Research in Matrix-Converter based Three-Phase Power-Electronic Transformers

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***Abstract*—This paper presents a review of the current research in the area of ac/ac power conversion with power electronic transformer. The topologies considered have the following features: 1) generation of adjustable frequency and magnitude PWM ac voltage waveform from a balanced three-phase ac voltage source with a high frequency ac link, 2) bidirectional power flow capability, and 3) single stage power conversion without any storage elements. All of these topologies provide power factor correction. Based on the operation and control, these topologies have been classified into three groups. The operation, advantages and drawbacks of each of these topologies have been presented along with a comparison of their performance in the presence of leakage inductance, complexity to control and reliability.**

I. Introduction

Three-phase ac/ac power converter with a high frequency ac link has a wide range of applications including wind power generation [1]. A transformer in the system provides required voltage transformation along with galvanic isolation. Power electronic transformers (PET) potentially offer an attractive alternative to the conventional line-frequency transformers in terms of reduced weight and volume. Use of high frequency transformers results in high power density and reduction in the cost of copper and iron.

Single phase ac to constant frequency controllable magnitude ac with a high frequency ac link is presented in [2] and [3]. In [4], a modulation strategy based on phase modulated converter is proposed to get soft switching when the output voltage and current are in the same quadrant. Single and three-phase ac/ac converters with high frequency transformer based on flyback and push-pull converters with multiple power conversion stages and storage elements are described in [5], [6] and [7].

The use of matrix converter in high-frequency ac link based power conversion results in the elimination of bulky energy storage capacitor. Presence of dc-link capacitors reduces the reliability of the system particularly at higher temperatures. Thus, matrix converter based PET results in a high power-density converter system which is also suitable for future high-temperature power electronics. In this paper, ongoing research on several new matrix converter based topologies for PET are described. These new topologies ensure single-stage power conversion with bidirectional power flow capability. These topologies can be classified into three groups.

The first type, as discussed in section I, is based on the indirect modulation of matrix converters [8]. The virtual dc-link is chopped to a high-frequency ac voltage and fed to a high-frequency transformer. A variation of this topology is being investigated in [9], where the mid-point of the secondary winding is used to provide three levels for the secondary side converter. The output matrix converter is modulated to eliminate common-mode voltage at the load terminals.

In the second group of topologies, described in section II, the three-phase ac voltage waveform is chopped into a high-frequency ac and fed to a bank of three transformers. In the secondary side, a matrix converter is employed to generate the desired output voltage waveform. There are two variations possible in the primary side configuration: full-bridge [10] [11], and push-pull [1] [12]. In the push-pull topology, the primary side which is normally the high-voltage side, has only two controlled switches.

The windings of the high-frequency transformer have leakage inductances. The load is generally inductive in nature. In all of the above-mentioned topologies, the transition of each switching state of the output converter requires commutation of leakage energy. A clamp circuit can be used. However, this leads to power loss, loss in the generated output voltage, distortion in the output load current waveform and common-mode voltage switching [13].

To eliminate the above-mentioned drawbacks a third group of topologies are introduced in [14]. In this group, the modulation of the output voltage waveform is done in the primary side. This minimizes the number of switching transitions between the leakage inductance and the load. Also in [14] a loss-less source-based-commutation technique is presented which leads to the soft switching of all the switches in the secondary side converter.

II. Topologies based on the indirect modulation of the matrix converter

The first approach is based on the indirect modulation of the matrix converter [15]. In this method only 18 of the available 24 active switching states are used. The remaining 6 active states, that produce synchronously rotating vectors are not used. The indirect modulation of matrix converter is equivalent to the simultaneous modulation of two two-level converters connected back to

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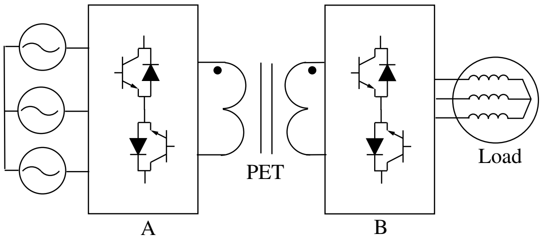

Fig. 1. Topology based on indirect modulation (A1)

back. The input converter is a voltage source rectifier or current source inverter (CSI) and the output converter is a voltage source inverter (VSI). The virtual dc-link connects both of these converters.

