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Source based Commutation in Matrix Converter fed Power Electronic Transformer for Power Systems application

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***Abstract*—This paper proposes a source based commutation method for a matrix converter fed power electronic transformer. Two converters produce high frequency voltage across a transformer, with open ended primary. A third matrix converter converts the high frequency chopped voltage to line frequency. The leakage inductance of the transformer creates a commutation delay in the primary side to secondary side voltage transfer. During the commutation interval, difference in the load current and secondary leakage current flows to the clamp circuit. Thus, power is lost in the clamp circuit during every commutation interval.**

The source based commutation described in this paper minimizes the power loss during commutation interval. No additional switching is needed at the primary side power converters for source based commutation. The proposed method has been simulated in SIMULINK and the results have been presented.

***Index Terms*—high frequency power transformer, leakage inductance, matrix converter, source based commutation.**

I. Introduction

Transformers are one of the most essential parts of a power system. However, present transformers occupy a large space. Large volume and weight of transformers are a limitation for several applications like off-shore wind power generation. In order to reduce size, high frequency transformers are required. To address this problem, a high frequency power electronic topology using matrix converters has been proposed in [3]. Though, DC bus based systems are advocated in current proposals, but since most loads are AC, 3-phase AC to AC conversion is an alternative. So the topology proposed in [3] uses a 3-phase AC to AC conversion.

Leakage inductance is one of the important factors which affect the performance of the converter proposed in [3]. Use of clamp circuit for current commutation in leakage inductance requires a energy recovery circuit. This paper proposes a source based commutation method by which use of clamp circuit is minimized. The proposed source based commutation has been simulated in SIMULINK.

II. Current commutation in power electronic transformer

The topology proposed in [3] is shown in Fig. 1. The primary of the high frequency transformer is excited from both ends, by two converters (MC-1 and MC-2), connected to the same source. MC-1 and MC-2 are similar to a matrix converter with three bi-directional switches removed. The secondary of the transformer is star connected and is connected to a third matrix converter (MC-3) [6][7]. High frequency voltage is produced across the transformer by MC-1 and MC-2. MC-3 converts the high frequency transformer output back to line frequency. MC-1, MC-2 and MC-3 are switched in synchronization to generate null common mode voltage [3]. Four step commutation is used for MC-1 and MC-2 and two step commutation is used for MC-3. A clamping circuit is connected at the input of MC-3. The principle of operation of the converter and simulation results has been presented in [3]. The leakage inductance in the transformer creates a commutation delay in the primary side to secondary side voltage transfer. During the commutation interval, difference in the load current and secondary leakage current flows to the clamp circuit [2]. The power lost in clamp circuit can be recovered by using an energy recovery circuit.

This paper proposes a source based commutation method to save power during the commutation interval. By source based commutation the use of clamp circuit is minimized. Also, the clamp circuit can be eliminated by using MC-1 and MC-2 as two matrix converters with nine bi-directional switches each.

III. Principle of source based commutation

The basic principle of source based commutation can be explained with Fig. 2, Fig. 3 and Fig. 4. Fig. 2 shows two phase to single phase matrix converter with controllable source voltages V1 and V2. The controllable source voltages V1 and V2 are obtained from a source converter, such that they provide opposite voltage inequalities before and after switching, i.e. before switcihing the source converter if voltage inequality provided is V1>V2 then after switching, the voltage inequality provided is V2>V1. The source inductance L_{lk} represents the leakage inductance of the high frequency transformer.

