Research Report

96-38

The Auxiliary Resonant Commutated Pole Matrix Converter-A New Topology for High Power Applications

S. Bernet, K. Bernet, T.A. Lipo

Wisconsin Power Electronics Research Center
University of Wisconsin-Madison
Madison WI 53706-1691

Wisconsin
Electric
Machines &
Power
Electronics
Consortium

University of Wisconsin-Madison
College of Engineering
Wisconsin Power Electronics Research Center
2559D Engineering Hall
1415 Engineering Drive
Madison WI 53706-1691

The Auxiliary Resonant Commutated Pole Matrix Converter- A New Topology for High Power Applications

Steffen Bernet, Kerstin Bernet and Thomas A. Lipo
University of Wisconsin-Madison
1415 Engineering Drive
Madison, Wisconsin 53706
U. S. A.

Abstract–**The paper proposes the new three-phase auxiliary resonant commutated pole matrix converter. It is shown that the use of special pulse patterns and an auxiliary commutation unit enable PWM control and soft switching. The function of the converter is analyzed and simulation results are presented to verify the function of the converter. An accurate loss model is used to compare the losses of a hard switching and the auxiliary resonant commutated pole matrix converter.**

1.INTRODUCTION

In recent years the three-phase to three-phase matrix converter (MC) has received considerable attention as an alternative to hard and soft switching dc-link converters (e.g. [1], [4], [8]). The latest developments of the MC are characterized by the implementation of space vector modulation [5], the application of the MC to field oriented induction motor drives [3] and the use of reverse blocking NPT-IGBT's as the required four quadrant switches (4QSW's)[2].

The MC has several distinct advantages over conventional hard switching PWM rectifier/ dc-link/ inverter structures. For example the MC does not require a dc-link capacitor due to its single stage power conversion. Furthermore it realizes less losses than the comparable dc-voltage link topology because of the substantially lower average commutation voltage [2]. Although the dc-link converter requires only 24 semiconductors (e.g. 12 IGBT's, 12 diodes) and the MC needs 36 semiconductors (e.g. 18 IGBT's, 18 diodes) the total installed switch power of both converters is generally the same due to the possible reduction of the current ratings of the switches in a MC by one third [4]. However, the substantial switching losses limit the maximum switching frequency of both hard switching converters to about 10kHz - 25kHz in the medium power range if IGBTs are used [2]. Increased switching fall and tail times of high voltage devices such as GTO's, IGBT's and MCT's amplify this effect even more in high

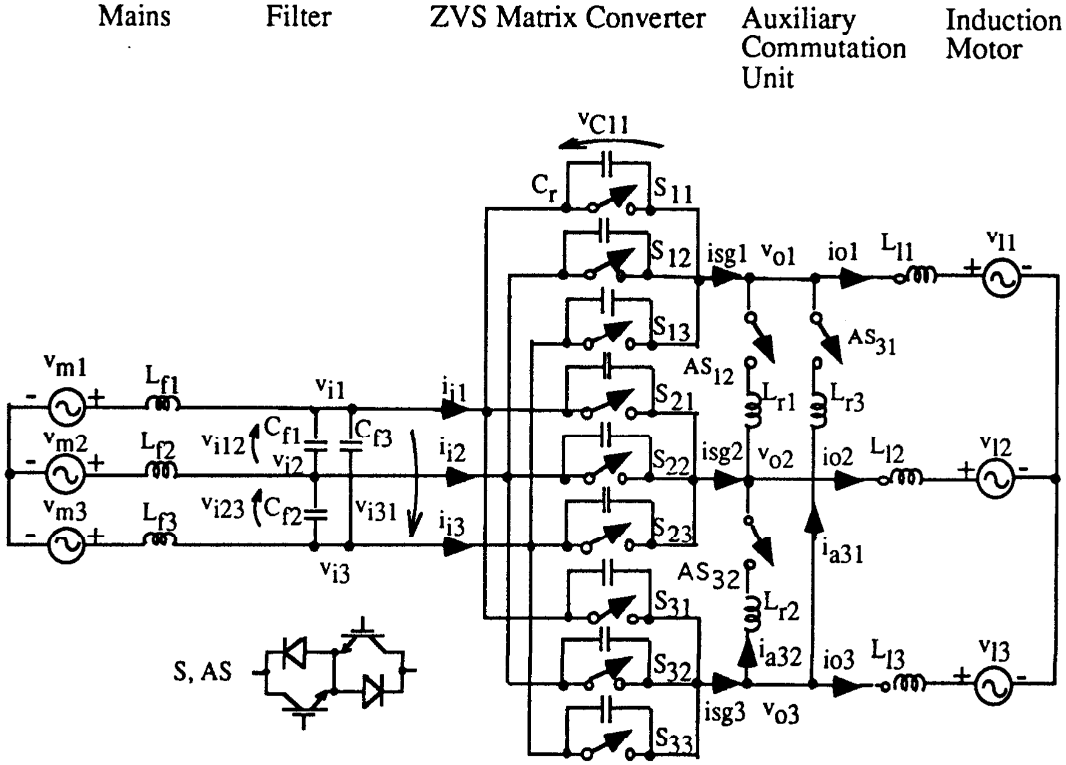

Fig. 1 Circuit configuration of the three-phase ac to ac matrix converter

power applications leading to bulkier and more expensive filter components or higher motor losses in a drive. If higher switching frequencies are necessary to increase the power density of the converter or to reduce the motor losses particularly in high power applications there are at least two interesting soft switching-dc-voltage link topologies which could be applied - the auxiliary resonant commutated pole converter [6] and the resonant dc link converter [9]. However there has been proposed only one soft switching MC which did not gain much importance because of the high currents flowing through the switches and the resonant inductors [7].

