Soft-Switching Modular Multilevel Converters for Efficient Grid Integration of Renewable Sources

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***Abstract* – The *Modular Multilevel Converter* (*MMC*) concept is a modern energy conversion structure that stands out for a number of interesting features that opens wide application chances in Power Systems, for example for efficient grid integration of renewable sources. In these high-voltage, high-power application fields, a high efficiency is mandatory. In this regard, an interesting and promising development opportunity could be to make *soft-switching* the elementary converters of the submodules (cells), *half H-bridges* or *full H-bridges*, obtaining at the same time the advantage of increasing the switching frequency. The *ARCP* or the *AQRDCL* soft-switching topologies appear adequate for this purpose. This paper is dedicated to examining these development possibilities.**

Index Terms: **soft switching, Modular Multilevel Converter, Grid Integration, Solid State Transformer**

I. INTRODUCTION

Within the Power Electronics scenario, the *Modular Multilevel Converter* (*MMC*) [1] concept doubtless represents, currently, one of the most complex and advanced multilevel energy conversion topology.

Several features, such as the remarkable modularity and the high quality of the output voltage and the input current, make the *MMC* concept attractive especially for high-power and high-voltage applications; the MMC gives also the opportunity to realize - with the same concept - various types of energy conversion, like DC/AC or AC/AC with any number of phases, and offers a great availability and fault tolerance, because a fault submodule can be easily bypassed and the operation can continue with the healthy submodules.

These features require, on the other hand, a high number of power devices and somehow complex control strategies: for each branch, the cascade-connected submodules can be seen like variable voltage sources that operate in dependence of the actual voltage of their capacitors.

So substantially different from the more traditional conversion systems, the *MMC* principle of operation is based on proper management and input/ouput balance of the energy stored inside the submodules capacitors.

In the world of Power Systems, especially in the energy transmission and distribution areas, the *MMC* architecture has rapidly gained wide interest and application opportunities for the so-called *FACTS – Flexible Alternating Current Transmission Systems*. Its distinctly modular structure permits to build effective very high-voltage/very high-power converters like *STATCOMs – Static Synchronous Compensators* for reactive power, *HVDC*s – *High Voltage Direct Current* DC/AC (inverters) or AC/DC (rectifiers) converters for efficient energy transmission [2-5] and - more recently - for the transmission from the marine wind generation plants (commonly referred as *offshore wind farms*) to the AC grids on the mainland, and *SFC – Static Frequency Converters* for the interconnection and energy exchange between large AC grids with different frequencies, for example AC/AC three-phase/three-phase 50/60 Hz, or AC/AC three-phase/single phase 50/16.7 Hz, being 16.7 Hz the frequency for railway traction systems in some North-Europe countries (15 kV – 16.7 Hz).

In these "*top-end*" static power conversion systems a high *efficiency* is mandatory, also because the gain of a fraction of a percentage in the efficiency can mean the saving of a large amount of power, maybe several thousands of kilowatts, and therefore of energy. At the same time, high *quality* of the conversion (reduced harmonic content of the input/output waveforms) and high *reliability* are other primary important features required.

Furthermore, interest around the *MMC* is related to the realization of the *Medium Frequency Transformer* or *Solid State Transformer* (*SST*), an evolution of the classical electromagnetic transformer toward a complex power conversion system in which the magnetic coupling between two circuits, operating at a different voltages, is realized by a transformer working at a frequency level of some kHz, with expected advantages in terms of size, weight and efficiency. A marked development effort is aimed nowadays toward this technology; it looks attractive especially for medium voltage levels, so as a part of the *power distribution* area. The *MMC* acts as a frequency converter between the grid and medium frequency transformer.

The *MMC* concept, whatever type of conversion is considered, includes several *branches*, each comprising a cascade connection of *submodules* equal to each other. A single submodule is organized as a *half H-bridge* or *full H-bridge*, with a DC-link capacitor acting as an energy storage device. So, the *MMC* is originally conceived as a *hard-switching* converter. Then, taking into account the expectations about *efficiency* and *quality of the processed power*, the question was raised whether, by adopting some *soft-switching* strategy inside the submodules [6], it is possible to improve the efficiency of the *MMC* converter and increase its switching frequency so as to enhance the waveforms quality, without cause an intolerable increase of the power losses. This paper is devoted to examine these opportunities.