For the direction of current as shown in Fig. 2, IGBT SA1 was conducting. At any time instant t1, a commutation is needed from SW1 to SW2. At time instant t1,

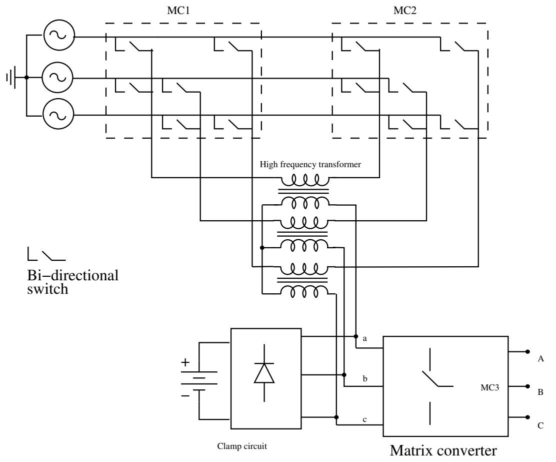

Fig. 1. Matrix converter driven high frequency transformer

IGBT SA2 is gated. Therefore, both SA1 and SA2 are ON at time instant t1. At time instant t1, the circuit resembles a diode bridge with leakage inductances at the source. If V2>V1, then both diodes DB2 and DB1 gets forward biased and the current in leakage inductances commutates through the source. Hence a source based commutation takes place in the two phase to single phase matrix converter.

The difference between source based commutation in a diode bridge and a source based commutation in a matrix converter, is in the direction of load current. In a matrix converter load current can flow in both directions. Therefore, depending on the direction of load current, the voltage inequality required at the source for commutation varies. Providing the correct voltage inequality according to the direction of load current, source based commutation can be achieved.

At time instant t1, if the voltage inequality provided by the source is V1>V2, then the source converter has to be switched. Switching the source converter makes the voltage inequality V2>V1 and a source based commutation can take place.

The time required for current to commutate in the leakage inductances is decided by three factors - the value of leakage inductance, the magnitude of current and the difference between voltages V1 and V2. This time interval is referred as commutation time interval in this paper. After providing, the correct voltage inequality for commutation, both IGBTs SA1 and SA2 has to remain ON atleast for the commutation time interval. The commutation time interval can be accounted for by activating a timer after providing the correct voltage inequality.

The above explained commutation method can be implemented with a state machine. The state diagram is shown in Fig. 3. Whenever a commutation is required from SW1 to SW2, the matrix converter goes into 1010 or 0101 states depending on the direction of the current. At this point the voltage inequality condition provided by V1 and V2 is checked.

Fig. 4 shows the details of switching when a commutation from SW1 to SW2 is required and the direction of current is as shown in Fig. 2. At time instant t1, SA2 is turned ON. At time instant t1, if V2>V1 then a timer is activated and SA1 is turned OFF after the timer pulse goes low, shown as time instant t2 in Fig. 4. But at time instant t1, if V2<V1 then SA1 remains ON till V1 and V2 change such that V2>V1. When V2>V1 is obtained, then a timer is activated and SA1 turns OFF at time instant t3. The timer provides a pulse equal to the commutation time interval. During the interval the timer is ON (till t2 or t3), the matrix converter remains in the 1010 state. After the commutation is over (at time instant t2 or t3), the matrix converter is switched to the final state of 0010.

As explained above, at time instant t2 the source converter is switched and at time instant t1 a commutation from SW1 to SW2 is needed. Therefore, by shifting the switching time instant of source converter ahead of the switching time instant of SW1 and SW2, automatic source based commutation can be achieved without any additional switching in the source converter.

The principle explained above can be extended to a three phase to three phase matrix converter. The modulation strategy explained in [3] uses only clockwise or anti-clockwise vectors. Therefore, if abc is the input voltage to MC3 then using anti-clockwise vectors, the output will be abc, bca or cab. So, MC3 switches from abc to bca, bca to cab and cab to abc. In each leg of the matrix converter, at any instant the commutation takes place between two bi-directional switches. So, each leg requires one voltage inequality according to the direction of current in that leg and therefore, three legs give three voltage inequalities.

Table 1 shows the voltage inequality conditions required for source based commutation, depending on the directions of current in a three phase balanced load and the change of switching in MC-3. As shown in Fig. 5, a three phase supply can be divided into six zones based on the voltage inequality satisfied by that zone. Therefore, at any time instant one out of the six voltage inequalities are provided by MC-1 and MC-2. Also, these are the six voltage inequalities that are needed for source based commutation as shown in Table 1.

