Comparison of Quasi-Two-Level Operation of a Flying Capacitor Converter with Quasi-Two-Level Operation of a Modular Multilevel Converter

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***Abstract*—Today's medium voltage converters are often multilevel converters. These converters require many large passive components. The new Quasi-Two-Level operating (Q2O) mode is intended to minimize the passive components while preserving the advantages of the multilevel topology as far as possible. This novel operation mode is investigated for the Modular Multilevel Converter (MMC) and the Flying Capacitor Converter (FCC). This paper briefly summarizes and compares the control, modulation and minimization potential of the passive components of the Q2O-mode for these two topologies. Thereby, the different topologies are introduced and compared. Finally, the advantages and disadvantages of this new mode of operation in these two topologies are discussed.**

***Index Terms*—Multilevel Converter, Modular Multilevel Converter, Flying Capacitor Converter, Quasi-Two-Level Operation, Passive Components**

I. Introduction

The applications for medium voltage converters will become more present in the grid and increase in relevance in the future. For example, inverter-based power generation systems for renewable energy are increasing in individual power and overall count. Additionally, power transmission is more and more dominated by power electronics e.g. conventional transformers are replaced by solid state transformers [1]. Today's standard medium voltage converters for these applications are either based on MMC technology with a high number of cells or on 3- or 5-level converter topologies which are operated at low switching frequencies and contain bulky line filters. Both concepts still lead to relatively high costs due to extensive use of materials for the passive components. One promising concept is the Q2O of multilevel converters to minimize the passive components. This concept has already been investigated for the MMC [2]–[5] and for FCC [6]–[13].

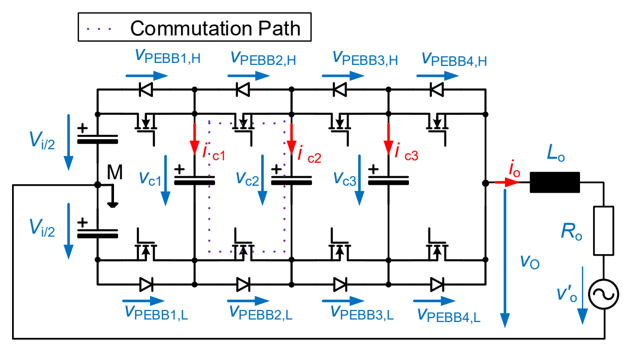

Fig. 1. 5-level FCC, single phase design [6]

In these publications, [6]–[9] show all necessary aspects of the Q2O for the FCC and [5] shows all elements of the Q2O for the MMC.

II. Topology comparison

In this section, the FCC and MMC topologies are compared and the advantages and disadvantages analyzed. The concept of FCC was first introduced in [14]. The multilevel voltage is generated by switching capacitors into the active current path. A N-level FCC ($N \in \mathbb{N}$) is build with $2 \cdot (N-1)$ power semiconductor switches and $(N-2)$ capacitors in addition to the DC link capacitor. The commutation cells of the FCC consist of one high side and one low side semiconductor and the corresponding capacitor. Since the commutation cell is the repeating circuit element, the Power Electronic Building Block (PEBB) consists of one commutation cell without the second capacitor. An exemplary 5-level FCC is shown in fig. 1.

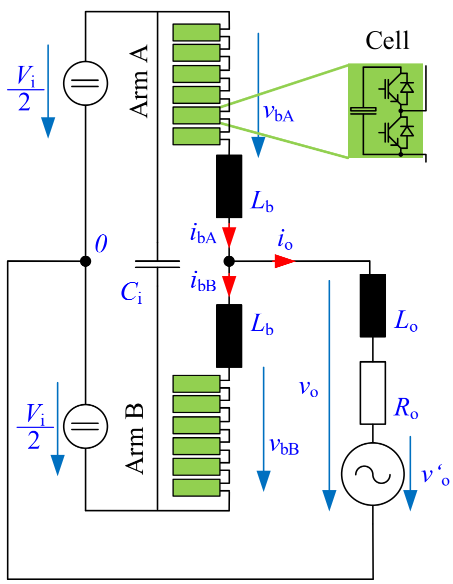

Fig. 2. MMC single phase design [5]

