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Braking Chopper Solutions for Modular Multilevel Converters

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Abstract

In many converter applications, the usage of a braking chopper system is required for energy dissipation. Thus, braking chopper solutions need to be found for Modular Multilevel Converters (MMLC). This paper describes braking chopper solutions for the indirect and the direct MMLC. For each converter topology a solution utilizing cells is analyzed. Additionally, taking the direct MMLC as an example, a solution which utilizes thyristors is shown. All chopper solutions have been simulated; this paper shows some of these simulation results.

Introduction

In order for Modular Multilevel Converters (MMLC) to connect generating plants to the grid, MMLC must follow the grid code. To fulfill these requirements, the use of a breaking chopper system might be necessary. Additionally, in drive applications, the usage of braking choppers might also be necessary.

In this paper, braking chopper solutions for indirect [1] and direct [4] MMLCs have been analyzed on the example of a converter which connects a generating plant to the grid. Both kinds of MMLC consist of cells. Together with an inductor, these cells form branches. The branches of the direct MMLC directly connect the phases of two AC systems, whereas the branches of the indirect MMLC connect the phases of an AC system to a common DC link.

It is possible to employ concentrated and distributed (integrated in the cells of the MMLC) braking chopper systems for indirect and direct MMLC. In this paper, the focus is set on concentrated solutions which can be attached to the DC link or the AC side of the MMLC. All deliberations have been conducted with the help of simulations with a cell number n of two per branch. The simulation parameters can be found in table II-IV.

Indirect MMLC

Composition of the analyzed indirect MMLC

The analysed indirect MMLC (Fig.1a) is composed of 2 branches for each AC phase; a branch is connecting one phase of a three phase AC system to either a positive or a negative DC link. Every branch consists of an inductor and n identical cells (Fig. 1b). Such a cell is composed of a capacitor for energy storage and a half bridge, consisting of IGBTs and antiparallel diodes. A cell has two possible output voltages U_{Cell}. The output voltage U_{Cell} is equal to the capacitor voltage U_C if $IGBT_1$ is switched on and $IGBT_2$ is switched off. If $IGBT_2$ is switched on and $IGBT_1$ is blocking, the output voltage U_{Cell} is zero. $IGBT_1$ and $IGBT_2$ are never switched on combined, as this would short circuit the cell capacitor C.

