NEW MODIFICATION OF A SINGLE PHASE AC-AC MATRIX CONVERTER WITH AUXILIARY RESONANT CIRCUITS FOR AC LOCOMOTIVES

VEERA VENKATA SUBRAHMANYA KUMAR BHAJANA¹,², PAVEL DRABEK³, MARTIN JARA¹, BEDRICH BEDNAR¹

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This paper is focused on a new modification of a single phase ac-ac matrix converter with auxiliary resonant circuits for the ac locomotive applications. Soft switching ac-ac matrix converter with additional auxiliary resonant circuits has been proposed. The major advantage of this topology is to reduce the switching losses to enhance the operation of hard switched ac-ac matrix converter. The main aim of this paper is to achieve the zero-current turn-off of the main switches. This paper describes the operation, simulation analysis and its experimental validation for the proposed 76 V/136 W converter.

1. INTRODUCTION

In recent years of research, the development of ac-ac (matrix converter) converters for traction applications has gained a lot of attention. The main problem of matrix converters is commutation between the switches resulting in current spikes. Resonant soft-switching topologies have already been successfully employed in classic power converters. But still resonant soft switching (ZVS or ZCS) has not been yet employed in single phase matrix converters especially for traction applications. In order to reduce commutation spikes between conductive valves in HVDC converter topology, the capacitor commutation is used [1]. The single phase conventional matrix converter with enhanced control technique is well presented in e.g. [2]. Three phase matrix converter presented in [3] uses an auxiliary resonant circuit in order to obtain soft switching condition, and other three phase matrix converter presented in [4] uses a soft switched bidirectional switches in order to obtain zero switching losses. It has a major drawback that, each bidirectional switch requires resonant elements which results the increase of losses. This topic concerns the matrix converters which is more attractive for further research. Zero current switching in matrix converters results the switching loss reduction and also reduction of current/voltage spikes during commutation interval. The single phase matrix converters with the high switching frequency presented in the e.g. [5], where the soft switching condition is achieved by additional resonant elements to the load. The suggested topology in this paper has the major advantages like reduced voltage and current spikes, reduced switching losses and etc. The only disadvantage of the proposed topology is the excess of components due to an addition of a soft switched cell with resonant elements e.g. an inductor, capacitor and a diode rectifier. By the inclusion of this resonant circuit the conventional matrix converter operates as a soft-switched ac-ac matrix converter with reduced switching losses and more efficiency. The topology shown in Fig. 1 is classical direct matrix converter for electric trains (ac locomotives) with 15 kV/16.7 Hz as input voltage and frequency and it has 400 Hz output frequency. The main aim of this paper is to verify soft switched single phase matrix converter using the auxiliary resonant circuit for the traction applications, mainly in electric trains (ac locomotives). In this paper a new topology of matrix converter is presented. The proposed matrix converter comprises of input inductor (L₁), and input capacitor (C₁) act as input filter components, S₁₁-a₁, S₁₂-a₂, S₁₁-c₂, S₁₂-c₂ are the main switches. The resonant circuits have bidirectional switches (S₁₁-S₁₂) connected as shown in Fig. 2 with resonant inductors L₁, L₂ and resonant capacitors C₁, C₂. The output of the converter connected with the output inductor (Lₒ) and output resistor (Rₒ). The auxiliary resonant circuit allows the half of the main switches turned off under zero current switching of each bidirectional switch. The proposed concept is beneficial, when multiple matrix converters connected in series, for increasing the output power. The proposed circuit uses two auxiliary switches for the output phase, one for positive load current and other switch for the negative load current. The positive and negative conducting switches are connected to the diode rectifier as shown in Fig. 2.

Fig. 1 – Ac traction topology.
The proposed system verified on a laboratory prototype 76 V as input voltage with frequency 16.7 Hz and output 136 W/400 Hz output frequency taken into consideration to develop resonant soft switched matrix converter.

The results shown in this paper are the proposed converter can be applicable for ac locomotives by increasing the high output power level by choosing the proper auxiliary resonant elements.

2. OPERATION OF AUXILIARY RESONANT AND MAIN CIRCUITS

2.1. AUXILIARY RESONANT CIRCUIT

As seen in Fig. 2, the proposed auxiliary resonant circuit consists of two diode rectifiers \((D_1, D_2, D_3, D_4)\), two switches \((S_{r1}, S_{r2}, S_{r4}, S_{r4})\) which are turned on and off simultaneously, a small inductor \((L_1, L_2)\) and capacitors \((C_{r1}, C_{r2})\) whose current direction and voltage polarity are unidirectional. Now consider the turn on process, initially the capacitor \(C_{r1}\) voltage is charged to some value before turning on. When \(S_{r1}, S_{r2}, S_{r4}\) and \(S_{r4}\) are turned on during the proper commutation period of the main switches \(S_{a1}, S_{a2}, S_{a3}\) and \(S_{a4}\), they can be turned off under zero current switching conditions as the auxiliary circuit takes over their working current. The commutation of the auxiliary circuit switches shows soft switching characteristics, hence the loss increase by employing a number of auxiliary switches is mitigated.