The concept of the MMC was first introduced in [15]. An MMC consists of two arms per phase and each arm consists of a certain amount of similar cells. Each cell acts as a switchable voltage source and the simplest design of a cell is a half bridge with a capacitor. These cells represent the PEBB's at the MMC. The structure of one phase is shown in fig. 2.

The number of output voltage levels (N) of the MMC is not as easy to determine as the ones of the FCC. The sum of the arm voltages ($v_{\mathrm{bA}} + v_{\mathrm{bB}}$) is equal to the DC input voltage V_{i}. The difference of the arm voltages ($v_{\mathrm{bA}} - v_{\mathrm{bB}}$) results in the output voltage v_{O}. A N-level output voltage of the MMC requires m_{out} cells per arm for the output voltage ($N = 2{\cdot}m\mathrm{out}{+}1$). If the DC voltage V_{i} is of the same absolute value as the maximum amplitude of the output voltage $\hat{v}_{\mathrm{O}}$, another m_{DC} cells per arm are required, which results in a total number of $m = m_{\mathrm{out}} + m_{\mathrm{DC}}$ cells per arm.

Using a 5-level output voltage as an example, the FCC requires 8 semiconductors per phase. With the MMC, two cells per arm are needed for the output voltage, and with the above assumption, two cells are needed for the DC voltage as well. In total, with 4 cells per arm, 16 semiconductors per phase are required - twice as many as for the FCC. Generally, it can be shown that with the MMC significantly more semiconductors are needed for the same number of output voltage levels than with the FCC. The number of capacitors in these topologies also differ. In this example, the FCC requires 4 capacitors per phase plus the DC-Link, the MMC requires 8 capacitors per phase because it needs significantly more cells.

Another difference between the two topologies is the voltage of the corresponding capacitors. With the MMC, the voltage of the capacitors is the same for all cells. Therefore, the isolation voltage of the individual components per cell are identical, which leads to an easier design. In the FCC, each capacitor C_i has a different nominal voltage $V_{\mathrm{c,nom},i}$.

$$V_{\mathrm{c,nom},i} = V_{\mathrm{dc}} \cdot \frac{N-1-i}{N-1} \quad i \in [1...(N-2)] \qquad (1)$$

This is due to the principle of generating the same voltages across the semiconductors. The disadvantage is that the isolation voltage of the components changes depending on their position in the inverter. The same unit can only be used for all positions, if the isolation is designed for the highest capacitor voltage of the DC-Link V_{i} of an FCC.

A fundamental difference between FCC and MMC is the current flow through the capacitors. In an FCC there are two switching states in which the output current does not flow through any of the capacitors within the topology but only through the central DC link. These are the $+\frac{V_{\mathrm{i}}}{2}$ and $-\frac{V_{\mathrm{i}}}{2}$ voltage levels used in two-level operation. With the MMC cells, there is only the possibility that the output current flows through the capacitor or not. Due to the series connection and the necessary arm voltage, the output current flows through a part of the capacitors. As mentioned above, the arm voltage must set a voltage in opposition to the input voltage, so at each state a minimum number of cells and capacitors must be connected in the current flow path. There is no output voltage level which can be used for a relevant amount of time, where the output current does not flow through any capacitors in the arms. This must be considered when minimizing the capacitors in these topologies (see section III-C).