II. RESONANT TOPOLOGIES FOR POWER CONVERTERS

Several circuital solutions have been proposed to make *soft* the switches commutation process in power converters, especially in the late '80s and early '90s, when the semiconductor devices then available had much more limited performance than now, especially with reference to the maximum allowed switching frequency. Planned applications were the most varied: aeronautical, PV solar, induction heating or variable speed drives. The main *soft-switching* principle was based on a *resonant circuit,* able to set up *Zero Current Switching* (*ZCS*) and/or *Zero Voltage Switching* (*ZVS*) conditions for the commutation process of the semiconductor devices. Power levels for these converters commonly ranged from a few kW to a few hundred kW; only some solutions have been dedicated to higher power levels. Compared to the *hard-switching* topologies, the greatest number of the necessary components - active and passive - was balanced by a series of advantages, the main ones being: the net reduction or cancellation of the switching losses, with consequent increase of the conversion efficiency; the improvement of the quality of the input/output waveforms with a reduction of the harmonic content and improved *THD*; the maximization of the *specific power* [kW/kg] and the *power density* [kW/m^3] of the converters; the knocking-down of the acoustic noise and a more convenient sizing of the magnetic components.

In the following years, with the availability of higher performance *snubberless* power components, the interest in *soft-switching* solutions was reduced; nevertheless, the *soft-switching* technology showed to be an interesting idea, potentially capable to improve performance of the modern multilevel converters, where the total power is shared between multiple modules or subassemblies.

Among the several proposed *soft-switching* solutions, it was necessary to identify the most suitable ones with reference to the present research, that is the submodules (*full H-bridges* or *half H-bridges*) for the *MMC* converters, looking at an effective balancing between the largest number of components required and the performances offered. Typically, several functional characteristics linked to the presence of resonant circuits can introduce limitations or inadequacies: increase in voltage or current stresses on the main converter power components (in some cases very pronounced, more than 2 p.u., so requiring their net oversize); not safe *soft-switching* operations in all operating conditions of the converter (not fully controllable Zero-Voltage-Switching *(ZVS)* or Zero-Current-Switching (*ZCS)* process, depending of the load current or other constraints); "impact" of the *soft-switching* circuit with the overall structure of the converter; inadequacy or only partial adequacy to the *PWM* modulation.

The *soft-switching* solutions can be classified in three main families: 1) - *resonant switch*, if resonant circuit is applied to the individual switches of the converter; 2) - *resonant pole*, if the resonant circuit acts on a branch of the converter; 3) - *resonant link*, if the resonant circuit acts on the DC-link of the converter.

With the obvious purpose of reducing as much as possible the number of additional components, our research it was directed toward the last two ones. Several topologies were examined: A) - *Resonant DC-link Converter* (*RDCL*) [7 – 9, 13, 11 - 14]; B) - *Active Clamped Resonant DC-link Converter* (*ACRDCL*) [10]; C) - *Notch Commutated PWM Inverter* [7, 15, 16]; D) - *Quasi-Resonant PWM Inverter* (or *Modified Active Clamped Resonant DC-link Inverter*) [7, 17]; E) - *Zero Switching Loss PWM Converter with Resonant Circuit* [7, 18 – 20]; F) - *Active Resonant Commutated Pole Converter* (*ARCP*) [7, 21, 23]; G) - *Auxiliary Quasi Resonant DC-link Inverter* (*AQRDCL*) [22].

Almost all these topologies were originally proposed for *three-phase* inverters for electric drives; anyway, their adaptation to a single-phase H bridge is still quite easy.

Taking into account the various constraints described above, the *ARCP* and the *AQRDCL* topologies seem to be the most suitable to realize *soft switching* submodules for a *MMC* converter.

III. RESULTS

The *ARCP* circuit is a *resonant-pole* type *soft-switching* topology, as shown in Fig. 1, so each branch of the converter includes a L-C resonant circuit built by two switches + diode pairs, A_1 and A_2, a resonant inductor L_1, a capacitive divider with a central tap C_{d1} - C_{d2} and two snubber capacitors in parallel to the main devices, C_1 and C_2.

The *ARCP* is able to operate in *PWM* without limitations, in contrast to other topologies that cannot, instead, operate in *PWM*, or they can do so with limitations, requiring a somehow adapted *PWM* modulation (*quasi-PWM*).