Fig. 1 shows the schematic diagram of this topology. In this implementation, the virtual dc-link is chopped by the input converter (A in Fig. 1) to a high frequency square wave and fed to the primary of the power electronic transformer. The output converter (B in Fig. 1) first rectifies this high frequency voltage to the same virtual dc-link and then inverts it to generate adjustable frequency and magnitude three-phase ac at the load terminals. The output converter can be implemented with a H-bridge and a conventional two level inverter as shown in [8]. The use of a snubber or clamp circuit for the commutation of leakage energy will require four quadrant switches in the output inverter.

An improvement of this topology has been proposed in [9]. This eliminates common-mode voltage at the load terminals. In this topology, the mid point of the secondary winding of the transformer is used to create three levels for the output converter as shown in (Fig. 2). A H-bridge rectifier (B in Fig. 2) is connected to the other two terminals of the secondary winding. The output converter operates as a three level inverter (C in Fig. 2).

The output three level inverter has 27 switching states. Out of which only 6 active states result in zero common-mode voltage at the load terminals. These six states along with zero states are used to generate the output voltage waveform. Hence, the output three level inverter is used as a two level voltage source inverter. This reduces the modulation index of the output converter. In order to synchronize the output and input converter, a variable slope carrier is used to generate the PWM pulses for the output three level inverter.

The peak value of the output voltage is given by, $V_o = \sqrt{3}K_iK_oV_i$. Where K_i is the modulation index of the

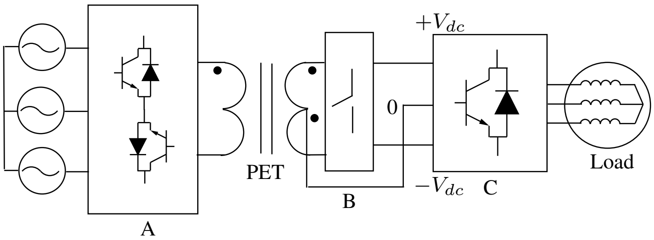

Fig. 2. Topology for common-mode voltage suppression (A2)

input converter and is set to its maximum value 0.5. The modulation index K_o of the output inverter is limited to 0.866. V_i denotes the peak of the input line to neutral voltage.

The advantages of this topology are input power factor correction, partial common-mode voltage elimination and a simple carrier based PWM control. This topology employs only one PET. The presence of leakage inductance requires all switches in the output side converters to be four quadrant. This implies that the H-bridge and three level inverter can be replaced by a matrix converter. One main objective of this topology is common-mode voltage elimination. But presence of leakage inductance causes common-mode voltage switching for each of the switching transitions of the output converter.

III. The Second Group of Topologies

In this approach the input three-phase balanced ac voltage is chopped to a high frequency ac waveform with 50 % duty cycle and fed to the primary of a bank of three single-phase transformers [1] [10] [11] [12]. In the secondary or the load side, a matrix converter is used to generate adjustable frequency and magnitude PWM ac voltage waveform. The chopping of the input voltage waveform can be done in two possible ways, either using a push-pull or by a full-bridge configuration in the primary side.

A. Push-pull

In this topology (Fig. 3), the three-phase balanced input voltages are converted into high frequency ac by switching S1 and S2 in a complementary fashion with 50% duty cycle. This converter follows the principle of push-pull topology. Each input voltage source is connected to the mid point of the corresponding primary winding. The secondary windings are star connected. In the first half of the cycle, when S1 is on, the terminals a_1, b_1 and c_1 (in Fig. 3) are shorted together; hence the upper-half of the primary windings forms a star connection. The voltages developed in the secondary windings are in phase with the corresponding input voltages i.e. $V_{AN} = nV_a$ (n is the turns ratio of the transformer). During the other half of the cycle, when S2 is on, the secondary voltages are 180 degrees out of phase with the corresponding input voltages i.e. $V_{AN} = -nV_a$. During this state, the terminals a_2, b_2 and c_2 are shorted through switch $S2$. The voltage waveform in the secondary of the transformer along with the corresponding input voltage waveform, in one of the phases, is shown in Fig. 4. The flux in each of these transformers are maintained over the full cycle.