III. Quasi-Two-Level-Operation

The basic idea of the Quasi-Two-Level operation (Q2O) is to use the multilevel topology in combination with a two-level modulation scheme. Hence, the applied control and modulation strategies are very similar to the ones used for a standard two-level converter. Additionally, the switching characteristics benefits from multilevel converters in terms of reduced $\mathrm{d}v/\mathrm{d}t$, small overvoltage stress and high number of output voltage levels can be achieved. The voltage trajectory across the output filter is comparable to the two-level modulation. Reducing $\mathrm{d}v/\mathrm{d}t$ and achieving small overvoltage stress is described in [16]. In addition to that, the further advantages of the Q2O compared to a two level topology are discussed.

A. Control structure

The Q2O attempts to control the multilevel inverter as if it were a two-level inverter. In fig. 3 the classic control structure of an output current control is shown. This structure does not change for the Q2O. Simply, the underlying control structure of the block of the converter is modified.

A more detailed schematic of this block for use in an FCC is shown in fig. 4. The structure includes the elements modulation, FCC hardware and capacitor voltage measurement. The modulation is the main feature of this novel operation and is split into the balancing algorithm (SY) and the carrier-based modulators (Mod) for the respective semiconductors. There is

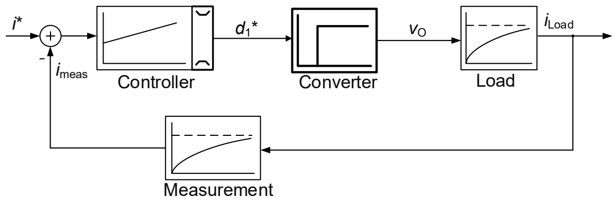

Fig. 3. Standard Two-Level Converter Control Structure

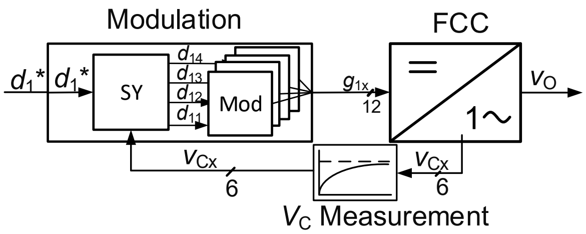

Fig. 4. Structure of the FCC with modulation and balancing [8]

only one additional loop for capacitor voltage balancing within this low level control structure.

For the MMC the structure of the block converter is shown in fig. 5 [5]. It requires more input variables than the FCC and contains more elements. This structure has two additional loops - one loop for balancing the capacitor voltages in the cells (Module Capacitor Voltage Balancing) and another loop for regulating the arm energies. The last loop contains an additional internal current control of the arm currents (see fig. 6). In summary, the structure has more elements than the Q2O control of the FCC.

B. Balancing and modulation

Since an MMC has numerous equal cells, the capacitor voltages within an arm must be equalized. In Q2O this must be achieved as well. In fig. 7 an algorithm for Q2O of MMC is shown. Depending on the number of currently necessary cells n_b^* and currently active cells, it is decided whether a cell is added or removed. Thereby, it is decided downstream, which module is switched based on the direction of the arm

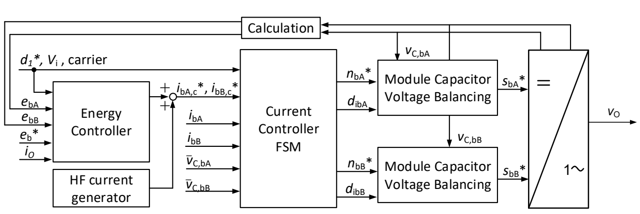

Fig. 5. High level signal structure of the MMC by Q2O [5]

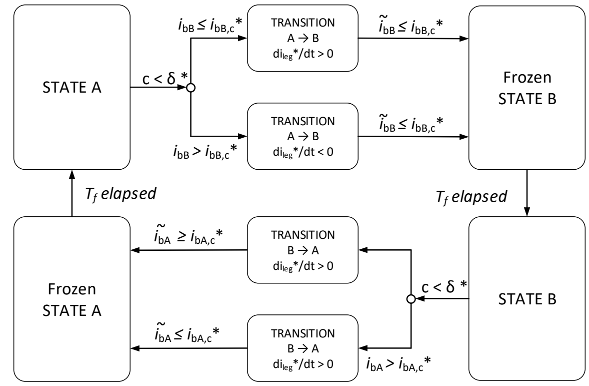

Fig. 6. The additional arm current control of the MMC (Current Controller FSM) [5]