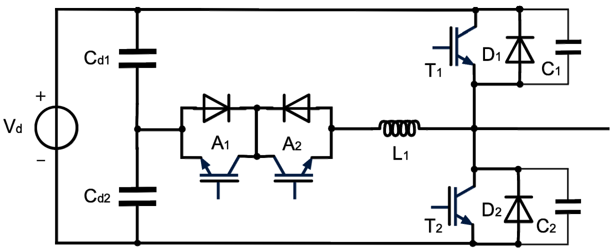

Fig. 1 – *Active Resonant Commutated Pole Converter* (*ARCP*), one arm.

The commutation of the main switches T_1 and T_2 occurs in *ZVS*: the turn-off is *ZVS*, by itself, thanks to the capacitive *snubber*; the turn-on is *ZVS* for the effect of the resonant circuit, because the *snubber* capacitors C_1 and C_2 also act as a resonant capacity. The auxiliary switches A_1 and A_2 turns-on and off in *zero-current* soft-switching mode, requiring a minimal turn-off current capability. Unlike other competing topologies, an important property, advantageous for this application, is the resonant circuit connected in *parallel* to the commutating switch only in a small time interval around the switching; outside the switching conditions, all the components of the resonant circuit are not influenced by the load current. So, the operation "to the terminals" of the *ARCP* resonant cell is almost similar to that of a common *hard-switching* cell, and therefore it does not influence or “disturb” the overall operation of the *MMC*. More, this is a benefit for the resonant inductance size, which must not sustain continuously the load current. The auxiliary switches A_1 - A_2 and the inductor L_1 can be sized in a convenient mode too, because they conduct the resonant current, whose peaks can be relatively high (1.6 – 1.8 p.u. according to [21]), but the *duty cycle* is low, so the *RMS* current is low as well, and therefore the losses are small, too. On the contrary, in other simpler topologies, requiring less auxiliary components, the resonant inductance is series-connected to the DC-link cell, so it must conduct the load current; furthermore, the width control of the *ZVS* interval is more difficult and often depends on the load current.

The *ARCP* presents several advantageous features compared to other competing resonant solutions: it is claimed to be suitable for high power converters (≈ 1 MVA), can operate with relatively high switching frequency, 10 ÷ 30 kHz, its efficiency is high and the *silicon area* increase, compared to a conventional *hard-switching* solution, is about 20% due to a favourable sizing of the auxiliary switches.

In Fig. 2 some simulation diagrams, referred to a *single cell* (one *MMC* submodule, *full H-bridge*) *ARCP*, are shown. The *ZVS* turn-on and turn-off are clearly appreciable; the *edges* of the output voltage are less steep than in *hard-switching*, so the power components are less subjected to *dv/dt* stress.

Fig. 3 shows the simulation diagram of the output voltage of a *MMC* (only 4 submodules for branch, for simulation speed reasons) equipped with *full H-bridges soft-switching ARCP* submodules: one can appreciate a waveform that does not differ appreciably from that of an usual *hard-switching* MMC converter, represented in same figure.The results of a study about the implementation of the *ARCP* topology to the submodules for *MMC* for high-power, high-voltage *STATCOM* and *HVDC* (1100 MW, 400 kV) are shown in [24]

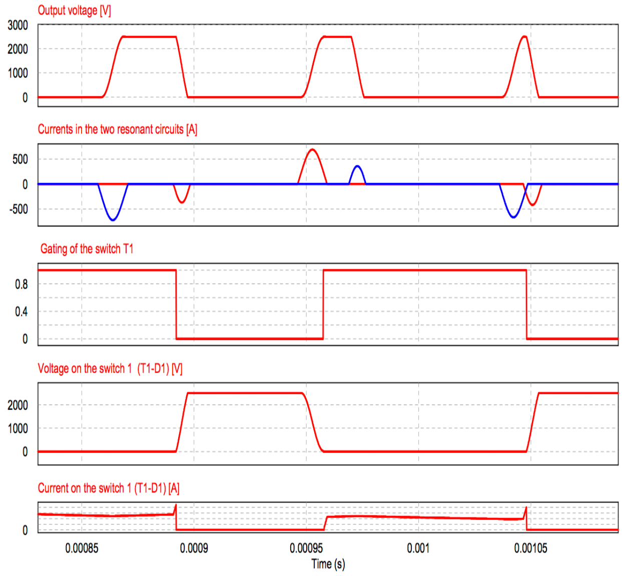

Fig. 2 - *Full H-bridge ARCP* single submodule simulation diagrams. *Top to bottom*: 1)- output voltage [V]; 2)- currents in the resonant circuits (one for each of the two branches) [A]; 3)- *gating* of the switch T_1; 4)- voltage on the switch 1 (T_1-D_1) [V]; 5)- current on the same switch [A].