As explained in [2] and [3], the high frequency voltage obtained from MC-1 and MC-2 is such that the volt second balance is maintained in the transformer. Therefore, alternating voltages with 180^o phase shifts are applied in one switching time period. This indicates that if at any time instant a given voltage inequality was satisfied, the opposite voltage inequality is satisfied after MC-1 and MC-2 are switched. For example, in Fig. 7 at time 0.0045s (shown by red dashed line), Vc>Vb>Va. After switching MC1 and MC2, at time 0.0047s (shown by green dashed line), Va>Vb>Vc i.e. the opposite voltage inequality is satisfied. Therefore, a source based commutation can be obtained by shifting the switching time instants of MC-1 and MC-2 ahead of the switching time instants of MC-3 as shown in Fig. 6.

The commutation in three phase to three phase matrix converter can be explained with Fig. 4, Fig. 8, Fig. 9,

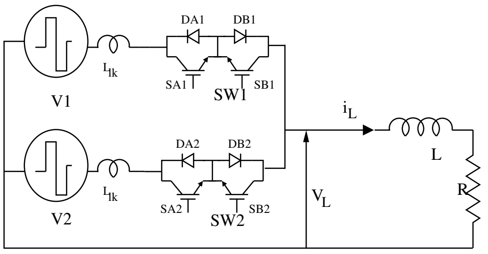

Fig. 2. Two phase to single phase matrix converter with source inductance

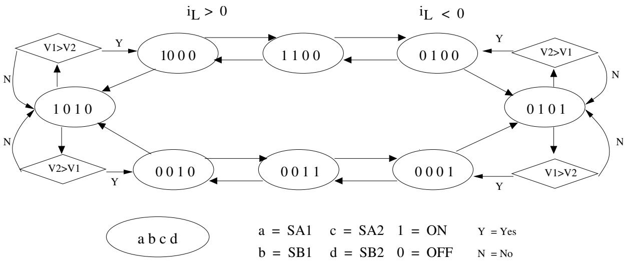

Fig. 3. State diagram for source based commutation of a two phase to single phase matrix converter

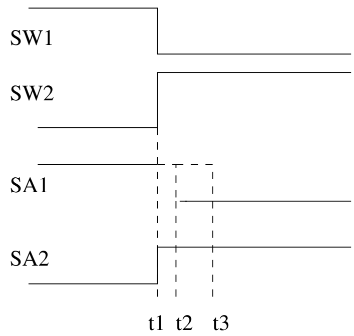

Fig. 4. Commutation from SW1 to SW2

Fig. 10 and Fig. 11. Suppose the values of load currents i_{LA}, i_{LB} and i_{LC} before commutation i.e. before time instant t1, are +5, +7 and -12 respectively and a switching from abc to bca is required. This is shown in Fig. 8. The switches which are not conducting before t1 are not shown in Fig. 8 for clarity. The current in leakage inductances L_{lka}, L_{lkb} and L_{lkc} are $+5$, $+7$ and -12 respectively. At time instant t1, SbA1, ScB1, SaC2 are turned ON. This is shown in Fig. 9.

From table 1 the voltage inequality required for commutation is Vc>Vb>Va. Suppose MC-1 and MC-2 provides a voltage inequality Vb>Vc>Va, so out of the three required inequalities two inequalities Vb>Va and Vc>Va are available. Therefore, the diodes of SbA1 and SaC2 will get forward biased. So, the currents in SaA1 and ScC2 become zero after a commutation time interval. The diode of ScB1 remains reverse biased. Therefore, the current in SbB1 continues to be +7. The currents in leakage inductances L_{lka}, L_{lkb} and L_{lkc} change from +5, +7 and -12 to -12, $+12$ and 0 respectively. At time instant t2, SaA1 and ScC2 are switched OFF. This is shown in Fig. 10.

After time t2, MC1 and MC2 are switched. So the voltage inequality provided by MC1 and MC2 becomes Va>Vc>Vb. Now, the third inequality required for source based commutation Vc>Vb is also satisfied. The diode of ScB1 gets forward biased. The current in SbB1 becomes zero after the commutation time interval. SbB1 is turned OFF at time instant t3. The currents in leakage inductances L_{lka}, L_{lkb} and L_{lkc} change from -12, +12 and 0 to -12, $+5$ and $+7$ respectively. This is shown in Fig. 11.