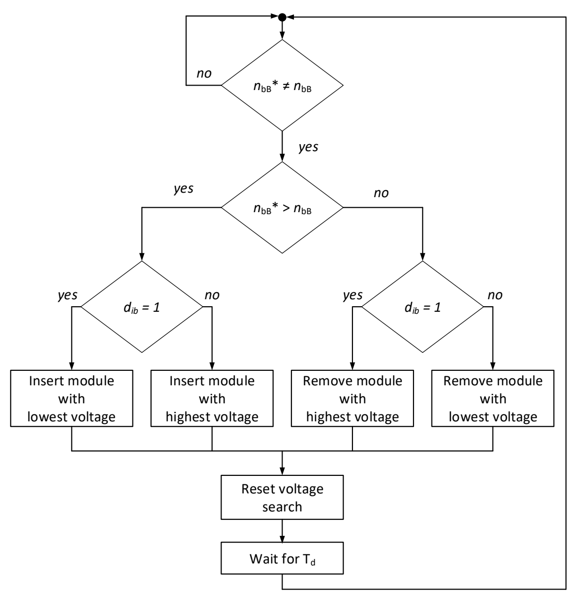

Fig. 7. Selection and balancing of the cell voltages of an arm at the MMC by Q2O [5]

current. The principle of choice is ultimately the same as for conventional operation. So in case of positive current and too many cells in the arm, the cell with the highest capacitor voltage is switched out. In contrast to conventional modulation the sequence of sorting is not executed at the switching times, but at intervals of T_d. The time T_d of possible switching events. The time T_d is the time distance between possible switching operations of the MMC cells. Thus, in the Q2O of the MMC, the possible switching end times of a cell are decoupled from the modulation period for the quasi-two-level voltage. These sorting intervals are much smaller than the period of the two-level output-voltage T_f ($T_\mathrm{d} << T_\mathrm{f}$).

A main goal of for the Q2O is the reduction of the overvoltage. To achieve minimal overvoltage, only one PEBB is allowed to change state per switching state transition in

Q2O. Thus, the commutation circuit is within one PEBB and therefore as small as possible. This results in a restriction on the balancing algorithm of the FCC.

In fig. 8 the switching scheme of a single-phase 5-level FCC is shown with the aforementioned restriction. The capacitor current i_{cx} is positive if the output current i_o flows in the same direction. It can be seen that in the voltage steps between $+\frac{V_{dc}}{2}$ and $-\frac{V_{dc}}{2}$ any current flow through the respective capacitor is possible in positive as well as in negative direction. At the voltage levels $+\frac{V_{dc}}{2}$ (state HHHH) and $-\frac{V_{dc}}{2}$ (state LLLL), the output current does not flow through any of the capacitors.

The balancing methods published so far can be divided into two methods: The first method [10], [11] has a fixed switching sequence and varies t_p, i.e. the time an intermediate voltage is active. However, t_p must always be greater than the switching time t_s of the semiconductor to achieve multiple levels. The second method, formulated and investigated in the authors' previous work [6], varies the switching sequence while t_p is fixed. In [17], a combination of these two methods was presented.

