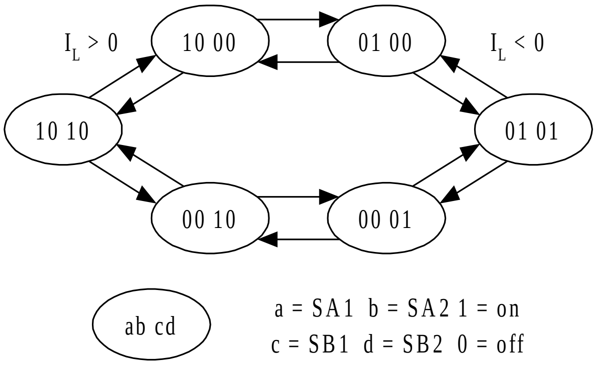

Figure 10. State diagram for 2 step commutation strategy

3.3 Potential Hazard

A potential difficulty occurs if the load current changes direction when a commutation between cells is required.

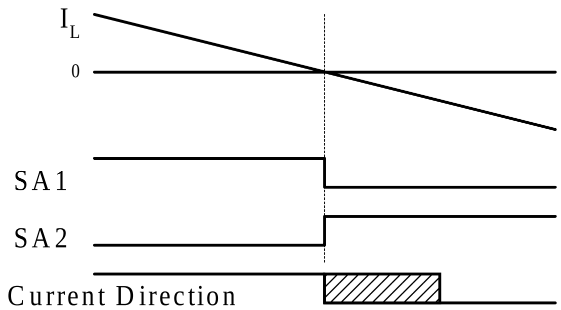

Figure 11. Current reversal including current direction propagation delay

Figure 11 shows a timing diagram for the current reversal process. The hatched area on the current direction line indicates the propagation delay in sending the data to the next gate drive cell. It can be seen that if a commutation between cells is required before the correct data has reached the next gate driver, switch SB1 will be turned on causing a shoot through condition.

This problem is solved by having a small dead time where no device is gated when the

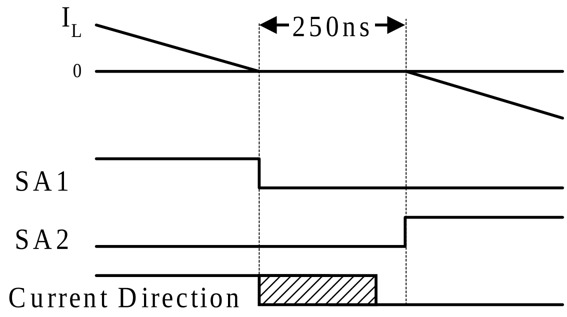

Figure 12. Current reversal including propagation delay compensation

current reaches zero. This is shown in figure 12. The reverse device is not gated until the new information is received by the other gate drivers. This delay is small and only depends on the propagation delay inherent in the communications lines (typically 250ns) and does not unduly distort the current waveforms.

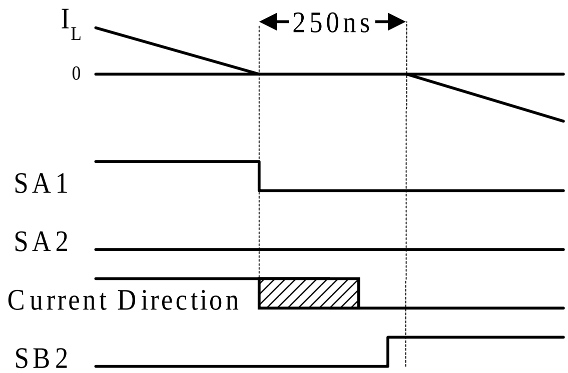

Figure 13. Commutation during current reversal.

Figure 13 shows a timing diagram for commutation during current reversal. It can be seen that since the outgoing device is already switched off a one step commutation is achieved. If the incoming cell is activated during the hatched period the incorrect device will be gated. However IL = 0 and no other devices are gated so no hazard conditions are produced. The incoming commutation cell quickly determines that no current is flowing and gates the opposite device. A revised state to cover this situation is shown in figure 14.