Thus, a clamp circuit is not required for the current commutation in leakage inductance. When the difference in voltage between two phases becomes very small, the time interval needed for commutation becomes very large. At this stage the clamp circuit is used to achieve a fast commutation.

IV. SIMULATION RESULTS

The proposed source based commutation method has been verified by simulation in SIMULINK/MATLAB. Simulation results with source based commutation with switching frequency of 1kHz are shown in Fig. 13 and Fig. 14. Fig. 12 shows the voltage across the secondary winding of the high frequency transformer and the clamp circuit current without source based commutation i.e. only using clamp circuit. In Fig. 12, during every commutation interval the voltage across the secondary winding is the clamp circuit voltage, whereas in Fig. 13, the clamp circuit voltage appears during commutation interval, only when the difference between input voltages of MC3 becomes very small. Comparison of Fig. 12 and Fig. 13 indicates a significant reduction in power loss. Fig. 14 shows the voltage and current at output of MC3. The swicthing time instants of MC1 and MC2 are delayed

TABLE I
VOLTAGE INEQUALITIES FOR SOURCE BASED COMMUTATION

MC3 switching	i_{LA}	i_{LB}	i_{LC}	Voltage inequality required
abc to bca	+	+	-	Vc>Vb>Va
	+	-	+	Vb>Va>Vc
	-	+	+	Va>Vc>Vb
	-	-	+	Va>Vb>Vc
	-	+	-	Vc>Va>Vb
	+	-	-	Vb>Vc>Va
bca to cab	+	+	-	Va>Vc>Vb
	+	-	+	Vc>Vb>Va
	-	+	+	Vb>Va>Vc
	-	-	+	Vb>Vc>Va
	-	+	-	Va>Vb>Vc
	+	-	-	Vc>Va>Vb
cab to abc	+	+	-	Vb>Va>Vc
	+	-	+	Va>Vc>Vb
	-	+	+	Vc>Vb>Va
	-	-	+	Vc>Va>Vb
	-	+	-	Vb>Vc>Va
	+	-	-	Va>Vb>Vc

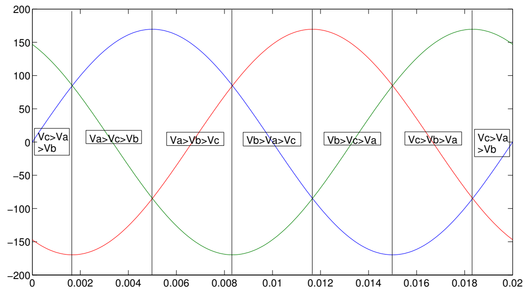

Fig. 5. Six voltage inequality conditions in three sine waves

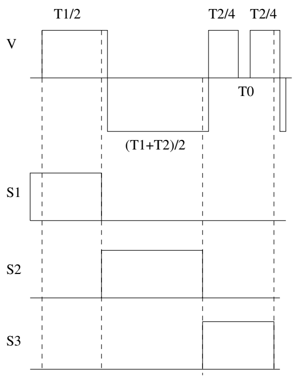

Fig. 6. Voltage across one winding of transformer and the three modulation pulses of MC3

by $10\mu s$ to the switching time instants of MC3. By this automatic source based commutation is achieved with no additional switching in MC1 and MC2.

V. Conclusion

A source based commutation method for a high frequency transformer controlled through matrix converter is proposed. Current commutation in leakage inductance of high frequency transformer with clamp circuit leads to power loss and requires an energy recovery circuit. The source based commutation minimizes the use of clamp circuit significantly and thus increases overall efficiency of the system. No additional switching is required in the primary side power converters to obtain source based commutation.