When the auxiliary circuit is turned on the current rise is limited by a coil \(L_1\) or \(L_2\), therefore the turning on comes under near ZCS conditions. On the other hand, ZVS turning off is obtained due to slow voltage rise of the \(C_{r1}\) or \(C_{r2}\). In order to achieve soft-switching for all the switching devices of matrix converter, it is necessary to add two more auxiliary resonant circuits \((AR_3, AR_4)\) to the other node.

2.2. MAIN CIRCUIT

The purpose of the auxiliary resonant circuits is to obtain the sink or source current from/to the switching node of the matrix converter as shown in Fig. 2. As they are unidirectional, one of the auxiliary resonant circuits connected to the common node can be operated at the moment depending on the current direction.

The appropriate auxiliary circuit should be turned on soon after the first step of the typical four-step commutation technique. When the auxiliary switches are turned on, the current of the conducting main switch is decreased to zero. Then, the new conductive path can be created. The operating auxiliary switch should be turned off before the final step. Since the new path creation is made with no current flowing through the switches simplified three step technique can be employed.

Figure 2 illustrates the single phase matrix converter with only two auxiliary circuits providing soft-commutation for the left leg only. The operation of the converter (during commutation period) is explained with the help of theoretical waveforms shown in Fig. 3, where \(V_{Cr1}\) is voltage of the resonant capacitor \((C_{r1})\), \(i_{Sr}\) is the inductor \((L_1)\) current, \(V_{Sr}\) is the voltage across the inductor \((L_1)\), \(i_{Sr}\) is the collector-emitter voltage of the auxiliary switch \(S_{r1}\) and \(i_{Sr}\) is the collector-emitter current of the auxiliary switch \(S_{r4}\). The operating modes are divided into five modes. The \(S_{a1}, S_{a2}\) and \(S_{a3}, S_{a4}\) are assumed as the incoming switches and outgoing switches, respectively. At \(t_0\), the main switches \(S_{a1}\) and \(S_{a0}\) are conducting state, during this period the auxiliary resonant capacitor is charged up to \(V_{DC}\). The gating signals are applied to \(S_{r1}, S_{r2}\) and \(S_{r3}, S_{r4}\) at \(t_1\). From \(t_1\) the load current is commutated by \(S_{r1}, S_{r2}, S_{r3}, S_{r4}\).

![Fig. 2 – Modified new single phase ac-ac matrix converter.](image)

![Fig. 3 – Key waveforms of resonant circuit operation.](image)

![Fig. 4 – Simplified auxiliary circuit.](image)

During \(t_1\) to \(t_2\) the resonant capacitor current remains constant equal to load current and charged voltage is discharged linearly. At \(t_2\), all the main switches are turned off, between \(t_2\) and \(t_3\) the auxiliary switches are in conducting state and the voltage on resonant capacitor \(C_{r1}\) reaches zero. At \(t_3\), the resonant switches \(S_{r1}, S_{r2}\) and \(S_{r3}, S_{r4}\) are turned off, the voltage across resonant capacitors \(C_{r1}\) linearly increases to greater than the input voltage until \(t_4\). At \(t_4\), the voltage on \(C_{r1}\) clamps to higher voltage \((> V_{DC})\).

Figure 3 shows the theoretical waveforms for an auxiliary resonant switch during commutation [3].

To determine the timing of the auxiliary switch duration of each commutation interval, \(t_1\) to \(t_3\) must be calculated.

The simplified resonant circuit is shown in Fig. 4, and the analysis of simplified circuit gives the differential equation as follows:
Single phase ac-ac converter with auxiliary resonant circuits

Fig. 5 – Theoretical auxiliary current.

\[ L_1 \frac{di}{dt} + \frac{1}{C_{rl}} \int i(t) dt - V_a = 0, \]  
(1)

\[ i_a(t) = I \cos(\omega t + \varphi), \]  
(2)

\[ \omega = \frac{1}{\sqrt{L_1 C_{rl}}}. \]  
(3)

To calculate the time of load current commutates from the main switches to auxiliary resonant circuit, it is assumed that the initial conditions of capacitor voltage \( v_c(t_1) \) and current through resonant circuit \( i_a(t_1) \) are set to zero (Fig. 5), and the equation (1) is solved with these initial conditions.

\[ i(0) = I_L, \]  
(4)

\[ v_c(0) = v_a = v_{max} - v_o, \]  
(5)

where \( v_a \) is the capacitor voltage \( (C_{rl}) \) and \( v_o \) is the output voltage, equation (2) becomes Eq. (6).

\[ i_a(t) = I_L \cos \omega t. \]  
(6)

Time taken from \( (t_1 - t_2) = T/4 \) and capacitor voltage at \( t_1 \)

\[ v_c(t_1) = v_a + \frac{L_1}{L_4} \cos \omega dt = v_{cr1} + I_L \frac{L_1}{\sqrt{L_1 C_{rl}}}. \]  
(7)