The modulation of the output matrix converter is similar to a matrix converter connected to a low frequency three-phase ac voltage source, where the duty cycles for the switches in the converter are generated from the reference for the output voltage and sensed input voltage waveforms. The only difference is that the effective carrier for the output voltage generation must be synchronized with the switching of S1 and S2. The maximum modulation index (the ratio of the peaks of the input and

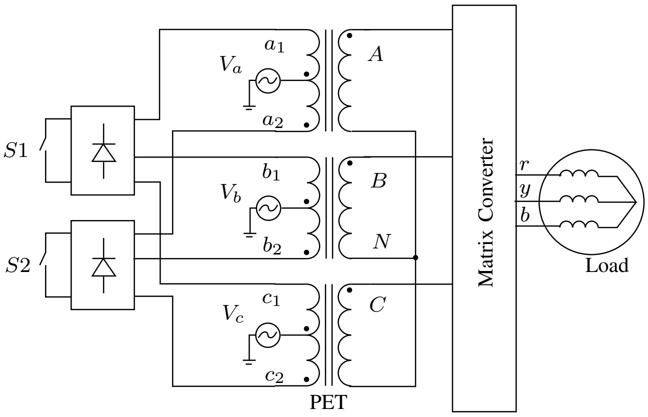

Fig. 3. Topology based on push-pull configuration (B1)

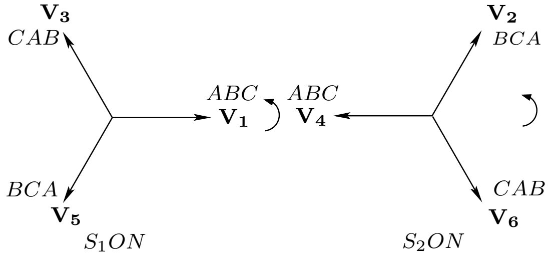

Fig. 5. Synchronously rotating vectors (CCW)

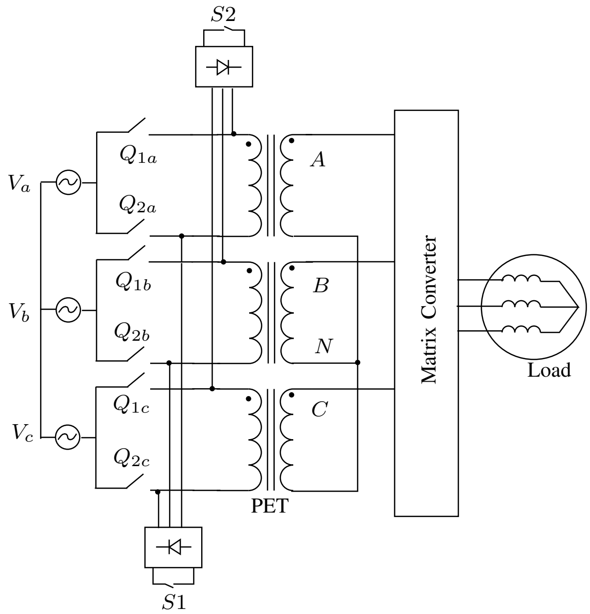

Fig. 6. Topology based on full-bridge configuration: line to neutral (B2)

synthesized average output voltage waveform) is 0.866 times the turns ratio of the transformers.

It is known that in a matrix converter, the common-mode voltage is zero when synchronously rotating vectors are applied [16]. With a single matrix converter, only three vectors, rotating in one direction (clock wise or anti clock wise), are available at a given instant of time. The maximum modulation index in this case is 0.5. Also, the distortion in the output voltage waveform will be more compared to a two level VSI where there are six vectors available for modulation. In this case, over the full cycle, in any one direction of rotation, six voltage vectors are available. The available counter clockwise set as shown in Fig. 5. In this figure ABC refers to the switching state of the output matrix converter when the terminals A,B,C are connected to r, y and b (Fig. 3) respectively. As each set of three voltage vectors are available only for 50% of the time, the maximum attainable modulation index is 0.75, as explained in [12].

The most important advantage of this topology is that there are only two controlled switches at the primary side of the converter where the ac voltage sources are connected. This is often the high voltage side. This topology has all other advantages of input power factor correction, single stage power conversion, high power density, common-mode voltage suppression at the load end. The modulation of this converter is comparatively simpler compared to the first group.