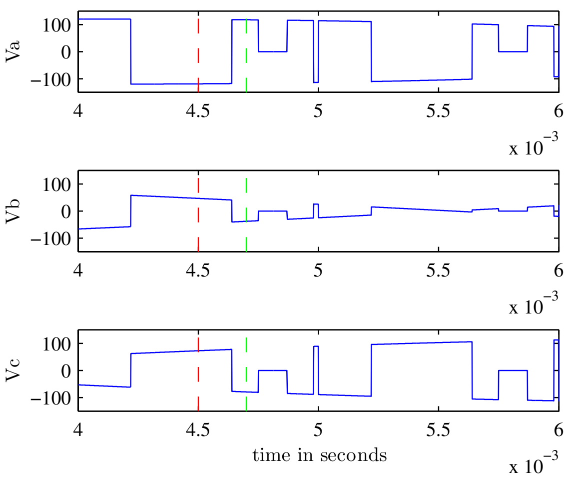

Fig. 7. Voltage across primary winding of transformer

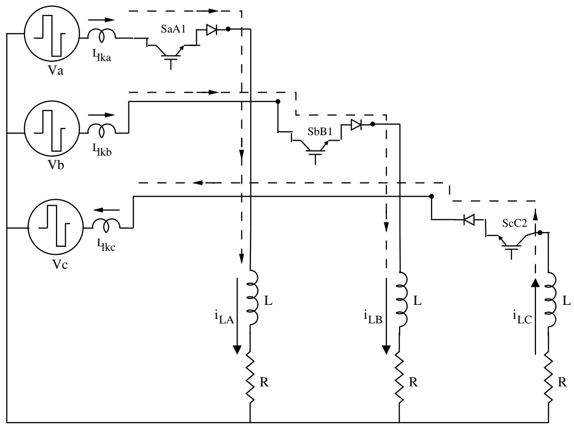

Fig. 8. MC3 before time instant t1

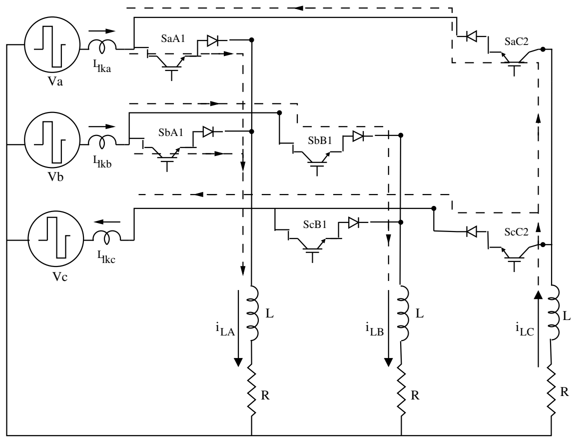

Fig. 9. MC3 at time instant t1

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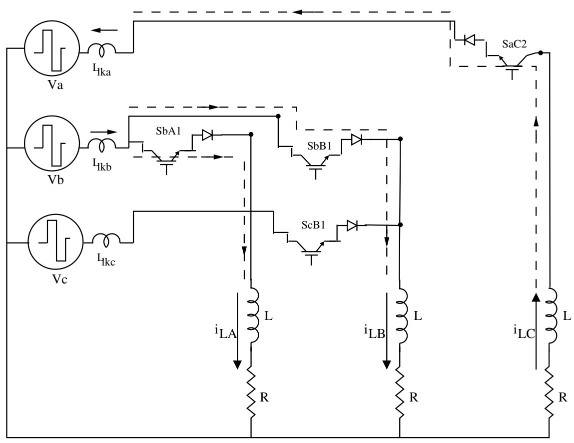