This paper proposes the new auxiliary resonant commutated pole matrix converter (ARCPMC) which overcomes these drawbacks (Fig.1). In this circuit special pulse patterns and an additional commutation unit which consists of three four quadrant switches and three resonant inductors enable soft switching of the entire converter and PWM-control. Hence the main switches of the MC can be operated as Zero Voltage Switches (ZVS's) and the auxiliary switches of the commutation unit operate as Zero Current Switches (ZCS's). The paper presents both a description of the special developed pulse patterns and a detailed analysis of the converter. Simulation results are used to verify the operating principle. A sophisticated semiconductor loss model allows a comparison of the losses of a hard switching MC and the ARCPMC.

II. FUNDAMENTAL SWITCHING TRANSIENTS OF A HARD SWITCHING MC AND THE ARCPMC

The commutation of an output phase current of a hard switching MC from one switch to another in each of the three switch groups can be described by the equivalent commutation circuit presented in Fig. 2. In this case the load current i_L corresponds to the motor phase current under consideration, the commutation voltage v_C represents the effective line-to-line voltage at the input and the minimum values of the commutation inductance and the commutation capacitance of a hard switching MC are given by the stray inductance of the circuit and the output capacitance of the semiconductors respectively. Corresponding to the power of the load, two fundamental types of commutations can be distinguished - the so called inductive commutation and the capacitive commutation.

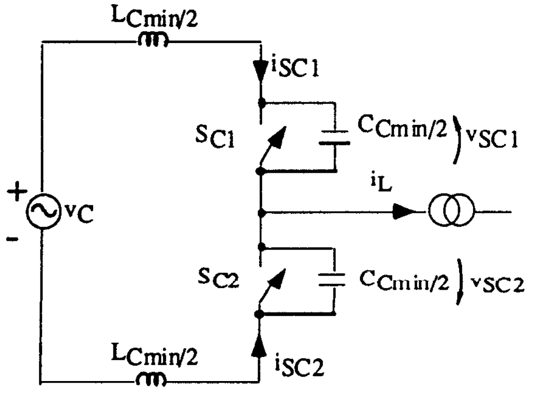

Fig. 2 Equivalent commutation circuit

If the voltage v_C and the current i_L are positive and the switch S_{C2} is on, an inductive commutation can be started only by an active turn-on transient of the switch S_{C1}. Because nearly the entire voltage drops across the switch S_{C1} there are substantial turn on losses in the turn on transistor (IGBT) and the switching transient is called *hard*. The commutation is completed by the passive turn off of the switch S_{C2} during the interruption of the reverse current.

If switch S_{C1} is on and both the voltage v_C and the current i_L are positive, a capacitive commutation can be achieved only by an active turn-off of the switch S_{C1}. Because L_C and C_C are minimal, the voltage of S_{C1} is increasing during the decrease of the voltage v_{SC2} until S_{C2} turns on passively at zero voltage. The current commutation starts only after this point causing substantial turn-off losses in the turning off transistor (IGBT). Therefore the active turn-off transient of such a capacitive commutation is also a hard switching transient. Because both the commutation voltage (line-to-line input phase voltage) and the load current (motor phase current) change their polarity during the operation of the MC, switches S_{11}-S_{33} must be forward and reverse blocking bi-directional current conducting switches (4QSW's).

A substantial reduction of the high switching losses can be achieved if instead of hard switching the MC an ARCPMC principle is applied. In this case there are only capacitive commutations between the main switches of the MC. Hence, these switches can be operated as Zero Voltage Switches and the turn off transient can be relieved by an increase of the commutation capacitance ($C_C>C_{Cmin}$; $L_C=L_{Cmin}$). In contrast the auxiliary switches carry out only inductive switching transients which can be relieved by increasing the commutation inductance ($L_C>L_{Cmin}$; $C_C=C_{Cmin}$). Therefore these switches work as Zero Current Switches.

III. PULSE PATTERNS OF THE ARCPMC

Venturini derived in reference [1] a control scheme for the MC which generates sinusoidal input currents at adjustable power factor and wherein the maximum possible voltage transfer ratio of $q=v_i/v_o=0.866$ is achieved. Since this basic algorithm determines only the duty cycles of the nine 4QSW's there is still a degree of freedom to chose the optimum pulse patterns in the hard switching MC. However, in the case of the ARCPMC the switch sequence is determined by the function of the auxiliary commutation unit. Assuming symmetric input voltages

$$\begin{aligned} v_{i1}&=V_i\cdot\cos(\omega_i t+\Theta_i)\\ v_{i2}&=V_i\cdot\cos(\omega_i t+\Theta_i-120°)\\ v_{i3}&=V_i\cdot\cos(\omega_i t+\Theta_i+120°)\end{aligned} \qquad (1)$$

where

$$\omega_i = 2\cdot\pi\cdot f_i = \frac{2\cdot\pi}{T_i}$$

the three-phase system enables the definition of six 60°-voltage intervals in which none of the three line-to-line input