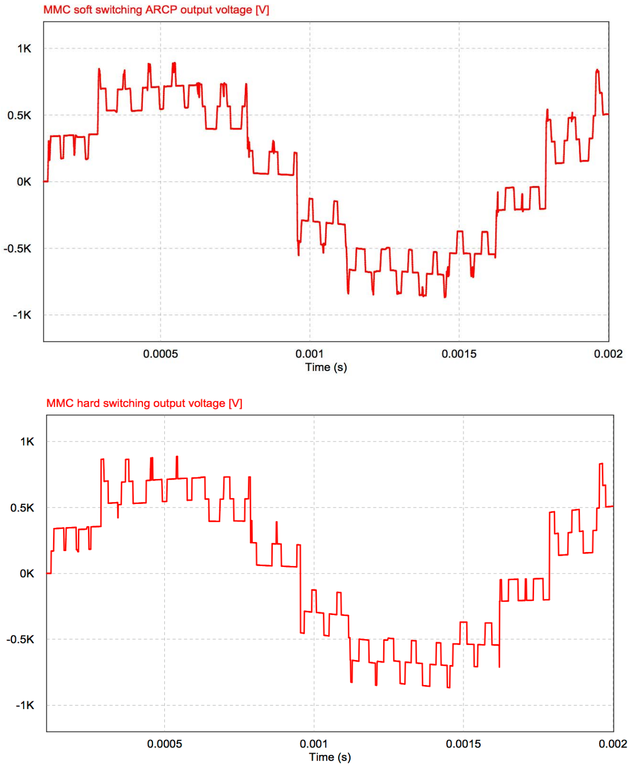

Fig. 3 – Comparison between the phase output voltages of: (top) - a *full ARCP soft-switching MMC* converter (4 submodules for branch, all *ARCP*), and (bottom) conventional *hard switching MMC*. The ratings and operating conditions are the same. (Note: here power and voltage values are *scaled*, for testing only).

The power components examined are 4.5 kV - 4 kA IGCTs: the improvement of efficiency is up to 45% compared to a conventional *hard-switching* solution.

Another *soft-switching* topology that seemed to be worthy of consideration is the *AQRDCL*: it belongs to the *resonant-link* family instead to the *resonant-pole* one, but it is closely derived from the *ARCP* and it presents some similar modes of operation. Furthermore, this scheme shows a *topological similarity* with the Divan's *ACRDCL* [10], being also provided by a *clamp* switch, as shown in Fig. 4.

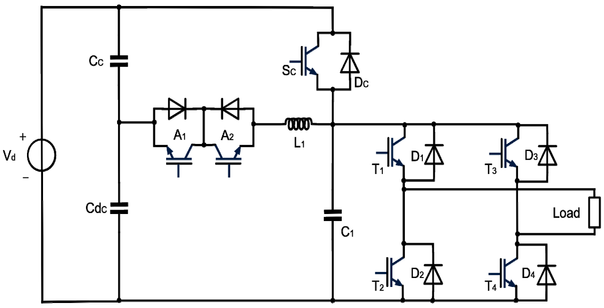

Fig. 4 – Full H-bridge *Active Quasi-Resonant DC-Link Converter* (*ARCP*).

Unlike the *ARCP*, where each converter arm requires a dedicated resonant circuit, (so two resonant circuits for a full H-bridge, and only one resonant circuit for a half H-bridge), the *AQRDCL* exploits only a single resonant circuit for the whole converter, acting on its DC-link. This means that, compared to the *ARCP*, this scheme needs less auxiliary components (active and passive), but at the price of an increased control complexity and somehow higher limitations.

The resonant circuit includes the auxiliary switches + diode pairs A_1 and A_2, the input capacitive divider with central tap C_c - C_{dC} and the passive resonant components L_1 and C_1. Please note that, differently from the *ARCP*, the snubber capacitors, in parallel to the main switches, here are not necessary. Nevertheless, a *clamp* switch (IGBT S_c and parallel diode D_c) here is included: substantially it disconnects the DC link from the source during the commutation intervals.