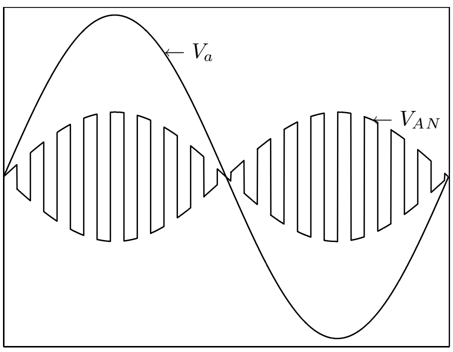

Fig. 4. The secondary voltage waveform

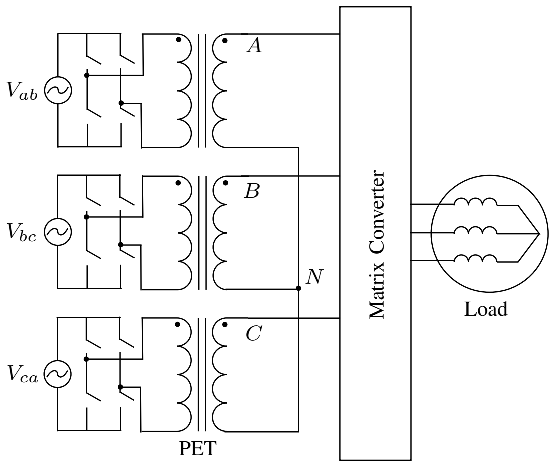

Fig. 7. Topology based on full-bridge configuration: line to line (B3)

B. Full-bridge

This is the full-bridge version of the previous topology. There are two possibilities, either use line to neutral voltage [10] or use line to line [11]. Fig. 6 shows the full-bridge implementation with line to neutral voltage. During the first half of the cycle Q_{1a}, Q_{1b}, Q_{1c} are on along with $S1$. The primary windings form a star. The switching of

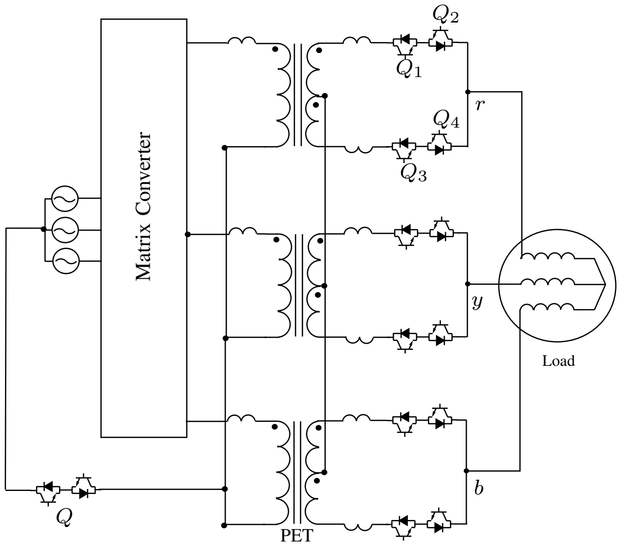

Fig. 8. Topology for loss less commutation of leakage energy (C)

Q_{1abc} and Q_{2abc} is complementary with 50% duty-cycle. This is also true for $S1$ and $S2$.

In the other type [11] as shown in Fig. 7, the line to line voltages are chopped with 50% duty-cycle with an input H bridge and fed to the transformer primary for each of the phases. The secondary voltages (V_{AN}, V_{BN} and V_{CN}) are the same as the push-pull case. The only difference here is that the line to line voltages appear instead of the phase to neutral voltage of the input ac source i.e. $V_{AN} = nV_{ab}$. Similar modulation strategies for the output matrix converter are applicable here.

In this group of topologies, the problems associated with leakage inductance are present. For the push-pull configuration, unlike the case of other topologies, separate commutation is needed for the primary leakage inductance.

IV. The Third Approach

The three-phase load is generally inductive in nature and there are leakage inductances present in the windings of the high frequency transformer. Any switching between the load and the transformer windings requires commutation of current in the leakage inductance. Note that this actually happens in all of the above mentioned topologies when the output converter makes a switching transition. This commutation results in output voltage loss, distortion in the output current and common-mode voltage switching [13]. In the third approach (Fig. 8), the output converter is simplified and the switching between the load and the transformer is minimized. The synthesis of the output voltage is done in the primary side. A source based commutation technique has been proposed that leads to the loss-less commutation of leakage energy [14].

In [17], it is shown that source based commutation is possible in the full-bridge configuration.