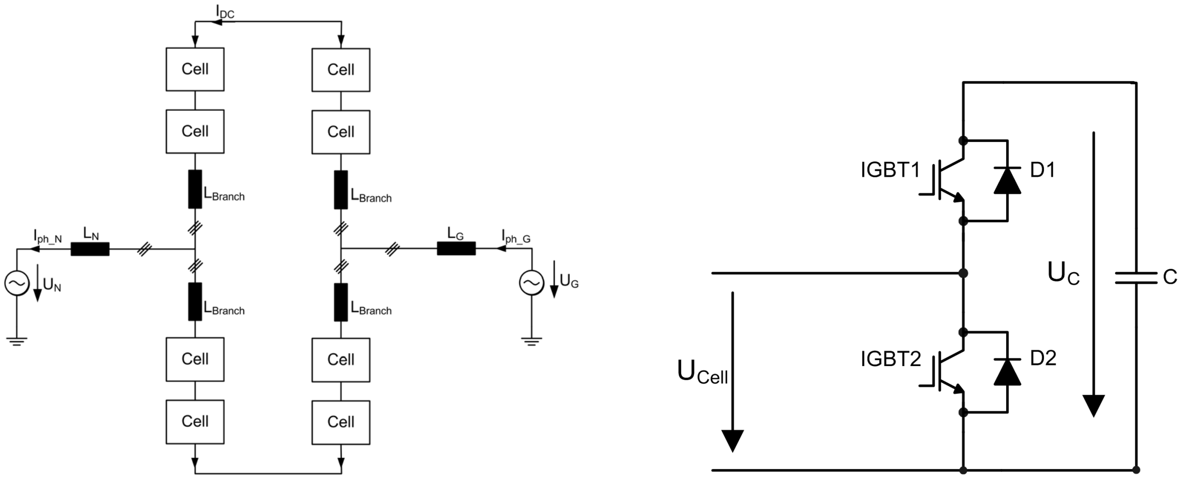

Fig. 1: a) Indirect MMLC, b) cell of the indirect MMLC

According to [2], the output voltage of the indirect MMLC is limited to

$$|U_N| \leq \frac{1}{2} n U_C \tag{1}$$

and the DC link voltage is kept constant at

$$U_{DC} = nU_C . \tag{2}$$

Braking chopper solution for the indirect MMLC

The reason why the MMLC needs a special braking chopper solution is because it is not possible to utilize a conventional braking chopper consisting of a resistor, a switch and a free-wheeling diode on the DC-link. The inductive current flowing through the branches (Fig. 2a) cannot be switched off by this chopper without causing overvoltages, as the current through the branch inductors would be forced to jump. Furthermore, because the IGBT in the braking chopper has to block the whole DC link voltage, this solution is not in agreement with the good scalability of the MMLC topology.

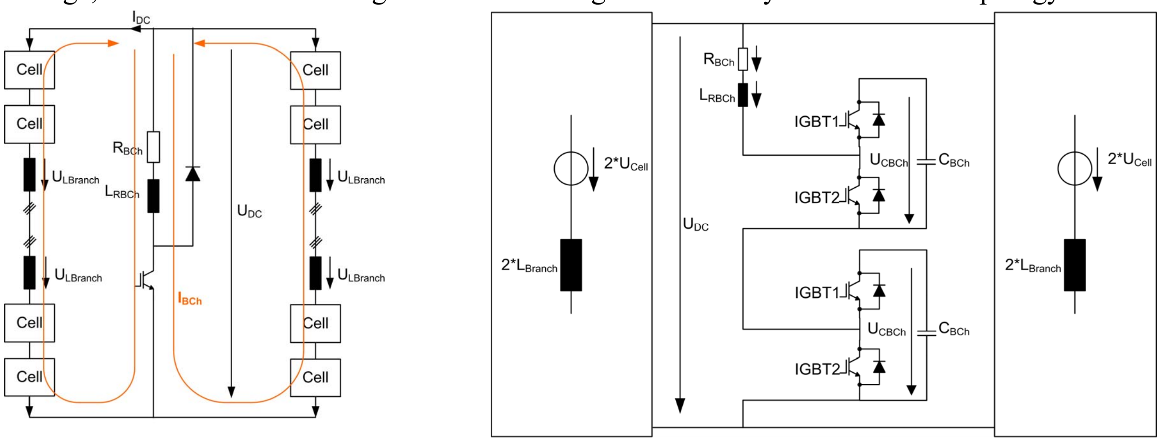

Fig. 2: a) Conventional Braking Chopper applied on the DC link of the MMLC b) Analyzed Braking Chopper for the indirect MMLC

The analyzed braking chopper layout is shown in Fig. 2b, where the branches on each side are simplified as a voltage source with $U_q = nU_C$ and an inductor $L = nL_{Branch}$. This is justified by the fact that in two branches connected to one phase always two cells are switched to $U_{Cell} = U_C$ and so $U_{DC} = nU_C$. The analyzed braking chopper consists of n cells and a braking resistor [2], which is modeled as a resistor and a parasitic inductance. If the $IGBT_2$ of the braking chopper cells are turned on, current starts flowing through the resistor. This action is defined as turning on the chopper. The chopper is controlled by a hysteresis controller: if the DC Link voltage increases above a certain limit, the chopper is turned on. As soon as the DC link voltage decreases to a lower limit, the chopper is turned off again.

Switching Order of the braking chopper cells

If the $IGBT_2$ of all cells are switched on at the same time, the DC link voltage will fall towards zero, as the inductive current, which will create a voltage drop on the braking resistor, is not built up fast enough when the IGBTs start conducting. This causes an overvoltage on each branch inductor of

$$\Delta U_L = -\frac{1}{2} n U_C . \tag{3}$$

Thus, the additional voltage stress of these inductors caused by the braking chopper is proportional to the DC link voltage. If all $IGBT_2$ are switched off at the same time, the DC link voltage jumps to

$$U_{DC} = nU_C + nU_{BCh} . \tag{4}$$

The inductive current through the braking chopper commutates to diode D_1 and starts flowing through the braking chopper cell capacitors. This causes an overvoltage on each branch inductor of

$$\Delta U_L = \frac{1}{2} n U_{BCh} . \tag{5}$$

In Fig 3a and b, the simulated switching behaviour of the voltages and current at the braking resistor are shown. In Fig. 4a and b, the influence of the braking chopper switching on the branch inductor voltages is shown.