Once the switching sequence and holding time t_{pi} for each level have been identified, the final step is to calculate the individual duty cycles of each PEBB. The individual duty cycles are given to the individual sine-triangle modulators, each of which is directly assigned to a PEBB. The principle is shown in fig. 9. The balancing and modulation of the Q2O of the FCC is more complex than that of the Q2O of the MMC, since the balancing must take into account the restrictions of the different capacitor voltage levels and the predefined sequences from the switching state chart. Furthermore, the complexity of balancing does not increase linearly with the number of output voltage levels. The number of possible switching states increases with 2^{N-1}. Therefore, the technically reasonable limit is in the range of 9 output voltage levels, because there is no simple mathematically describable combination problem behind it. Due to the simpler balancing and sorting, the number of output voltage levels of an MMC is not limited by computational resources.

C. Smaller passive components

The components, which are primarily reduced in the Q2O with the multilevel converters, are the capacitors or more specifically their capacitance. The power semiconductors cannot be altered compared to conventional operation and the design of the output filters does not differ with the same number of effective output voltage levels and modulation frequency.

The formula for calculating the capacity C_{Q2O} at the Q2O of the FCC is eq. (2).

$$C_{Q2O} = \frac{t_{CC} \cdot \hat{i}_o}{\Delta V_{c,max}} \quad (2)$$

Here $\Delta V_{c,max}$ is selected in the range of 10% to 20% of $V_{com,nom}$. It is in eq. (3) defined.

$$V_{com,nom} = \frac{V_{dc}}{N-1} \quad (3)$$

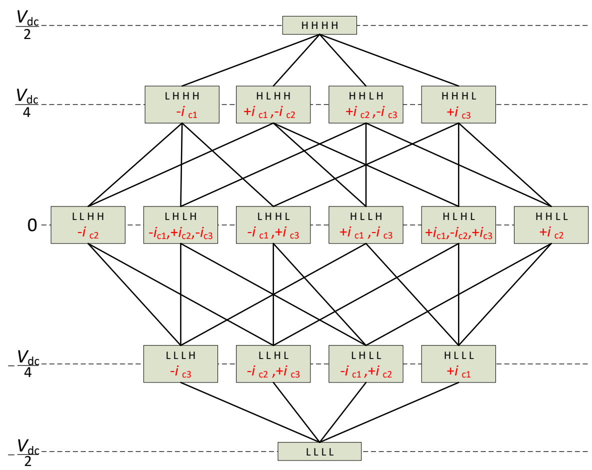

Fig. 8. Switching state chart for a 5-level flying capacitor [7]

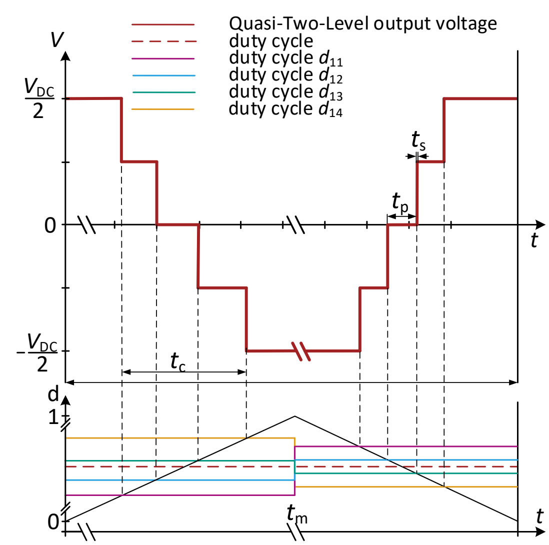

Fig. 9. Carrier-based modulation with balancing of the Q2O at FCC [7]

The maximum output current $\hat{i}_o$ is determined from the total system. The conduction time of one capacitor t_{CC} is determined based on the balancing algorithm. It varies between t_p and t_C.

The mechanism for reducing the capacitance is to realize t_{CC} as small as possible. This can be achieved by using fast switching semiconductors for the Q2O, so that t_s is small and t_p resp. t_c becomes small. The reduction in size is primarily due to the ratio of $\frac{t_{CC}}{t_M}$, i.e., the shortened conduction time of the capacitors. With fast switching semiconductors such as SiC, reductions in the range 10 to 100 are possible.