The entire operation of this converter is divided into two parts, modulation and commutation. During the modulation stage the switch Q in Fig. 8, is off. In the first half of the modulation, the switches Q_1 and Q_2 of each phase is turned on and power is transferred through the upper half of the secondary winding. The input side matrix converter synthesizes the required average voltage for the load. In the second half of the modulation, the lower half of the secondary winding conducts. The input side matrix converter generates a three-phase voltage that is out of phase with the commanded average voltage for the load. Note, that the magnetizing inductance forms a star connected load and appears to be in parallel to the actual three-phase load during the power transfer stages. So the net average voltage applied to the magnetizing inductance is zero over a full cycle of power transfer.

Commutation of the leakage inductance is required when, power transfer changes from upper half of the secondary winding to the lower half or vice verse. The commutation actually refers to the following processes 1) building the load current in the leakage inductance of the secondary winding that is coming into conduction 2) making the leakage inductance current of the secondary winding that is going out of conduction to zero and 3) the reversal of the current in the primary leakage inductance. This is done by applying proper voltages across the transformer primary windings and properly switching Q_1, Q_2, Q_3, and Q_4 (during this process the switch Q is turned on).

All the switches in the secondary converter and the switch Q, are switched with zero current (ZCS). The commutation process is loss less. The output voltage loss and common-mode voltage switching due to commutation is minimized (only once in one sampling cycle). Here, sampling cycle refers to the time period in which the output voltage is synthesized in an average sense. This topology ensure better quality of output voltage waveform. On the other hand there are more switches in the primary side (generally the high voltage side) and commutation requires extra switching.

V. Conclusion

All of the topologies discussed in this paper convert three-phase balanced ac to adjustable magnitude and frequency pulse width modulated three-phase ac. Power conversion is single stage and bidirectional. All of the above mentioned topologies provide input power factor correction. Table I presents a comparison of all of these topologies. From the first group, topology A2 is not considered. One of the main objective of A2 is common-mode voltage elimination at the load end, but each switching transition of the output converter results in common-mode voltage switching because of the leakage inductance commutation. In Table I, number of switches refers to the number of IGBTs with anti-parallel diodes. Here all the four quadrant switches are assumed to be implemented with the common-emitter connection of two IGBTs. Topology A1 has comparatively less number of switches. It has only one transformer, and the flux swing is constant. In this topology source based commutation of leakage energy is possible. The modulation of this

TABLE I
COMPARISON

Topologies	Number of switches in primary side	Number of switches in secondary side	Total	Maximum modulation index	Flux swing	Source based commutation
A1	12	12	24	$0.866n$	Constant	Possible
B1	2	18	20	$0.866n$	Variable	Not possible
B2	14	18	32	$0.866n$	Variable	Possible
B3	24	18	42	$1.5n$	Variable	Possible
C	20	12	32	$0.866n$	Variable	Possible

converter, based on the indirect modulation of matrix converter is relatively more complicated. From the second group, topology B1 has least number of switches. The most important advantage of this topology is that it has only two control switches in the primary side (normally the high voltage side). On the other hand it has two windings in the primary. Topology B2 has 12 switches more in the primary but has only one winding at the primary (less copper). Topology B1 has an additional problem of primary leakage inductance commutation and loss-less source-based commutation is not possible in this topology. Topology B3 has maximum number of switches. For a given turns ratio of the transformer, n, it provides the maximum voltage transfer ratio. Source based commutation is possible in this topology [17].

In Topology C, the number of switching of the transformer windings and the output load is minimized (only once in a sub-cycle). This topology has minimum amount of voltage loss, distortion of the output load current and common-mode voltage switching due to leakage inductance commutation. A complete source based, loss less commutation of leakage energy is possible. This also results in soft switching of all of the secondary switches. In topology A1, source based commutation is comparatively difficult to implement, as the leakage inductance commutation is required at variable instants of time. On the other hand topology C has maximum number of switches in the primary side. Also source based commutation increases number of switching and the complexity of control.

If leakage inductance is minimized with a better design of the transformer, topology B1 appears to be promising due to comparatively low switch count and relatively easy control. Topology C, provides a comprehensive solution to the leakage inductance problem, with more number of switches and complex switching strategy.

REFERENCES

[1] R. Gupta, G. Castelino, K. Mohapatra, and N. Mohan, “A novel integrated three-phase, switched multi-winding power electronic transformer converter for wind power generation system,” in *Industrial Electronics, 2009. IECON ’09. 35th Annual Conference of IEEE*, nov. 2009, pp. 4481 –4486.