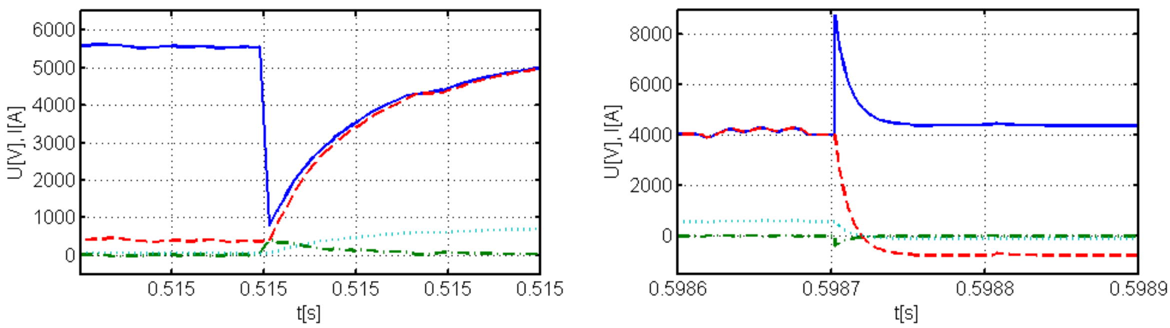

Fig. 3: Simulation Results: a) Turning on; b) Turning off (solid blue: DC link voltage, dashed red: braking chopper resistor voltage, dotted turquoise: braking chopper current, dash-dotted green: voltage at the parasitic inductance L_{RBCh})

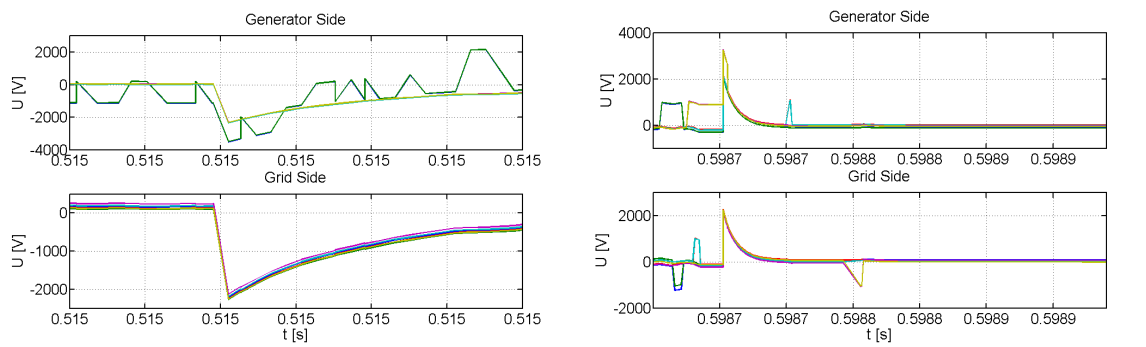

Fig. 4: Simulation Results, Voltages on Branch Inductors: a) Turning on; b) Turning off

To avoid this additional voltage stress of the branch inductors, it is proposed to switch $IGBT_2$ of the braking chopper cells consecutively. In doing so, the DC link voltage is decreased (switching on) or increased (switching off) only by the voltage of one braking chopper cell capacitor (Fig. 5). The next cell is only switched when the current has increased (switching on) or decreased (switching off) to a level where the DC Link voltage reaches its former level again. The delay needed between switching actions can be calculated with

$$\Delta t \geq 5\tau = 5\frac{L_{tot}}{R_{BCh}} = 5\frac{L_{RBCh} + \frac{L_{Branch}}{3}}{R_{BCh}} . \qquad (6)$$

To balance the braking chopper cell capacitor voltages, what is necessary because of the different charging times of the capacitors caused by the delayed switching, the following procedure is proposed: The cell which has the highest voltage is switched first when turning on the braking chopper. The capacitors of the cells which are not yet switched are charged by the braking chopper current which starts flowing through diode D_1. While the braking chopper is turned off, the switching is done the other way round: The cell with the capacitor which is charged lowest is switched first, and as the current starts now flowing through diode D_1 of this cell, the capacitor gets charged. The delay time Δt can be increased if it is necessary for capacitor voltage balancing.