For MMC, the choice of minimum capacitance is subject to other dependencies. According to [5], the capacitance can be calculated with eq. (4) for the Q2O.

$$C_{\mathrm{mod}} = k_{\mathrm{e}} \cdot \frac{2}{V_{\mathrm{C,max}}^2 - V_{\mathrm{C,min}}^2} \cdot \left(\frac{\Delta e_{\mathrm{b,max}}}{n_{\mathrm{mpb}}} + \Delta e_{\mathrm{mod,d,max}}\right) \quad (4)$$

Here, as with the FCC, the capacitance depends on the allowable capacitor voltage change ΔV_{C}. However, for the MMC, it is expressed as the maximum allowable change in energy $V_{\mathrm{C,max}}^2 - V_{\mathrm{C,min}}^2$. Further, the capacity depends on the maximum change in arm energy $\Delta e_{\mathrm{b,max}}$ and the change of energy within one cell of the arm $\Delta e_{\mathrm{mod,d,max}}$ due to the successive switching of the modules at Q2O.

The component of the maximum arm energy variation $\Delta e_{\mathrm{b,max}}$ can be calculated with eq. (5) [5].

$$\Delta e_{\mathrm{b,max}} = \frac{1}{2} \cdot L_{\mathrm{b}} \cdot (\hat{i}_{\mathrm{O,max}} + I_{\mathrm{b,c,max}})^2 \quad (5)$$

The influencing factors are the maximum output current $\hat{i}_{\mathrm{O,max}}$ and the permissible current between the arms $I_{\mathrm{b,c,max}}$ for balancing. Up to 60% of the output current is chosen as the allowable current between arms for balancing. With FCC, the output current is also an influencing factor for the capacitance design. There exists no additional current for the balancing by the FCC. In addition, for MMC the arm energy variation depends on the arm inductance , which can be estimated with eq. (6) [5].

$$L_{\mathrm{b}} \leq \frac{1 - \delta_{\mathrm{max}}}{f_{\mathrm{PWM}}} \cdot V_{\mathrm{i}} \cdot \frac{I_{\mathrm{b,c,max}}}{(i_{\mathrm{O,max}} + \frac{I_{\mathrm{b,c,max}}}{\frac{1+\delta_{\mathrm{max}}}{2}})^2} \quad (6)$$

The arm inductance L_{b} depends on the selected modulation frequency $f_{\mathrm{PWM}} = \frac{1}{T_{\mathrm{d}}}$ and the maximum duty-cycle δ_{max} as well as the output current $i_{\mathrm{O,max}}$ and the allowed current between the arms $I_{\mathrm{b,c,max}}$. Thus, there is a coupled dependence in the influence of the arm energy fluctuation.

The energy fluctuation of the cells within an arm $\Delta e_{\mathrm{mod,d,max}}$ can be determined by eq. (7) [5].

$$\Delta e_{\mathrm{mod,d,max}} = (n_{\mathrm{mpb}} - 1) \cdot T_{\mathrm{d}} \cdot V_{\mathrm{C,max}} \cdot (\hat{i}_{\mathrm{O,max}} + I_{\mathrm{b,c,max}}) \quad (7)$$

The dependencies are the number of cells per arm n_{mpb}, i.e. the number of possible modulation times T_{d} for the single cell, the actual modulation time T_{d}, the maximum capacitor voltage $V_{\mathrm{C,max}}$ and the current dependency of $\hat{i}_{\mathrm{O,max}} + I_{\mathrm{b,c,max}}$. For the FCC at the Q2O there is also a dependence of the capacitance on the number of cells or capacitors, depending on the balancing algorithm. The dependence on the modulation time T_{d} does not exist. For the MMC in Q2O there is a coupling of the sorting with the switching frequency of the cells, i.e. semiconductors. The larger the switching frequency of each cell can be, the smaller T_{d} can be selected.