When the *PWM* modulation commands the commutation of the main switches T_1 ÷ T_4 of the H-bridge, the *turn-off* of the *clamp* switch S_c and the sequential *turn-on* of the auxiliary switches A_1 - A_2, appropriately coordinated, occur. This triggers the resonance between L_1 and C_1: the effect is the zeroing, for a short interval, of the DC-link voltage, so the commutation (*turn-off* and *turn-on*) of the main switches occurs in *ZVS*. At the end of the process the resonant circuit is deactivated, the *clamp* switch S_c starts conducting and the DC-link voltage grows to its value. The auxiliary switches commutate in soft-switching zero-current mode, like in the *ARCP*. This topology exploits a full resonant cycle (a complete period), while the *ARCP* completes a soft-commutation in one-half period of resonance only. The *clamp* switch S_c introduces conduction losses because it conducts the load current, out of the commutation conditions. It commutates at the switching frequency, and its commutations should take place in *ZVS* both in *turn-on* and *turn-off*, like the main devices, but it is not yet assessed whether this is true in *any* operational situation.

Also the *AQRDCL* can operate in full *PWM* modulation, without limits. About the maximum power levels controllable with this topology, we haven't found reliable information; anyway, considering that a proper control requires that the *gating* of the power devices must occur respecting times of the order of a few µs, and which therefore requires the use of very fast power devices, it is safe to assume that the realistic level of maximum power for this topology is in the range of hundreds of kW.

Still wanting to express an aspect of comparison of this topology with the *ARCP* one, we can observe that, being there in this case only one resonant circuit for the whole converter, if the switching frequency is high and the modulation index is close to the unity, at equal operating conditions it is likely that it is necessary to employ a higher resonant frequency to ensure proper soft-switching in every situation. Also, for the same reason, with the *AQRDCL* topology *overlap* situations are frequent, events where a new resonant cycle (a new switching) is triggered before the previous one (the previous switching) is concluded. A correct control strategy must take into account these *overlap* situations, inserting an opportune delay if a commutation is commanded while another one is still in progress. This is a situation that however does not occur with the *ARCP* topology, which of course is more flexible due to resonance acting separately on each branch.

In Fig. 5 some simulation diagrams referred to a *single cell* (one *MMC* submodule, *full H-bridge*) *AQRDCL*, are shown. Even with this topology, the *ZVS* turn-on and turn-off are observable, as well as the smooth *edges* of the output voltage.

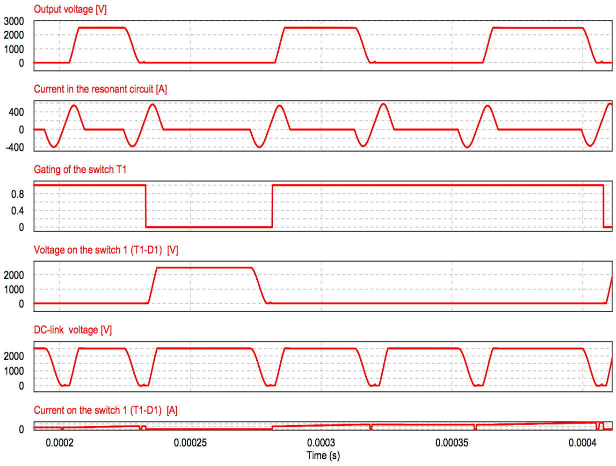

Fig. 5 - Full *H-bridge AQRDCL* single submodule simulation diagrams. *Top to bottom*: 1)- output voltage [V]; 2)- current in the resonant circuit [A]; 3)- *gating* of the switch T_1; 4)- voltage on the switch 1 (T_1-D_1) [V]; 5) – DC_link voltage [V]; 5)- current on (T_1-D_1) [A].

Fig. 6 shows the simulation diagram of the output voltage of a 4-submodules for branch *MMC,* equipped with *full H-bridges soft-switching AQRDCL* submodules: also in this case, one can see a waveform substantially identical to that of a *hard-switching* MMC converter.

The authors aimed to quantify, at least in an indicative mode in this preliminary stage of the research, the potential advantages in term of losses and switching frequency, related to the use of these *soft switching* topologies compared to the conventional *hard switching* one, in view of the specific applications on high power and high voltage power converters.