[2] M. Kang, P. Enjeti, and I. Pitel, “Analysis and design of electronic transformers for electric power distribution system,” in *Industry Applications Conference, 1997. Thirty-Second IAS Annual Meeting, IAS ’97., Conference Record of the 1997 IEEE*, vol. 2, Oct 1997, pp. 1689–1694 vol.2.

[3] H. Krishnaswami and V. Ramanarayanan, “Control of high-frequency ac link electronic transformer,” *Electric Power Applications, IEE Proceedings -*, vol. 152, no. 3, pp. 509–516, 6 May 2005.

[4] D. Chen and J. Liu, “The uni-polarity phase-shifted controlled voltage mode ac-ac converters with high frequency ac link,” *Power Electronics, IEEE Transactions on*, vol. 21, no. 4, pp. 899–905, July 2006.

[5] D. Tang and L. Li, “Analysis and simulation of push-pull three level ac/ac converter with high frequency link,” in *Industrial Electronics and Applications, 2009. ICIEA 2009. 4th IEEE Conference on*, May 2009, pp. 3366–3371.

[6] D. Chen, L. Li, J. Liu, S. Lin, and C. Song, “Novel current mode ac/ac converters with high frequency ac link,” in *Power Electronics Specialists Conference, 2005. PESC ’05. IEEE 36th*, June 2005, pp. 39–44.

[7] M. Manjrekar, R. Kieferndorf, and G. Venkataramanan, “Power electronic transformers for utility applications,” in *Industry Applications Conference, 2000. Conference Record of the 2000 IEEE*, vol. 4, Oct 2000, pp. 2496–2502 vol.4.

[8] H. Cha and P. Enjeti, “A three-phase ac/ac high-frequency link matrix converter for vscf applications,” in *Power Electronics Specialist Conference, 2003. PESC ’03. 2003 IEEE 34th Annual*, vol. 4, June 2003, pp. 1971–1976 vol.4.

[9] K. Basu, A. Umarikar, K. Mohapatra, and N. Mohan, “High-frequency transformer-link three-level inverter drive with common-mode voltage elimination,” in *Power Electronics Specialists Conference, 2008. PESC 2008. IEEE*, June 2008, pp. 4413–4418.

[10] R. Gupta, K. Mohapatra, and N. Mohan, “Novel topologies of power electronic transformers with reduced switch-count,” in *Grand Challenges in Modeling and Simulation (GCMS’09)*, July 2009.

[11] K. Mohapatra and N. Mohan, “Matrix converter fed open-ended power electronic transformer for power system application,” in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, July 2008, pp. 1–6.

[12] R. K. Gupta, K. K. Mohapatra, and N. Mohan, “A novel three-phase, switched multi-winding power electronic transformer,” in *Proc. IEEE Energy Conversion Congress and Exposition (ECCE) 2009*, San Jose, CA, Sep. 2009, pp. 2696 –2703.

[13] S. Nath, K. Mohapatra, and N. Mohan, “Output voltage regulation in matrix converter fed power electronic transformer for power systems application in electric ship,” in *Electric Ship Technologies Symposium, 2009. ESTS 2009. IEEE*, april 2009, pp. 203 –206.

[14] K. Basu, A. Somani, K. Mohapatra, and N. Mohan, “Three phase ac/ac power electronic transformer based pwm ac drive with loss less commutation of leakage energy,” in *SPEEDAM 2010, accepted for presentation*, June 2010.

[15] L. Huber and D. Borojevic, “Space vector modulated three-phase to three-phase matrix converter with input power factor correction,” *Industry Applications, IEEE Transactions on*, vol. 31, no. 6, pp. 1234 –1246, nov/dec 1995.

[16] R. Gupta, K. Mohapatra, A. Somani, and N. Mohan, “Direct-matrix-converter based drive for a three-phase open-end-winding ac machine with advanced features,” *Industrial Electronics, IEEE Transactions on*, vol. PP, no. 99, pp. 1 –1, 2010.

[17] S. Nath, K. Mohapatra, K. Basu, and N. Mohan, “Source based commutation in matrix converter fed power electronic transformer for power systems application,” in *SPEEDAM 2010, accepted for presentation*, June 2010.