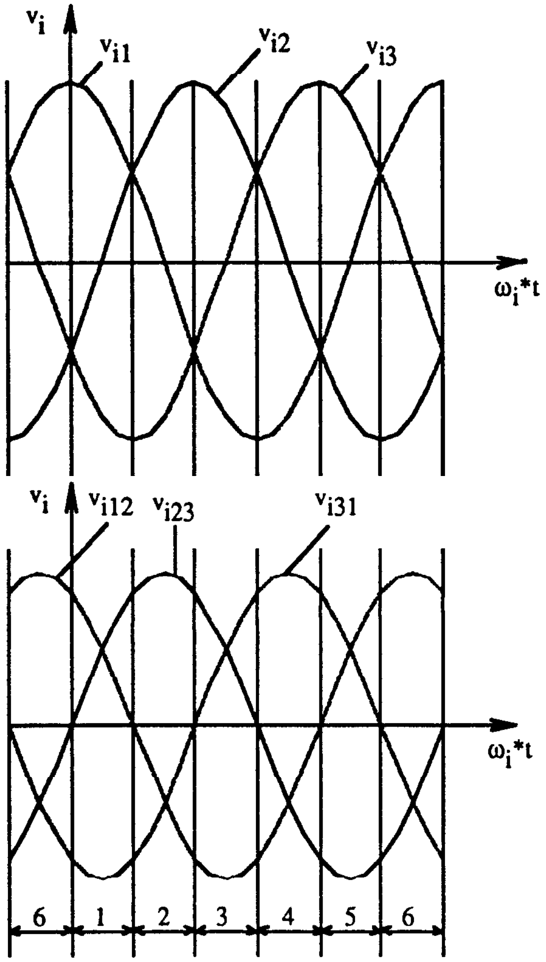

Fig. 3 Definition of 60°-voltage intervals of the input voltage

voltages v_{i12}, v_{i23} and v_{i31} change polarity (Fig. 3). For $\Theta_i=0°$ the voltage intervals are given by

$$\begin{aligned}
&\text{voltage interval 1:} && 0° \le \omega_i\, t \le 60° \\
&\text{voltage interval 2:} && 60° \le \omega_i\, t \le 120° \\
&\text{voltage interval 3:} && 120° \le \omega_i\, t \le 180° \\
&\text{voltage interval 4:} && 180° \le \omega_i\, t \le 240° \\
&\text{voltage interval 5:} && 240° \le \omega_i\, t \le 300° \\
&\text{voltage interval 6:} && 300° \le \omega_i\, t \le 360°
\end{aligned} \tag{2}$$

Table I shows, that there is always a switch sequence which enables two capacitive and one auxiliary resonant commutated pole (ARCP) commutations in one period T_s of the switching frequency f_s. An ARCP commutation is an inductive commutation transformed into a capacitive commutation. The transformation is realized by the auxiliary commutation unit which changes the polarity of the switch currents before the active switching transients of the main switches. If the output current does not change the polarity, the switch sequence alternates every 60°-voltage interval.

TABLE I
PULSE PATTERNS OF THE ARCPMC

Voltage-Interval	Direction of i_{ox} (x=1,2,3)	Pulse Patterns and Switching Sequence (F: Forward; B: Backward; x=(1,2,3); a: ARCP Commutation; c: Capacitive (ZVS) Commutation;	
1	$i_{ox}>0$	$S_{x3} \xrightarrow{a} S_{x1} \xrightarrow{c} S_{x2} \xrightarrow{c} S_{x3}$	F
	$i_{ox}<0$	$S_{x1} \xrightarrow{a} S_{x3} \xrightarrow{c} S_{x2} \xrightarrow{c} S_{x1}$	B
2	$i_{ox}>0$	$S_{x3} \xrightarrow{a} S_{x2} \xrightarrow{c} S_{x1} \xrightarrow{c} S_{x3}$	B
	$i_{ox}<0$	$S_{x2} \xrightarrow{a} S_{x3} \xrightarrow{c} S_{x1} \xrightarrow{c} S_{x2}$	F
3	$i_{ox}>0$	$S_{x1} \xrightarrow{a} S_{x2} \xrightarrow{c} S_{x3} \xrightarrow{c} S_{x1}$	F
	$i_{ox}<0$	$S_{x2} \xrightarrow{a} S_{x1} \xrightarrow{c} S_{x3} \xrightarrow{c} S_{x2}$	B
4	$i_{ox}>0$	$S_{x1} \xrightarrow{a} S_{x3} \xrightarrow{c} S_{x2} \xrightarrow{c} S_{x1}$	B
	$i_{ox}<0$	$S_{x3} \xrightarrow{a} S_{x1} \xrightarrow{c} S_{x2} \xrightarrow{c} S_{x3}$	F
5	$i_{ox}>0$	$S_{x2} \xrightarrow{a} S_{x3} \xrightarrow{c} S_{x1} \xrightarrow{c} S_{x2}$	F
	$i_{ox}<0$	$S_{x3} \xrightarrow{a} S_{x2} \xrightarrow{c} S_{x1} \xrightarrow{c} S_{x3}$	B
6	$i_{ox}>0$	$S_{x2} \xrightarrow{a} S_{x1} \xrightarrow{c} S_{x3} \xrightarrow{c} S_{x2}$	B
	$i_{ox}<0$	$S_{x1} \xrightarrow{a} S_{x2} \xrightarrow{c} S_{x3} \xrightarrow{c} S_{x1}$	F

Assuming symmetric output currents

$$\begin{aligned}
i_{o1} &= i_o \cdot \cos(\omega_o t + \Theta_o) \\
i_{o2} &= i_o \cdot \cos(\omega_o t + \Theta_o - 120°) \\
i_{o3} &= i_o \cdot \cos(\omega_o t + \Theta_o + 120°)
\end{aligned} \tag{3}$$

the two switch groups with the same polarity of the output currents i_{ox} (x=1,2,3) have always the opposite switch sequence than the remaining switch group. Furthermore the commutation voltage of the ARCP commutation is always the line-to-line input voltage with the highest absolute value. It will be shown later that this is a very favorable characteristic which simplifies the design and the operation of the ARCPMC considerably.