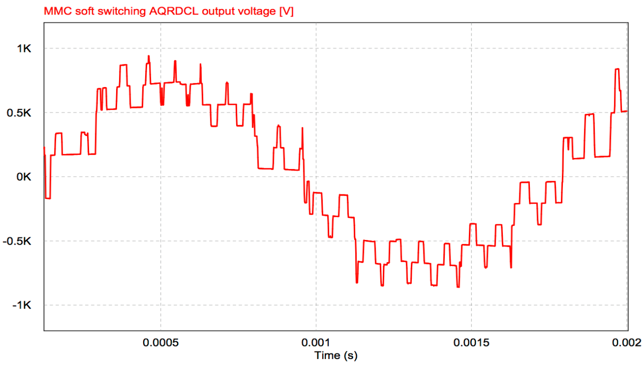

Fig. 6 - Phase output voltage of a *full AQRDCL soft-switching MMC* converter (4 submodules for branch, all *AQRDCL*).

Obviously, one must take into account that the resonant topologies involve a number of not negligible disadvantages, such as the increased complexity of the circuitry, a much greater number of components than a conventional *hard-switching* converter (therefore, in principle, a lower reliability), greater control limits and complexity, and an overall costs increase. It must be observed, in particular, that the higher number of components and related costs are not only referred to the auxiliary active and passive components included in the scheme, but also to the highest number of additional *gate drivers*, current/voltage transducers and heatsinks required and the increased sophistication of the cooling system. It is clear, therefore, that the innovative solution is actually befitting than the traditional to the extent that these limitations are compensated by much better performance in terms of efficiency.

By the use of PSIM software equipped with the Thermal Module, two *full H-bridges*, one of which *hard switching* and the other *soft switching*, with identical ratings and in the same operation conditions, have been put in comparison, especially looking to compare the losses - both the conduction and the switching ones - of the power semiconductor devices.

The voltage and power ratings of the *H*-bridges have been chosen coherently with the application of the *H*-bridge as a single submodule for a *MMC* intended for an application on Power Systems for a medium-high power level. So, the DC-link submodule voltage (that is, the voltage impressed by the energy storage capacitor of the single submodule) was fixed in 2000 V; for the AC-side current of the submodule (it would be the current of the *MMC* branch) a relatively restrained level, less than 100 A, has been chosen. Taking into account the research results presented in [24] about a very high power *MMC* intended for *STATCOMs* and *HVDCs*, and equipped with *ARCP* resonant submodules employing large size *IGCTs*, here, considering a lower power level for the *MMC*, the authors have intended to examine the behaviour of the *IGBTs* as *H-bridge* power semiconductors (main devices).

The power devices were selected from those commercially available by known manufacturers; their electrical and thermal characteristics, desumed from the respective data-sheets, have been integrate in the Thermal Module of the PSIM software. Large power semiconductors are available in rather few sizes, so in some cases is evident a certain oversizing with respect to the voltage / current levels used in the performed tests. The switching frequency has been chosen f_{sw} = 6 kHz, a value unsustainably high for an hard switching converter; tests were conducted with a medium value of the modulation index, $m_a = 0.65$. The resonant frequency has been set 70 kHz.

For the *hard-switching* model, considering the (main) devices to be *IGBT* modules ABB 5SNA 650J450300, 4500 V – 650 A, the simulation yields the following losses for the four switches, *IGBTs* and diodes (mean values in the simulation interval):

- overall *conduction* losses: 165 W;
- overall *switching* losses: about 11 kW.

It is obvious that such an high value of the switching frequency f_{sw} causes a large amount of switching losses, completely incompatible with a correct operation of the converter.

Using IGBT modules Infineon FZ400R33KL2C-B5, 3300 V – 400 A, “*low losses*” class, a better result has been obtained, but however switching losses are still too high:

- overall *conduction* losses: 155 W;
- overall *switching* losses: about 6.57 kW.

As expected, to obtain an acceptable value of the switching losses it would be necessary to lower f_{sw} at or below 1 kHz (for f_{sw} = 1 kHz the switching losses would drop to 1.99 kW with ABB devices, and 940 W with Infineon “*low losses”* devices, and in this way their junction temperature T_j would be maintained well below the maximum limits).

In the *same simulation conditions,* the authors have subsequently tested an *ARCP soft-switching* submodule. Also for these tests the same devices of the *hard-switching* case have been considered. Therefore, using all ABB 4500 V – 650 A modules (the same for both the main and the auxiliary switches), with f_{sw} = 6 kHz, the following results have been found:

- overall *conduction* losses on the *main* devices: 173 W;
- overall *conduction* losses on the *auxiliary* devices: 297 W;
- overall *switching* losses on the *main* devices: 60 W;
- overall *switching* losses on the *auxiliary* devices: 3.49 kW.