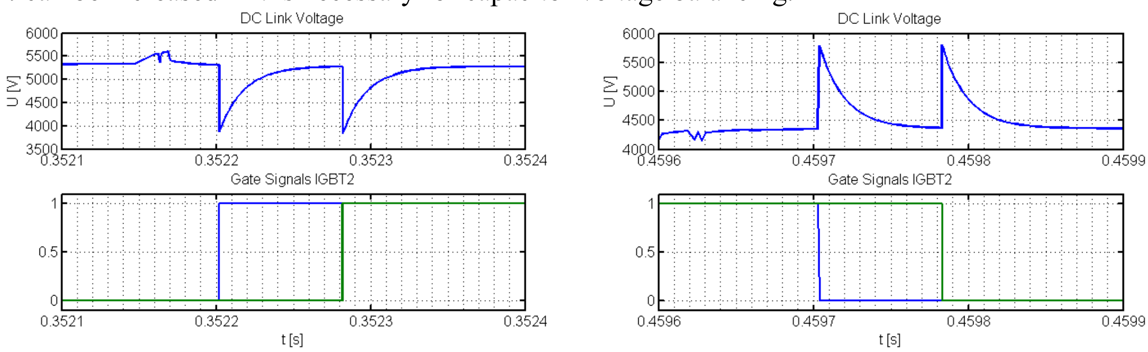

Fig. 5: Simulation Results: Consecutive Switching: DC Link Voltage and Switching Signals. Delay time Δt = 80us: a) Turning on; b) Turning off

In Fig.6, the consequences of the switching for the branch inductor voltages are shown. It can be seen that the effect from the braking chopper switching is less dominant than the effects from normal switching actions of the MMLC.

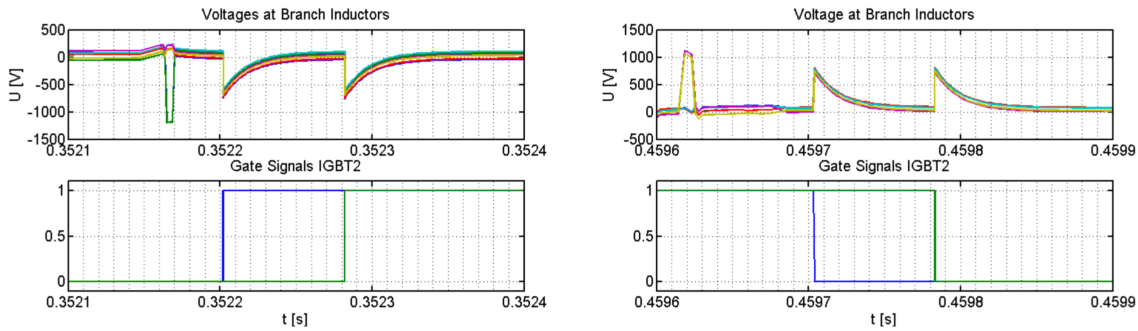

Fig. 6: Simulation Results: Consecutive Switching: Voltage at Branch Inductors and Switching Signals. Delay time Δt = 80us: a) Turning on; b) Turning off

Handling of the braking chopper cell capacitor voltages

As described above, the braking chopper switching and capacitor voltage balancing leads to a charging of the cell capacitors. This charging is not limited, and thus a possibility to discharge the cell capacitors is needed. Discharging is possible with closing $IGBT_1$ of all braking chopper cells while the braking chopper is not turned on. This leads to an equalizing current between the capacitors of the braking chopper cells and the ones of the MMLC cells. As soon as the required voltage of the braking chopper cell capacitor is reached, the $IGBT_1$ of all cells can be switched off again. This has to be done consecutively as well, to avoid an overstraining of the branch inductors.

Conclusions

With the usage of cells as switches, this breaking chopper can easily be applied for different DC link voltage levels, as it is as such scalable and offers a free wheel path for the inductive current while switching off. Furthermore, the chopper follows the modularity principle of the MMLC, as the same cells as for the assembly of the base converter can be used. Because of the delayed switching, the time for turning the braking chopper on or off is proportional to the number of cells, but the additional voltage stress on the inductors caused by the braking chopper is reciprocally proportional to the number of cells. Thus, additional voltage stress on the branch inductors can be minimized.