The realization of the ARCP commutations in all three switch groups require not only the use of the proper switch sequence given in Table I but also the synchronization of the three ARCP commutations of the three switch groups during each period T_s of the switching frequency. If the pulse patterns given in Table I are used, the switch group with the shortest duty cycle of the three initially conducting switches (one in each switch group) triggers the ARCP commutations in all three switch groups. The remaining portions of the two longer duty cycles are then realized at the end of T_s. However, if one changes the initial state of the pulse patterns given in Table I such, that first the two capacitive commutations are realized, it appears to be possible to synchronize the three ARCP commutations of the three switch groups at the end of T_s as well. Because both proposed pulse patterns realize two thirds capacitive and only one third ARCP commutations they differ essentially from conventional switching schemes for hard switching MC's which realize 50% inductive and 50% capacitive commutations (e.g. [4], [8]).

IV. ANALYSIS OF THE ARCPMC

A. Operation of the ARCPMC in the ZVS-Area

If the pulse patterns described in section III are applied in each of the six voltage intervals of the input voltage there are two capacitive commutations and one ARCP commutation in each switch group per period T_s. Hence the main switches S_{11}-S_{33} of the matrix converter turn off actively and turn on passively at zero voltage (ZVS) and the auxiliary switches AS_{12}, AS_{32}, AS_{31} turn on actively and turn off passively with the interruption of the reverse current (ZCS). Below the ARCP commutation principle is described. It transforms a natural inductive commutation into a capacitive commutation by changing the polarity of the switch currents. To simplify the analysis it is assumed, that the line-to-line input voltages (v_{i12}, v_{i23}, v_{i31}) and the output currents (i_{o1}, i_{o2}, i_{o3}) are constant during the commutation. Furthermore, the switches are considered to be ideal. The ARCPMC (Fig. 1) shall be operated in the sixth voltage interval using the pulse patterns given in Table I for $i_{o1}>0$, $i_{o2}>0$ and $i_{o3}<0$.

Interval I ($t < 0$) *:*
The ARCPMC operates in the starting position of Fig. 4. The switches S_{12}, S_{22} and S_{31} carry the output currents i_{o1}, i_{o2} and i_{o3} and all auxiliary switches AS are opened.

Interval II ($0 \leq t \leq t_1$; t=0 : Turn on of AS_{32} and AS_{31}
t_1 : Turn off of S_{12})
Interval II is initiated by the simultaneous turn on of the auxiliary switches AS_{32} and AS_{31} (Fig. 4). The currents in the auxiliary branches increase linearly

$$i_{a31} = i_{a32} = \frac{|v_{i12}| \cdot t}{L_r} \tag{4}$$

caused by the positive voltages $v_{o31}=v_{o32}=v_{i12}$ across the auxiliary branches. The absolute values of the switch group currents

$$\begin{aligned} i_{sg1} &= i_{o1} - i_{a31} \\ i_{sg2} &= i_{o2} - i_{a32} \\ i_{sg3} &= i_{o3} + i_{a31} + i_{a32} \end{aligned} \tag{5}$$

decrease. The current i_{sg1} changes its polarity and reaches the negative boost current $-i_b$ at t_1.

Interval III ($t_1 \leq t \leq t_2$; t_1 : Turn off of S_{12};
t_2 : Turn on of S_{11})
Interval III starts at t_1 when the conducting switch S_{12} is turned off actively (Fig. 4). The current i_{sg1} commutates into the three parallel capacitors of the switch group 1 and recharges these during an oscillating process with the resonant inductor L_{r3}. The peak currents of the switch group 1 and the auxiliary switch AS_{31} reach

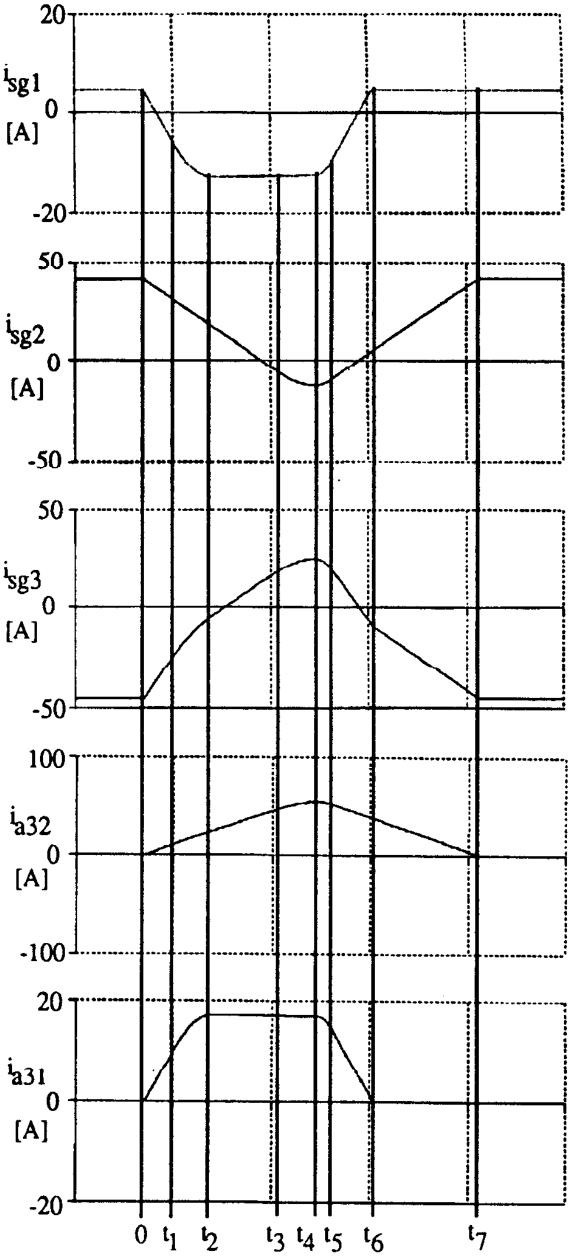

Fig. 4 Simulated waveforms of an ARCP commutation

$$i_{a31}(t_2) \approx i_{o1} + i_b + \frac{|v_{i12}|}{\sqrt{\frac{L_r}{3 \cdot C_r}}} \tag{6}$$

$$i_{sg1}(t_2) \approx -i_b - \frac{|v_{i12}|}{\sqrt{\frac{L_r}{3 \cdot C_r}}} \tag{7}$$

if i_b is small ($i_b \approx 0$). At t_2, S_{11} turns on passively at $v_s=0$.