Instead, using all Infineon 3300 V – 400 A modules:

- overall *conduction* losses on the *main* devices: 167 W;
- overall *conduction* losses on the *auxiliary* devices: 323 W;
- overall *switching* losses on the *main* devices: 48 W;
- overall *switching* losses on the *auxiliary* devices: 3.32 kW.

It is noticeable that, while the switching losses on the main devices are greatly reduced, almost cancelled using the *soft switching* technology, the same losses on the auxiliary devices are somewhat considerable; the turn-on and turn-off of the auxiliary devices really occur at zero-current, but this implies, anyway, a certain amount of losses in these *IGBT* devices, due to the fact that turn-on and turn-off commutations do not occur completely in ZCS, because of the relatively high steep of the resonant current pulses; more, the conduction paths in the auxiliary devices branch include the series connection of an IGBT and the antiparallel diode of the other IGBT, as shown in Fig. 1, worsening the conduction losses. These losses do not completely delete the efficiency gain of the *soft-switching* solution with respect to the *hard switching* one, but partially nullifies its the advantage, because substantially a part of the losses on the main devices is "transferred" to the auxiliary ones. The junction temperatures T_j on the auxiliary devices approach dangerously the maximum limit. This drawback can be overcome, at least partially, by using two antiparallel *fast switching thyristors*, or *medium frequency thyristors,* instead of the counter-phase series connection of the IGBT/diode pairs. This solution also has the virtue to simplify the auxiliary branch, because the two conduction paths include always one component only. Suitable components for this variant can be fast thyristors with ratings of the same class as those developed for induction furnaces and other medium frequency applications. Moreover, these components are quite inexpensive and can benefit from a very favourable design for a particular application, because they are very suitable to conduct current pulses with high peaks and short duration and low duty-cycle, like the resonant pseudo-sinusoidal current pulses in this application; so, it is possible to use devices with relatively low current rating. Then, in this *soft-switching* scheme, the auxiliary devices are loaded with one half the DC-link voltage only. Turn-off times t_q of some tens of microseconds appear adequate for these thyristors, compatible with the duty-cycle of the resonant current. The turn-on occurs by a gate pulse; the turn-off occurs when the resonant current falls below the holding value, usually very small. It is useful to keep in mind, however, that the correct choice of the thyristor ratings must be tuned with the design of adequate values for the resonant frequency and the resonant current peak.

About the size of the auxiliary devices, it can be placed in relief, at this point, given that the *soft switching* topologies require a number of active devices greater than the one needed by the conventional *hard switching* scheme, it makes sense to try to balance - at least partially - this unfavourable aspect by using a total silicon area slightly higher than that corresponding to the conventional solution: in other words, it is convenient to design the resonant circuit so that the auxiliary components are of the smallest size possible. Under this aspect, thyristors seems to be advantageous components, thanks to their ability to conduct high current peaks for a short time.

Currently few manufacturers produce medium frequency thyristors rated for a voltage of some kV and a current of a few hundreds A; a possible choice for the present study was the device Proton-Electrotex TFI643-500-22 rated for 2200 V – 500 A. Another suitable components of the same manufacturer could have been the TFI233-400-24, 2400 V – 400 A, (all *disc-type* devices) but the available data-sheets does not include all the necessary data for a complete modelling. Another device tested is the Poseico (Power Semiconductor Italian Corporation) ATF820 2000 V – 725 A, superabundant, perhaps, about the current rating.

For sizing these auxiliary *fast switching* thyristors, it is important to observe that, although they conduct a current with a high peak value but with limited mean and *RMS* values, the high frequency operation seems to involve some derating with respect to the nominal current $I_{T(\mathrm{AV})}$. This aspect needs further insights, as it impacts on the silicon area (then on the cost of the components), which should be limited as much as possible. In contrast, the voltage stress on these devices is limited only to half the DC-link voltage.

Another parameter which must be taken into account for the auxiliary thyristors is the turn-off time t_q, which must be adequately shorter than the period of the resonant current. Normally the *medium frequency* and *fast switching* thyristors feature t_q of some tens of microseconds, which allows a resonant frequency of some tens of kHz for the *ARCP* circuit. The *AQRDCL* topology, under this aspect, is most disadvantaged because it requires the auxiliary switches to operate with a higher frequency.