Fig. 10. MC3 at time instant t2

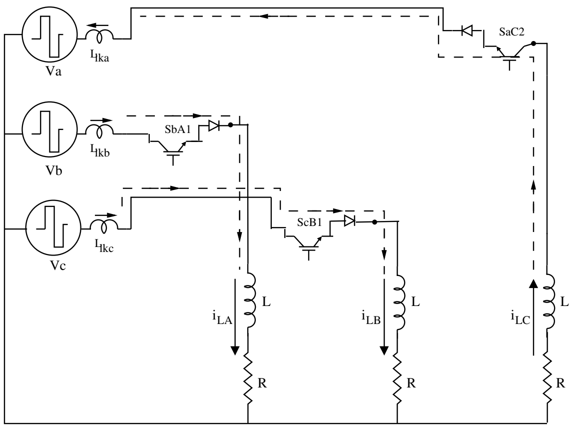

Fig. 11. MC3 at time instant t3

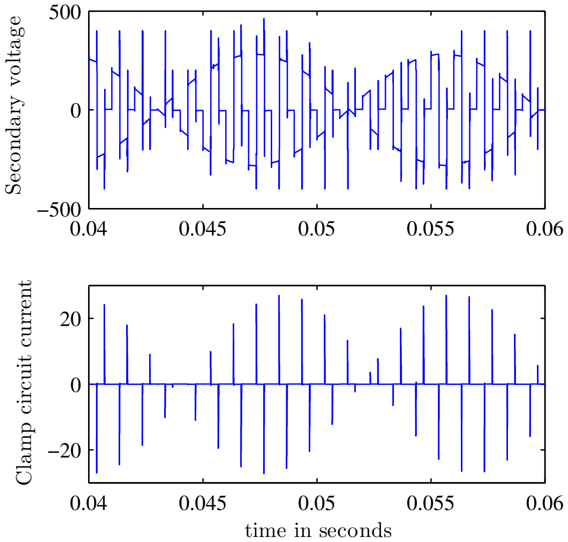

Fig. 12. Voltage across secondary winding and clamp circuit current without source based commutation

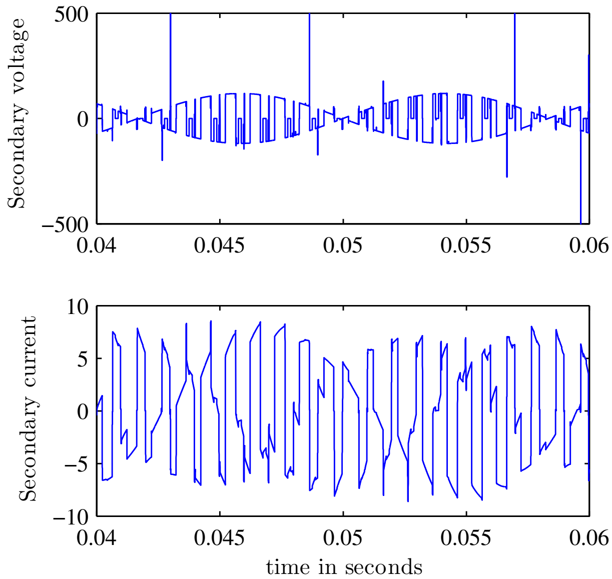

Fig. 13. Voltage across secondary winding and current with source based commutation

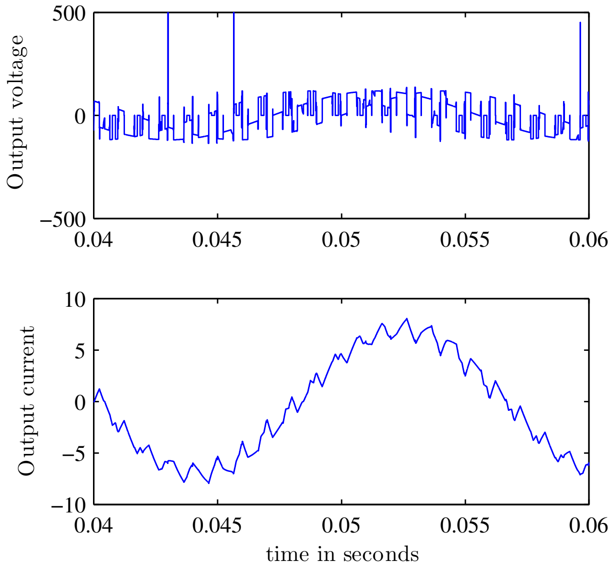

Fig. 14. Output voltage and current with source based commutation

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