Interval IV ($t_2 \le t \le t_3$; t_2 : Turn on of S_{11};
t_3 : Turn off of S_{22})

Since S_{11} turns on at t_2, the voltage across the auxiliary branch between output phase 1 and 3 is zero ($v_{o31}=0$). Hence the currents i_{sg1} and i_{a31} flow in the freewheeling circuit across S_{11} and S_{31} and remain constant (Fig. 4). The linearly changing currents i_{sg2} and i_{sg3} change their polarity and i_{sg2} reaches the negative boost current at t_3.

Interval V ($t_3 \le t \le t_4$; t_3 : Turn off of S_{22};
t_4 : Turn on of S_{21} / Turn off of S_{31})

This mode is caused by the active turn off transient of S_{22} at t_3 wherein the current i_{sg2} commutates into the three capacitors of the switch group 2 and recharges them during an oscillating process (Fig. 4). The currents reach

$$i_{sg2}(t_4) \approx -i_b - \frac{|v_{i12}|}{\sqrt{\frac{L_r}{3 \cdot C_r}}} \tag{8}$$

$$i_{sg3}(t_4) \approx 2 \cdot \left(i_b + \frac{|v_{i12}|}{\sqrt{\frac{L_r}{3 \cdot C_r}}} \right) \tag{9}$$

if $i_b \approx 0$ and S_{21} turns on passively at $v_s=0$.

Interval VI ($t_4 \le t \le t_5$; t_4 : Turn on of S_{21} / Turn off of S_{31};
t_5 : Turn on of S_{32})

Interval VI is initiated by the active turn off transient of S_{31} (Fig. 4). The current i_{sg3} commutates into the three capacitors of the switch group 3 and recharges them until S_{32} turns on passively at $v_s=0$.

Interval VII ($t_5 \le t \le t_6$; t_5 : Turn on of S_{32};
t_6 : Turn off of AS_{31})

The voltage $v_{o31}=v_{o32}=-v_{i12}$ across the two active branches of the auxiliary commutation unit cause a linear decrease of the currents

$$i_{a31} = i_{a31}(t_5) - \frac{|v_{i12}| \cdot t}{L_r} \tag{10}$$

and

$$i_{a32} = i_{a32}(t_5) - \frac{|v_{i12}| \cdot t}{L_r} \tag{11}$$

Hence the currents i_{sg1}, i_{sg2} and i_{sg3} change their polarity according Eqs. (5) (see Fig. 4).

Interval VIII ($t_6 \le t \le t_7$; t_6 : Turn off of AS_{31};
t_7 : Turn off of AS_{32})

At t_6 and t_7 the currents

$$i_{a31}(t_6)=0 \tag{12}$$

$$i_{a32}(t_7)=0 \tag{13}$$

reach zero and the switches AS_{31} and AS_{32} turn off passively at $i_s=0$ as ZCS (Fig. 4).

Interval IX ($t_7 \le t$; t_7 : Turn off of AS_{32})

The new switch state is reached when AS_{32} turns off at t_7. The current is commutated from S_{x2} to S_{x1} ($x=1,2$) and from S_{x1} to S_{x2} ($x=3$) respectively during the ARCP commutation.

It should also be noted that an overlap of the afore mentioned oscillating processes is possible. Analogous commutations take place in each 60°-voltage interval at arbitrary polarity of the output currents if the pulse patterns described in section III are applied. It is essential to use always the two auxiliary switches between the output phases with the opposite polarity of the output currents during the ARCP commutation. The voltage across the auxiliary branches during the ARCP commutation is always the highest absolute line-to-line input voltage (Fig. 4). Besides the ARCP commutation there are two non-synchronized natural ZVS commutations (capacitive commutations) in each switch group per period T_s which do not require the auxiliary commutation unit.

B. Change of pulse patterns at the border of the voltage intervals

An inductive commutation, meaning a hard turn on transient of one 4QSW, has possibly to be realized in each switch group, if at the end of one voltage interval, the old pulse patterns (Table I) are applied during the period T_s of the switching frequency and the new voltage interval starts during this period T_s. It is assumed that the pulse patterns for the new voltage interval will be used only at the beginning of the new period T_s. However, the resulting loss energy W_C of the turning on 4QSW can be generally neglected if the switching frequency f_s is sufficiently high, because the commutation voltage of these inductive commutations is the very small line-to-line input voltage which changes its polarity at the border of the voltage intervals (e.g. 480V main; f_i=60Hz; f_s=10Hz; C_r=5nF; W_C=0.235mJ).