Direct MMLC

Composition of the analyzed indirect MMLC

The analyzed direct MMLC (Fig. 7a) consists of 9 branches, each connecting one phase of a three phase AC system (phases ABC, generator side) with one phase of another three phase AC system (phases abc, grid side). The branches consist of a series connection of n cells and an inductor. A cell (Fig. 7b) contains an IGBT full bridge and a capacitor.

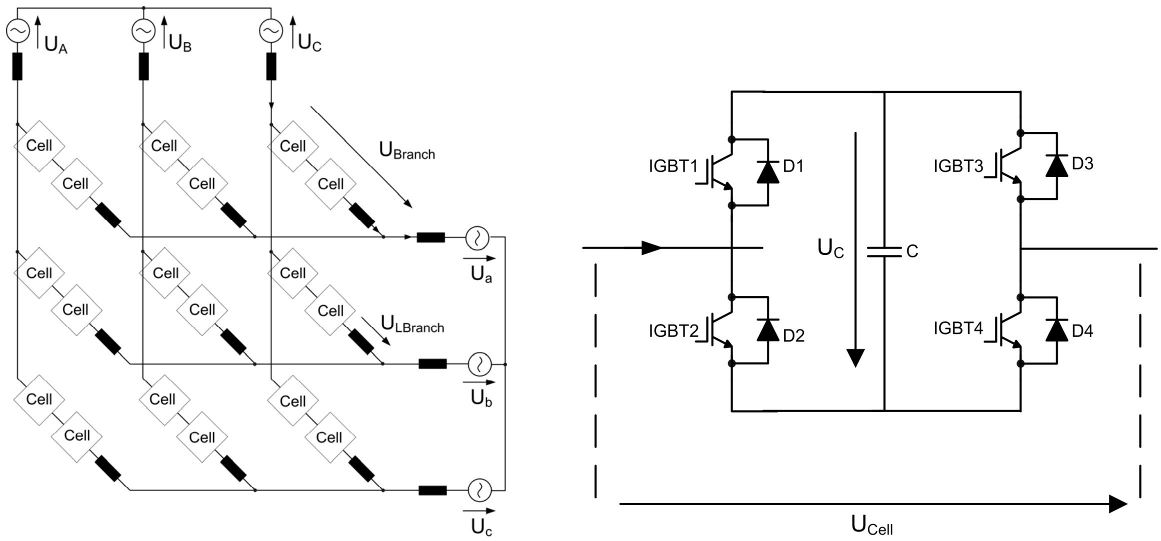

Fig. 7: a) Direct MMLC, b) cell of the direct MMLC

The output voltage U_{Cell} is equal to the capacitor voltage U_C if $IGBT_1$ and $IGBT_4$ are switched on. If $IGBT_2$ and $IGBT_3$ are switched on, the output voltage U_{Cell} is $-U_C$. If no IGBTs are switched on, the output voltage U_{Cell} is zero. $IGBT_1$ and $IGBT_2$ or $IGBT_3$ and $IGBT_4$ are never activated combined, as this would short circuiting the cell capacitor C. Neglecting the branch inductors, the possible branch voltages are

$$U_{Branch} = \{\pm nU_C, \pm(n-1)U_C, \ldots, 0\}\,. \qquad (7)$$

Braking chopper solution for the indirect MMLC utilizing cells

Two different braking chopper solutions have been analyzed for the direct MMLC. The first one, shown in Fig. 8a consists of three legs, which are star connected on the generator side. Every leg is built up with $\frac{n}{2}$ cells and a braking resistor (modeled as an ideal resistor and a parasitic inductance). This number of cells is sufficient to block the line to line voltage of the phases. The chopper is controlled by a hysteresis controller. As soon as the sum of the cell capacitor voltages of the MMLC reaches a certain limit, the chopper is turned on. As soon as the sum of these voltage decreases to a lower limit, the chopper is turned off again. To turn the braking chopper on, on all cells $IGBT_1$ and $IGBT_3$ or $IGBT_2$ and $IGBT_4$ are switched on.