At \( t_1 \) the auxiliary switches \( S_{r1} \) and \( S_{r2} \) are turned on, it has an effect of inverting the capacitor in Fig. 4 and provides a new set of conditions for (1).

\[ i_a(t_2) = 0 \]

\[ v_1 = -v_c(t_2). \]  
(8)

Equation (8) gives

\[ \int_{t_2}^{t_3} i_a(t) dt = \frac{1}{C_{rl}} \left[ v_1 + v_c(t_2) \right] \cos(\omega t + \frac{\pi}{2}). \]  
(9)

By rearranging (9) gives

\[ \int_{t_2}^{t_3} i_a(t) dt = \frac{i_1}{\omega} \sin \omega t, \]  
(10)

where

\[ i_1 = 2v_1 \frac{C_{rl}}{L_1} + I_L. \]  
(11)

By using Eq. (12), the time \( t_{ce} \) taken to commutate the load current to the auxiliary circuit can be calculated.

3. SIMULATION RESULTS

The simulations are performed for single phase matrix converter by using Matlab – PLECS. Figure 6 illustrates the zero current turn off of the main switches \( (S_{a1}S_{a2}) \) and auxiliary switches \( (S_{r1}) \) turn on and turn off voltage and the current during the commutation period.

Figure 7 shows the voltage and currents of the resonant capacitor and inductors.

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**Fig. 6** – a) \( S_{a1} \) collector to emitter voltage and current; b) \( S_{a2} \) collector to emitter voltage and current; c) \( S_{r1} \) collector to emitter voltage and current.

**Fig. 7** – a) Voltage of resonant capacitor; b) resonant capacitor current \( (C_{rl}) \); c) resonant inductor \( (L_{rl}) \) voltage; d) resonant inductor \( (L_{r2}) \) current.
4. EXPERIMENTAL RESULTS

Figure 8 shows the experimental setup of the proposed converter has been tested on 76 V/16.7 Hz as input source for 136 W output power with 400 Hz output frequency. SK 60 GM 123 IGBT modules (Semikron) were employed as the bidirectional switches. Switching pattern was generated by TMS320F28335 based control unit. The load resistance 13 Ω and inductance 2.3 mH are used.

These results confirm that the soft switching condition for the matrix converter with the additional auxiliary resonant circuit are provided by achieving ZCS turn off of the main switches during commutation period. The IGBTs type chosen for the auxiliary resonant circuits is IGW40 N120H3 and, the resonant capacitors $C_1, C_2$ of 0.2 µF and resonant inductances $L_1, L_2$ of 67 µH were used. The values of resonant capacitor and inductors have been chosen large values to increase the switching speed of auxiliary IGBTs ($S_{a1}, S_{a2}, S_{a3}, S_{a4}$) and to keep low current during the turning on process.

Fig. 8 – Experimental setup of the proposed converter.

![Experimental setup](image)

Fig. 9 – a) Hard switching of main switch ($S_{a1}$); b) ZCS turn off of the main switch ($S_{a1}$).

The resonant capacitor, inductor voltage and currents are shown in Fig. 10a and b. The auxiliary resonant switch $S_{a1}$ collector to emitter voltage and current is depicted in Fig. 11a and b, shows the output voltage and current. These results confirm that the soft switching condition for the matrix converter with additional auxiliary resonant circuit are provided by achieving ZCS turn off of the main switches during commutation period.

Fig. 9 – a) Hard switching of main switch ($S_{a1}$); b) ZCS turn off of the main switch ($S_{a1}$).

![Resonant capacitor and inductor voltages and currents](image)

Fig. 10 – a) Resonant capacitor voltage and current; b) resonant inductor voltage and current.

Fig. 11 – a) Measured voltage and currents of the resonant switch $S_{a1}$; b) measured output voltage and output current waveforms.
5. CONCLUSION

The article proposed a new modification of single phase ac-ac matrix converter with auxiliary resonant circuits for ac locomotives. The zero current switching condition was achieved for the half of the switches in this matrix converter by the addition of the auxiliary resonant circuit. Employing the same circuits connected to the second switching node of the converter would ensure soft switching for the whole matrix converter. This proposed auxiliary resonant circuit works during the 4-step commutation period. The major advantage is the reduction of the commutation spikes and switching losses, meanwhile the drawback is the additional circuit which increases the cost of the converter (additional resonant components and switchers).

The main aim of this paper is to verify the soft switching version of single phase matrix converter; Further scope of this proposed concept will be helpful to get soft switching condition (not only for one matrix converter), it will provide soft switching for multiple matrix converters especially in single phase when they are connected in series. An experimental setup has been implemented with 76 V/16.7 Hz input source and 136 W of output power with 400 Hz output frequency.

The experimental result proves that, the soft switching condition was obtained during the commutation period and that might improve the efficiency in terms of switching losses.

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