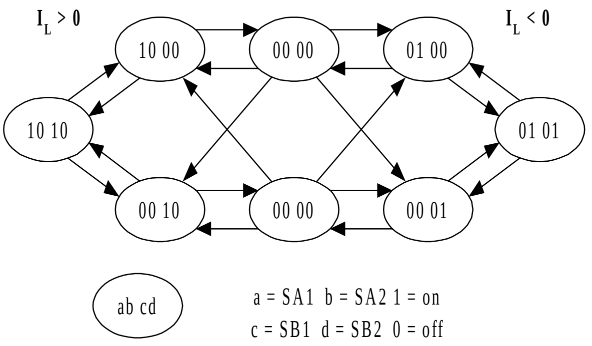

Figure 14. State diagram of commutation strategy including propagation delay

4. RESULTS

An experimental two phase to single phase converter (Figure 2) has been developed to evaluate the proposed method. The commutation cells were constructed with 16A, 1200V IGBTs and diodes and the converter was supplied from two phases of a three phase supply. A passive R-L load was used. Current direction has been reliably detected with currents down to 100μA. Figure 15 shows results for a supply voltage of 415V and a load current of 8A peak. The circuit operates without the need for any type of voltage clamping devices or snubber networks across the commutation cells. A third commutation cell was then added. Figure 16 shows the voltage and current waveforms for an output of 100Hz. This figure also demonstrates that small currents can be easily controlled using this method and that the dead time during zero crossing is not significant.

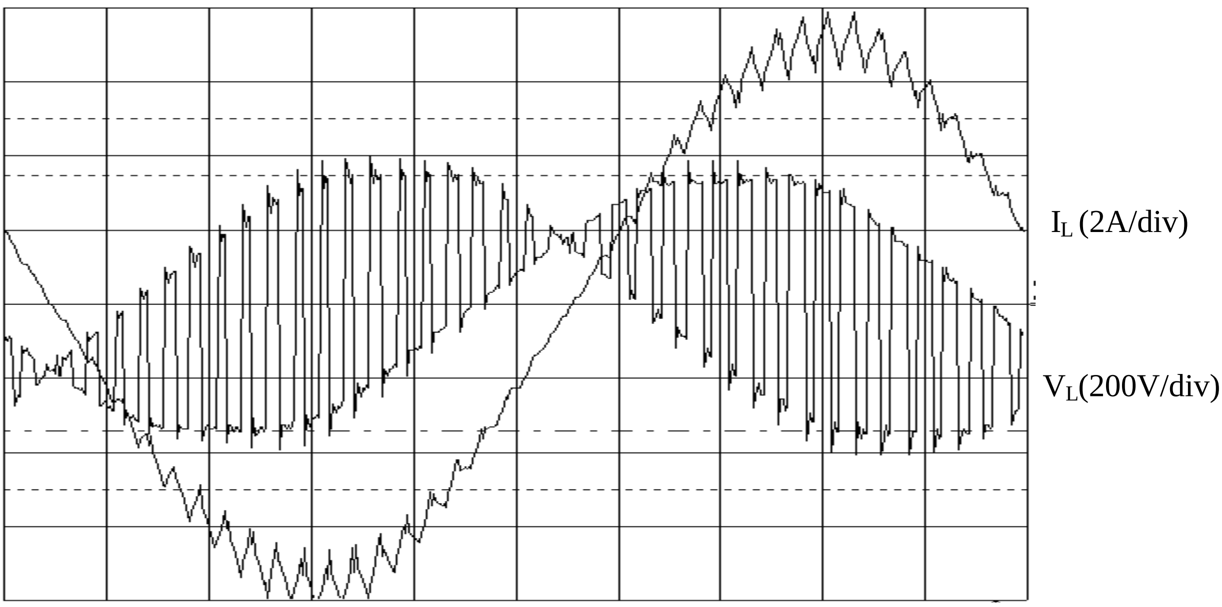

Figure 15. Output voltage and current waveforms for a 2 phase to single phase matrix converter