Anyway it would make sense if, in view of this *soft-switching* application, manufacturers develop a special devices family with suitably tuned ratings.

So, equipping the *soft-switching ARCP* submodule with Infineon 3300 V – 400 A *IGBTs* power modules for the main switches, and the Proton-Electrotex 2200 V –

500 A for the auxiliary switches, the following results have been obtained:

- overall *conduction* losses on the *main* devices: 298 W;
- overall *conduction* losses on the *auxiliary* devices: 120 W;
- overall *switching* losses on the *main* devices: 250 W;
- overall *switching* losses on the *auxiliary* devices: 2.11 kW.

that is a net improvement with respect to the use of the *IGBTs* for the auxiliary switches.

Again, using ABB 4500 V – 650 A *IGBTs* for the main devices, and Poseico 2000 V – 725 A thyristors for the auxiliary switches:

- overall *conduction* losses on the *main* devices: 304 W;
- overall *conduction* losses on the *auxiliary* devices: 112 W;
- overall *switching* losses on the *main* devices: 177 W;
- overall *switching* losses on the *auxiliary* devices: 1.24 kW.

a result only slightly worse than the previous one.

Finally, the simulation results of the *soft switching* submodule *AQRDCL*, equipped with ABB 4500 V – 650 A *IGBTs* power modules for the main switches, and the Proton-Electrotex 2200 V – 500 A for the auxiliary switches, are reported:

- overall *conduction* losses on the *main* devices: 154 W;
- overall *conduction* losses on the *auxiliary* devices: 138 W;
- overall *conduction* losses on the *clamp* device: 17 W;
- overall *switching losses on the main* devices: 347 W;
- overall *switching* losses on the *auxiliary* devices: 2.23 kW;
- overall *switching* losses on the *clamp* device: 218 W.

Switching losses on thyristors used as auxiliary devices are mainly due to the *reverse recovery*.

As already stated, these results are only orientative and are based on well-defined operating conditions and with certain components. Regarding the sizes selected for the devices, these were conditioned by the fact that the major manufacturers of large components produce only a few sizes of standardized ratings for voltage and current, in particular for the *single switch* version. Nevertheless, these results suggest that the resonant soft switching solutions possess the potential to introduce significant improvements in the efficiency of the *MMC*, allowing the individual sub-modules to operate at high frequencies, unsustainable with common components in the usual hard-switching mode of operation. It must not be forgotten that, anyway, an extensive and reliable study should be based on a realistic application of the whole *MMC* converter, with well-established electrical quantities and operating conditions, taking into account the losses in the resonant inductor(s) as well as the effect of parasitic parameters, no longer negligible at high frequencies as the resonant one.

As a next step of this research it would be interesting to investigate regarding the benefits of the *soft-switching* technology using Silicon Carbide (*SiC*) devices, still under development, repeating the comparison between a *hard-switching* converter and a *soft- switching* one. At the present time, only devices with a modest voltage rating (1200 V max), are commercially available; anyway it seems likely the launching, in the short, of 3.3 kV rating devices.

IV. CONCLUSIONS

Despite their age, *soft-switching* topologies like the *ARCP* and the *AQRDCL* still show interesting properties that suggest their application in modern high power/high voltage converters like the *Modular Multilevel Converter*. Nowadays, the *MMC* conversion concept strongly attracts the interest of the Power Electronic Researchers community thanks to its flexibility and extended modularity that allows its use in the Power System area, up to the highest levels of voltage and power. Much attention is given to the application of the *MMC* as part of the efficient grid integration of renewable sources like the so-called *Off-shore Wind Farms,* and for the implementation of the *Solid State Medium Frequency Transformer*. In an effort to elevate as much as possible the conversion efficiency, particularly important aspect at the highest power levels, the use of the resonant topologies inside the *MMC* elementary converters (submodules) appear a very promising way. In this paper, the *ARCP* and the *AQRDCL* schemes have been briefly discussed, and some preliminary simulation results of their comparison with the usual *hard-switching* solution have been shown: the advantages of these resonant topologies do emerge, capable of a net knocking-down of the switching losses inside the main semiconductor devices, thus allowing an overall increase in the submodule efficiency.

Most likely, even better results can be obtainable by the development of power semiconductors - particularly *medium frequency thyristors* - capable to optimize the operation and efficiency of the resonant tank.

As a further step, investigations will be done considering converters equipped with *SiC* devices.

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