C. Change of pulse patterns at the polarity change of the output current

If the output current of one phase changes its polarity at an arbitrary moment during T_s and the new pulse pattern will be realized only in the new period T_s of the switching frequency, the ARCP commutation at the beginning of T_s functions essentially as described before. This observation is valid even if the output current changes its polarity before or during the ARCP commutation. However, it is possible that in the worst case two capacitive commutations are transformed into two inductive commutations because of the wrong switching sequence of the old pulse pattern after the polarity change of the output current. Hence two active turn on transients could take place in which stored energy of the resonant capacitors of one switch group would be transformed into heat in the actively turning on of switches. It is advantageous however that the commutation voltage for both possible inductive commutations is always one of the two lower absolute line-to-line input voltages of a 60°-voltage interval.

D. Zero Voltage Switching Area

With the exception of the inductive commutations caused by the change of a 60°-interval of the input voltage and a polarity change of an output current the main switches S_{11}-S_{33} of an ARCPMC can operate as Zero Voltage Switches in principle. However, if the output current is very small before or after the zero crossing, the capacitive commutations should be finished by a hard active turn on transient after a maximum commutation time t_{Cmax} (e.g. $t_{Cmax}=1\mu s$) to avoid excessively long commutations. Hence there exists an interval

$$\frac{t_{hard}}{T_O} = \frac{2}{\pi} \arcsin \frac{3 \cdot \sqrt{3} C_r V_{llN}}{\sqrt{2}\, t_{Cmax}\, i_o} \tag{14}$$

where T_O: Period of the output current i_O

V_{llN}: Nominal line-to-line input voltage

t_{Cmax}: Maximum commutation time of a capacitive commutation

i_o: Amplitude of the output current

in which the ZVS Area must be abandoned because one or both capacitive commutations are to be completed by an active turn on transient. In a similar manner as the afore mentioned active turn on transients, the three resonant capacitors C_r of the respective switch group are recharged across the turning on switch. If the input voltage and the output current are determined by the application the remaining ZVS-Area

$$\frac{t_{soft}}{T_O} = 1 - \frac{t_{hard}}{T_O} \tag{15}$$

of the ARCPMC is defined by C_r and t_{Cmax}. It has been mentioned previously that the ZVS-Area can be left additionally at the border between two 60°-voltage intervals for maximally one switching transient per switch group.

V. DESIGN CONSIDERATIONS

The design of the resonant elements L_r and C_r and the choice of the boost current determine essentially the losses, the commutation times, the minimum duty cycles as well as the occurring di/dt's and dv/dt's of the ARCPMC. It is clear that all three values should be chosen so that on the one hand the losses are minimal and on the other hand sufficiently short commutation times can be achieved. The design of the resonant inductors is simplified substantially by the fact that the commutation voltage of the ARCP commutation varies only slightly. In contrast to the trade off's of the ARCP-dc-voltage link converter the necessity to leave the ZVS-Area at low output currents has to be considered for the design of the resonant capacitors C_r in the ARCPMC. The additional energy of the oscillating circuit caused by the boost current should clearly exceed the energy losses incurred during the resonant commutation phase. Two of the three auxiliary switches operate synchronously with the same switching frequency as the ZVS in the ARCPMC. Since the auxiliary switches carry only short current pulses, the current ratings of these switches can be much smaller than those of the main switches. In particular MCT's at medium and high switching frequencies or SCR's at low switching frequencies and high output power could be applied.

VI. SIMULATION RESULTS

A. Simulated Waveforms

An ACSL simulation program of the three-phase ARCPMC (Fig. 1) has been developed to demonstrate feasibility of the proposed circuit. The converter model assumes sinusoidal voltage sources at the input, ($C_f \to \infty$) and sinusoidal current sources at the output. The switches are modeled by resistors which vary between $r_s=0.05\Omega$ (e.g. 50A IGBT module) in the on-state and $r_s=100{,}000\Omega$ in the off-state. The duty cycles of the switches are computed corresponding to the control scheme derived in reference [1]. The simulation program applies the pulse patterns given in Table I. When an output current changes the polarity or the converter goes from one 60°-voltage interval into another the new pulse patterns are realized only at the beginning of the new period T_s. In the ZVS Area there are only ARCP and natural ZVS (capacitive) commutations. However, if an output current changes its polarity or a new 60°-voltage interval occurs, the program detects leaving the ZVS Area and realizes the consequent hard

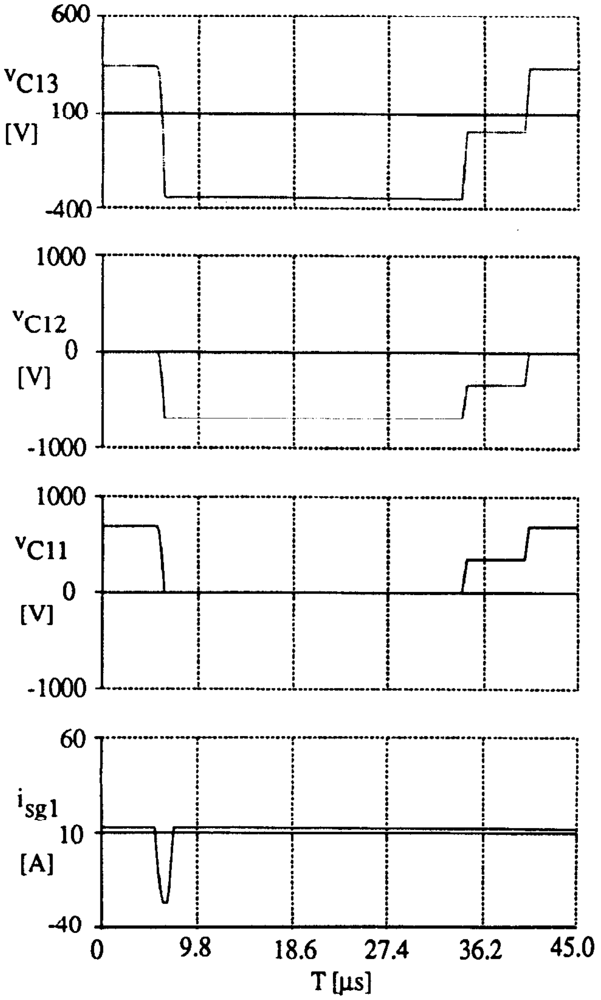

Fig. 5 Switch voltages and current of the switch group 1 of the ARCPMC (Voltage interval: 6; $i_{o1}>0$; $L_r=20\mu H$; $C_r=5nF$; $i_b=5A$; 480V mains; $i_o=50A$)