5. CONCLUSIONS

This paper has presented a novel approach to dealing with the problem of snubberless commutation in matrix converters employing bi-directional switch cells. The method employs current detection within intelligent gate drive circuits for each cell which communicate with the gate drives of other cells. The problems often arising with other methods at low currents are overcome. The technique can is easily extended to matrix converters with any number of input and output phases due to the modular nature of the gate drive and commutation cell arrangement. Extension of the method to higher powers should be straightforward and the increased forward voltage drop of larger devices would make the detection of the current direction more reliable. This is in contrast to other methods of current detection employing current transducers where resolution is lost as the current rating increases. Additionally, at each commutation either the incoming or outgoing device will switch under reverse bias conditions. This yields the so-called semi-soft (semi-natural) commutation[5] and typically reduces total device switching losses to 50% of other methods.

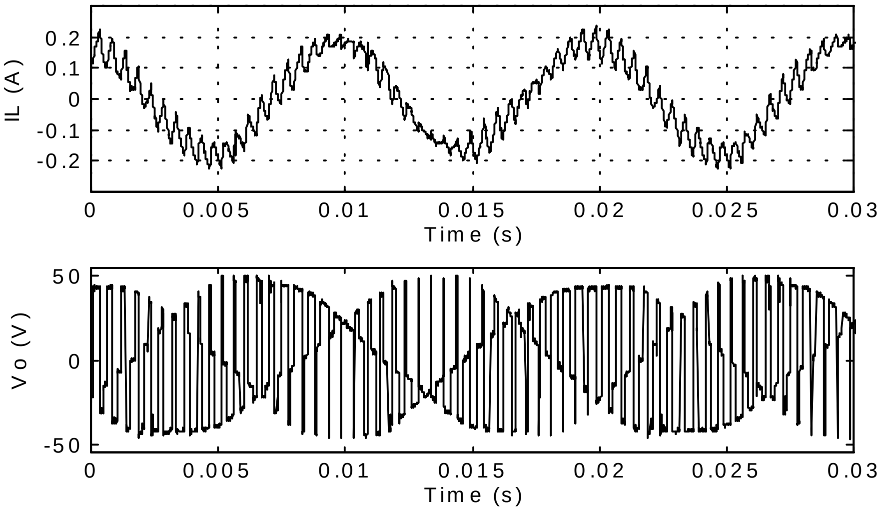

Figure 16. Voltage and current waveforms for 3 phase to 1 phase matrix converter

6. REFERENCES

[1] Venturini M, "A New Sine Wave In Sine Wave Out, Conversion Technique Which Eliminates Reactive Elements", Proceedings Powercon 7, pp.E3_1-E3_15, 1980.

[2] Alesina A and Venturini M, "The Generalised Transformer : A New Bidirectional Sinusoidal Waveform Frequency Converter With Continuous Variable Adjustable Input Power Factor", PESC Conference Record, pp.242-252, 1980.

[3] Burany N, "Safe Control of Four-Quadrant Switches", IEEE IAS Annual Meeting, pp.1190-1194,1989.

[4] Beasant R R, Beatie W C and Refsum A, "An Approach to the Realisation of a High Power Venturini Converter", IEEE, April 1990, pp.291-297.

[5] Wheeler, P.W.; Grant, D.A. "Optimised Input Filter Design and Low-Loss Switching Techniques for a Practical Matrix Converter", IEE Proceedings, Electrical Power Applications, pp.53-60, Vol. 144, No. 1, Jan 1997.

[6] Sunter S and Clare J C, "A True Four Quadrant Matrix Converter Induction Motor Drive with Servo Performance", IEEE Power Electronics Specialists Conference, pp.146-151, June 1996.

[7] Svensson, T.; Alaküla, M. "The modulation and control of a Matrix Converter – Synchronous Machine Drive." EPE Firenze Vol 4., 1991, pp 469-476.

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