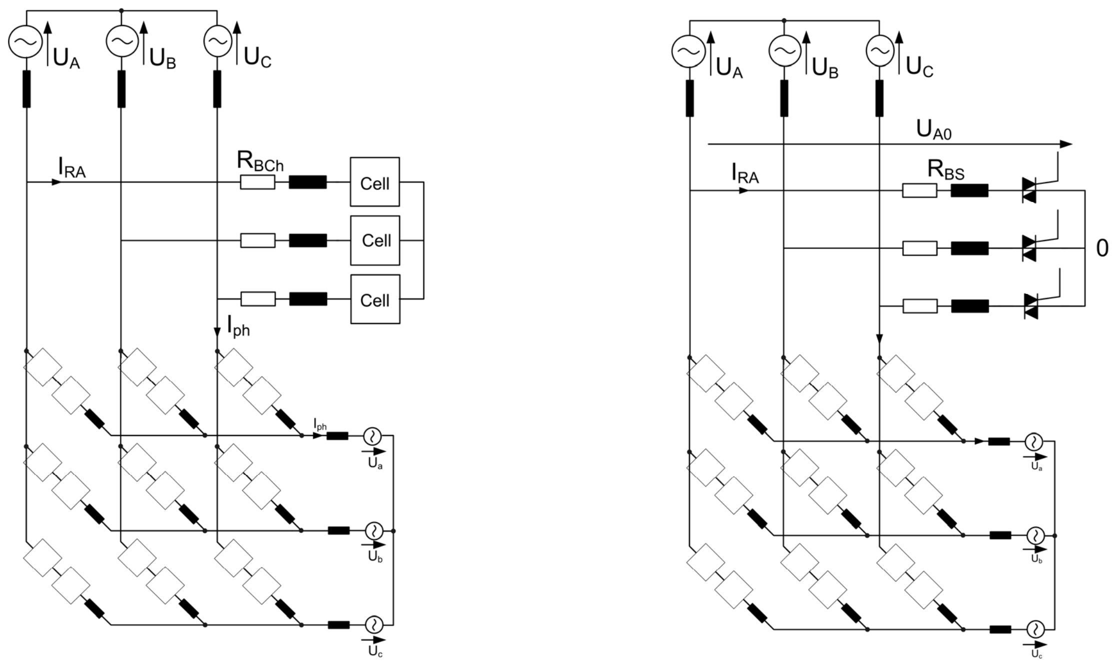

Fig. 8: a) Braking Chopper utilizing cells, b) Braking chopper utilizing thyristors

Switching Order of the braking chopper cells

Analogue to the braking chopper for the indirect MMLC, it is important to switch the cells consecutively while turning the braking chopper on and off. Otherwise, the line to line voltage decreases towards zero (turning on), or increases by the sum of two cell voltages (turning off). The voltage stress on one branch inductance for switching concurrently at time t is thus given by

$$\Delta U_{LBranch} = \frac{U_{LL}(t)}{2} \tag{8}$$

for switching on all cells concurrently

$$\Delta U_{LBranch} = \frac{nU_{CBCh}(t)}{2} \tag{9}$$

for switching off all cells concurrently.

If the cells are switched consecutively with an adequate delay, the inductive current which causes the voltage drop on the braking resistor adapts before the next cell is switched. This leads to the following voltage stress on the branch inductances caused by the braking chopper

$$\Delta U_{LBranch} = \frac{U_{LL}(t) - (n-1)U_{CBCh}}{2} \tag{10}$$

for switching on cells consecutively

$$\Delta U_{LBranch} = \frac{U_{CBCh}(t)}{2} \tag{11}$$

for switching off cells consecutively.

To balance the braking chopper cell capacitor voltages, which is necessary because of the different charging times of the capacitors, the cell with the highest capacitor voltage is switched first when the braking chopper is turned on. After an adequate delay time, the cell with the next highest capacitor voltage is switched next and so on. The capacitors of the cells which are not yet switched are charged by the braking chopper currents which flow through diode D_1 and D_4 or D_2 and D_3 (depending on the current direction). When the braking chopper is turned off, the reciprocal switching order is applied: the cell with the lowest capacitor voltage is switched first and so on. The capacitors of these cells which are already switched are charged by the braking chopper currents which flow through the diodes. The delay time between switching can be increased if it is necessary for capacitor voltage balancing.