turn on transients. Fig. 5 shows the voltages of the switches S_{11}-S_{13} and the current i_{sg1} in the sixth 60°-voltage interval for a switching frequency of f_s=25kHz. Since the output current i_{o1} is positive the pulse pattern S_{12} /S_{11} /S_{13} /S_{12} is realized in the first switch group. The polarity change of i_{sg1} indicates the ARCP commutation of i_{o1} from S_{12} to S_{11}. The two other commutations from S_{11} to S_{13} and from S_{13} to S_{12} are natural ZVS commutations which do not use the auxiliary commutation unit.

The conclusion of a very slow capacitive commutation from S_{11} to S_{13} in the sixth voltage interval caused by the very low value of the output current i_{o1} is to be seen in Fig. 6. Initially the switch S_{11} is turned off (transition of the variable S_{11} from 2 to -1) and the voltage of S_{11} increases very slowly. After a commutation time of $t_{Cmax}=1\mu s$ the capacitive commutation is completed by a hard active turn on transient of S_{13}. The voltage v_{C11} increases very rapidly to its new value $v_{C11}=V_{i13}$=340V and S_{13} takes over the current i_{o1}. Fig. 7 represents the simulated currents of the three switch groups of the ARCPMC for a period of time with several zero crossings of the output currents. Like expected from equations (7), (8) and (9), the two switch groups which carry the two output currents with the same direction realize only half of the current amplitude during the ARCP commutation than the remaining switch group.

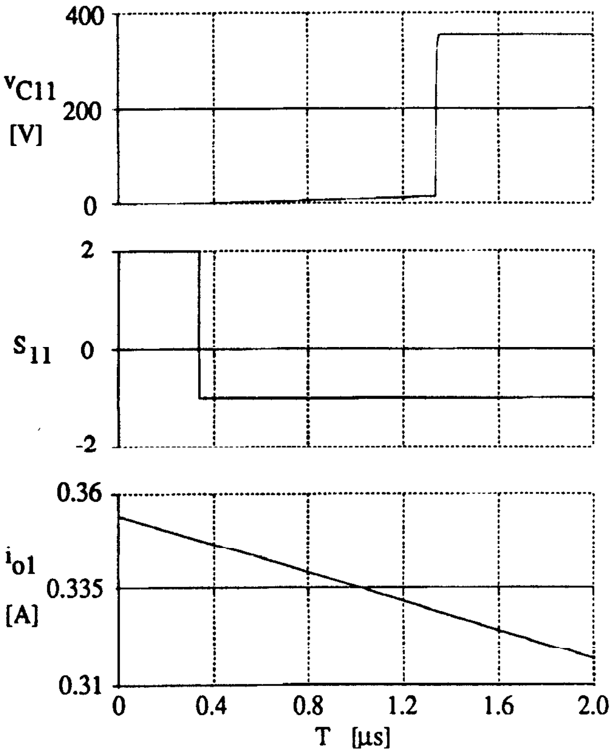

Fig. 6 Switch voltage, variable for the state of S_{11} and output current i_{o1} of the ARCPMC (i_{o1} low) (Voltage interval: 6; L_r=20µH; C_r=10nF; i_b=5A; 480V mains; i_o=50A)

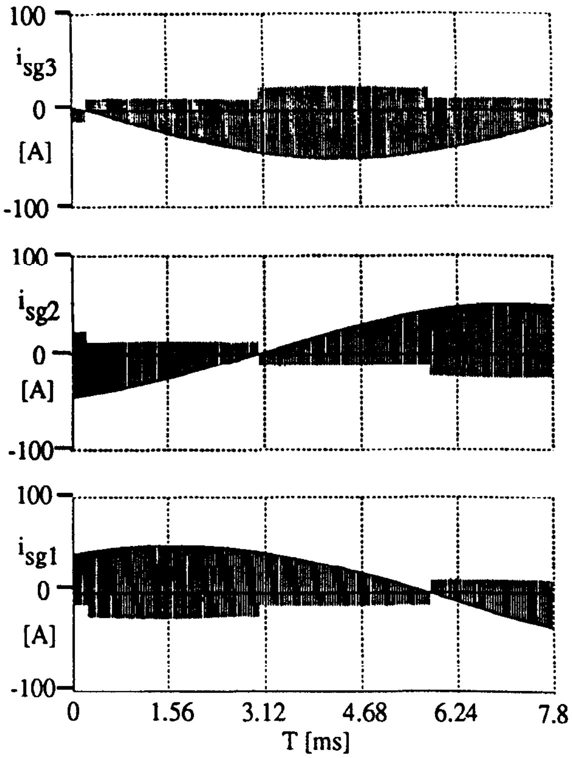

Fig. 7 Currents of the three switch groups of the ARCPMC (480V mains; i_o=50A; L_r=20µH; C_r=1nF; i_b=5A; f_o=60Hz; q=0.5; φ_i=0°; φ_o=35°)

One output voltage and one input current are to be seen in Fig. 8 for a phase shift of f_o=30° at the output and unity power factor at the input.