Handling of the braking chopper cell capacitor voltages

As described above, the turn on and turn off of the braking chopper charges the cell capacitors. This charging is not limited, and thus a possibility to discharge the cell capacitors is needed here as well. The following discharging mechanism is working while the braking chopper is turned on. While the braking chopper is in use, the capacitor connected to for instance phase A can be discharged according to the following pattern (see Fig.9):

$U_{AB}>0$ → $IGBT_1$: OFF, $IGBT_2$: ON, $IGBT_3$: ON, $IGBT_4$: OFF → $I_A>0$

$U_{AB}<0$ → $IGBT_1$: ON, $IGBT_2$: OFF, $IGBT_3$: OFF, $IGBT_4$: ON → $I_A<0$

A prerequisite for the discharging procedure to start is that the cell which capacitor is to be discharged needs to be in the path with the highest absolute line to line voltage (here U_{AB}). This ensures that the direction of the current through the cell is defined. Results can be seen in Fig. 10a and b. The current increase caused by the discharge is reciprocally proportional to the number of cells in one branch.

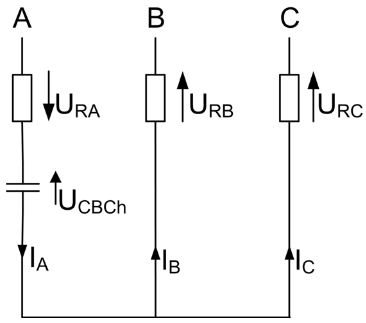

Fig. 9: Equivalent Circuit for discharging of cell A

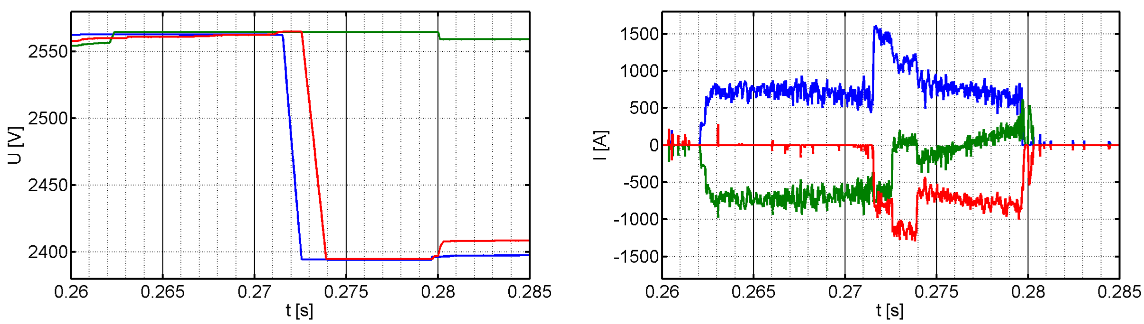

Fig. 10: a) Capacitor voltages, b) braking current

Conclusions

The advantage of this solution is that it is scalable and offers a freewheeling path for the inductive current while switching off. Furthermore, the modularity principle of the MMLC is followed, as the same cells as for the assembly of the MMLC can be used. The required time for turning the braking chopper on and off is proportional to the number of cells n. Additional voltage stress on the branch inductors can be minimized as the overvoltage on these inductors is reciprocally proportional to the number of cells n. Furthermore, this solution can also be applied for indirect MMLC and other converter solutions.

Braking chopper solution for the indirect MMLC utilizing thyristors

The second braking chopper solution is built up similarly, the cells are replaced by antiparallel thyristors (Fig. 7b). If the higher number of cells in the MMLC demands for higher voltages, thyristors can be put in series to be able to block the higher voltages. Always one thyristor in a chopper leg is forward blocking and the other one reverse blocking. For current to be able to flow, there must be a conducting thyristor in at least two legs of the braking chopper. Furthermore, it should be avoided that only one thyristor is conducting, as this pulls the phase voltage of the conducting phase to the potential of the star point. This leads to an $\sqrt{3}$ increased voltage stress of the blocking thyristors, as they then have to block the line to line voltage instead of the phase voltage. Because of this, the firing angle α is limited to a maximum of 60° (table I).