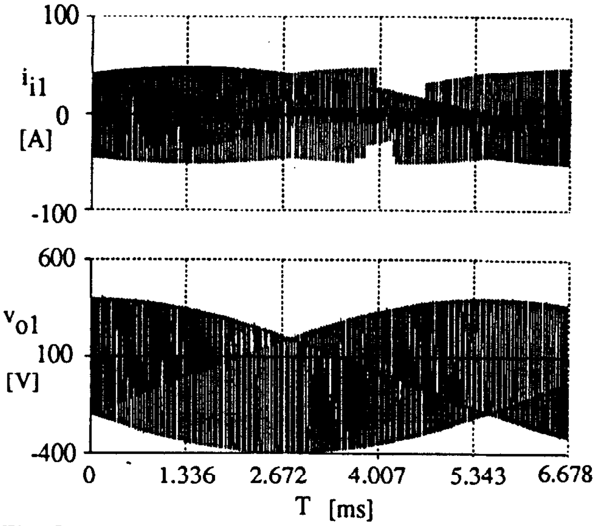

Fig. 8 Input current and output voltage of the ARCPMC (480V mains; i_o=50A; L_r=20µH; C_r=1nF; i_b=5A; f_o=60Hz; q=0.5; φ_i=0°; φ_o=30°)

B. Loss comparison of a hard switching MC and the ARCPMC

The losses of a hard switching MC and the ARCPMC have been calculated with a previously developed power converter loss model [3]. The model was modified slightly to enable an accurate loss calculation of the ARCPMC. The basis of the program is the loss approximation of the measured switching and on-state losses of the High-Speed PT-IGBT-module 2MBI50L-120 (1200V, 50A) for hard and soft switching.

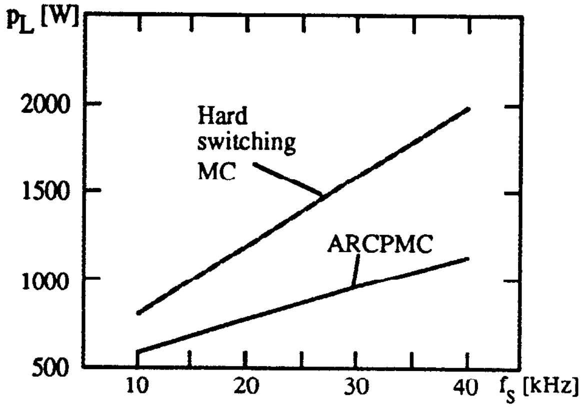

Fig. 9: Losses of a hard switching MC and the ARCPMC (2MBI50L-120; 480V mains; i_o=50A; L_r=20μH; C_r=1nF; i_b=5A; f_i=60Hz; f_o=30Hz; q=0.5; φ_i=0° ; φ_o=30° ; T_j=125° C)

The calculated losses and the loss distribution of both converters can be taken from Fig. 9 and Fig. 10 respectively. Although no additional capacitors were added for the realization of C_r in the ARCPMC (C_r=C_{oss}[IGBT]), the switching losses of the ARCPMC are only 46.5% of those of the hard switching MC. Hence the total losses of a MC topology can be reduced by 35.5% (20 kHz) and by 42.7% (40kHz) respectively if the ARCPMC is used instead of the hard switching MC. A further reduction of the losses of an ARCPMC seems to be possible by a slight increase of C_r.

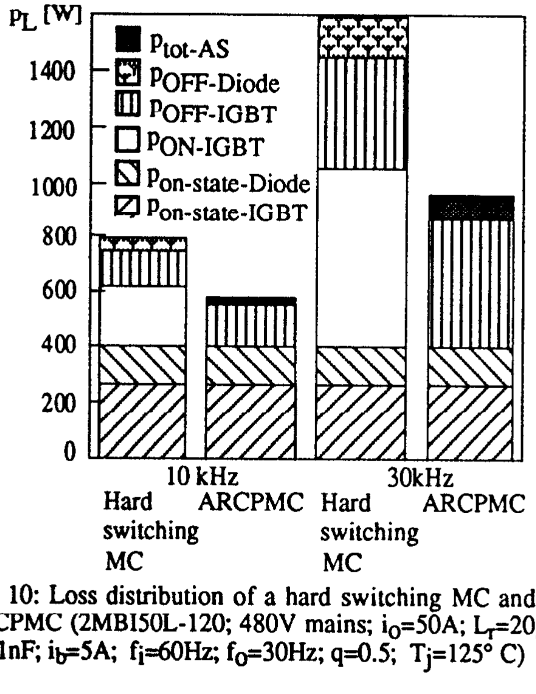

Fig. 10: Loss distribution of a hard switching MC and the ARCPMC (2MBI50L-120; 480V mains; i_o=50A; L_r=20μH; C_r=1nF; i_b=5A; f_i=60Hz; f_o=30Hz; q=0.5; T_j=125° C)

VII. CONCLUSIONS

This paper proposes a new Auxiliary Resonant Commutated Pole Matrix Converter (ARCPMC) as an alternative to hard and soft switching PWM rectifier/ dc-voltage link/ inverter structures for high power applications. Special pulse patterns and an additional commutation unit consisting of three resonant inductors and three, four quadrant switches enable PWM control and soft switching of the new three-phase converter. Hence, the main switches of the matrix converter operate as ZVS and the auxiliary switches function as ZCS. Since the auxiliary switches carry only short current pulses the current ratings of these switches can be much smaller than those of the main switches. Simulation results are presented to verify the function of the converter. The calculation of the losses on the basis of an accurate semiconductor loss model shows that the ARCPMC realizes substantially lower switching and total losses than a hard switching MC at medium and high switching frequencies.

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