Table I: Firing Angle α

α	**Maximal number of conducting thyristors**	**Minimal number of conducting thyristors**
$\alpha > 120°$	1	0
$60° < \alpha < 120°$	2	1
$0° < \alpha < 60°$	3	2
$\alpha = 0°$	3	3

The voltage of the MMLC cells is controlled by a PI controller. The output parameter of this controller is the firing angle α . For required firing angles of more than 60°, a hysteresis controller can be applied to control the braking chopper with a fixed angle of 60°. In Fig. 11, simulation plots are shown.

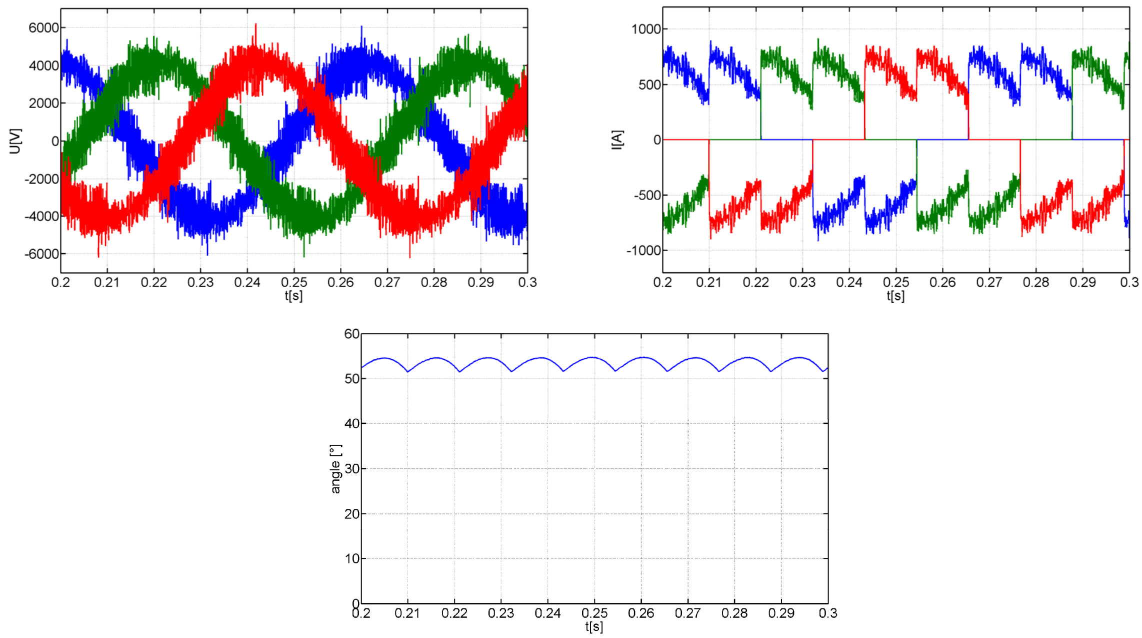

Fig. 11: a) line to line voltage at the braking chopper, b) current through the braking chopper, c) firing angle α

Conclusions

The advantages of this solution are the simple construction and the rather simple control compared to the solutions utilizing cells. Furthermore, this solution can also be applied for indirect MMLC and other converter solutions.

Simulation Parameters

All shown results in this paper stem from simulations with parameters as shown in table II-IV.

Table II: Simulation Parameters all Simulations

Parameter	Value	Parameter	Value
n	2	L_{Branch}	2%
U_{Cell}	2400 V	$L_N = L_G$	40%
f_N	50 Hz	f_G	15 Hz
$U_N = U_G$	2400 V	$S_N = S_G$	3 MVA
IGBT	4500 V / 1200 A		

Table III: Simulation Parameters indirect MMLC

Parameter	Value	Parameter	Value
C_N	2.7 mF	C_G	9 mF
R_{BCh}	7.1 Ω	L_{RBCh}	50 uH

Table IV: Simulation Parameters direct MMLC

Parameter	Value	Parameter	Value
C	9 mF	R_{BCh}	2.80 Ω
L_{RBCh}	50 uH		

Conclusion

It has been shown, based on simulations, that braking chopper solutions for Modular Multilevel Converters are feasible. Three solutions have been shown in detail; two utilize the same cells as the corresponding MMLC, which leads to highly modularized and scalable solutions. This comes at the cost of having to balance the cell capacitor voltages and discharge the capacitors.

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