The capacitance of the MMC in Q2O can be reduced by 10- to 100-times compared to conventional operation [3].

Besides Q2O, there are also other approaches to reduce the energy pulsation , e.g. using optimized arm current trajectories. [19]. However, the reduction is not in the same range as with the Q2O of the MMC , but it must be noted that the approach in [19] is used for a sinusoidal output with high voltage quality instead of a two-level voltage achieved by Q2O.

In summary, different dependencies exist for the minimization of capacities in these topologies at the Q2O. At the FCC t_{CC} is the time how long current flows through the capacitors during switching. With MMC, there is a dependence on the switching frequency or modulation frequency T_{d}, which defines the duration of how long current flows through the capacitors of the individual cells.

D. *Overview of validation*

The validation of the Q2O is still ongoing research. There are many simulative investigations with the Q2O. The verification has been shown so far only with prototypes. One application, which has been proposed in research, has not actually been realized. At the MMC with Q2O in [5] measurement results of a low voltage prototype were published. Simulation results of different aspects were presented in [2], [4], [20]–[22].

For the FCC with Q2O, things are a little different. Several researchers have already presented measurement results with low voltage and medium voltage prototypes. In [7], [12], [17], measurement results were presented with low-voltage, 5-level FCC prototypes. Measurement results with a 3-level prototype for medium voltage were published in [18]. For a three-phase full scale 7-level FCC, the power electronic building block was described in [9] and the complete three-phase converter system was described in [8] with measurement results at medium voltage. Simulation results of the different balancing algorithms were presented in [6], [7], [10], [11], [17]. In addition, a design process of a fullscale converter for a 40 kV application was executed in [11]. It should be noticed in this overview that an FCC prototype is easier to build. It can be built in single phase design. However, the MMC in conventional operation is a more often built topology than the FCC which is nearly not used commercially.

IV. SUMMARY

Due to the topology, the MMC is better suited for larger numbers of voltage levels and also for larger voltage ranges. With the FCC, the number of voltage levels and the voltage range is limited due to the different isolation voltages required. On the other hand, the control structure of the FCC is much easier to realize. For the MMC, more measurement variables are required for operation than for the FCC, since all capacitor voltages and the individual arm currents must be measured. Furthermore, more cells including capacitors and semiconductors are required for the same number of output voltage levels.

The balancing and modulation of Q2O by FCC is more complex, because the restrictions of the switching state chart with the different states and possible switching sequences must be taken into account. When reducing the capacitance of the capacitors in the Q2O of the FCC, the switching time of the semiconductors is decisive. In contrast, the switching frequency has no influence. This allows the advantages of fast-switching semiconductors such as silicon carbide to be used. With the same losses of the semiconductors, a higher switching frequency can be realized or a higher efficiency can be achieved with the same switching frequency. In the case of the Q2O of the MMC, the reduction in capacity and the increase in efficiency are not so easy to separate. Another disadvantage of the Q2O of the MMC is that there is no natural power balancing between the individual phases of a three-phase system. This must be achieved with the control of the MMC. With the FCC, this is achieved by the central DC link. The FCC's Q2O has a clear advantage in the output voltage range with small output voltage level numbers ($N \leq 9$). For larger voltage step numbers or higher output voltage ranges, the MMC would have a clear advantage.

V. Conclusion

The two most commonly studied converter topologies for Quasi-two-level operation - MMC and FCC - are compared and differences elaborated. The topological differences are highlighted with clear advantages and disadvantages for different voltage ranges and numbers of voltage stages. The control structures are compared with each other, where it is visible that the control structure of the FCC is clearly more compact and easier. The modulation and balancing has been described. The balancing algorithms of the capacitor voltages for the FCC is more difficult than for the MMC. The mechanisms for reducing the capacitance of the capacitors were analyzed and compared for both topologies. Based on the various comparisons, the Q2O of the FCC is deemed superior to the one of the MMC in the voltage range, where an FCC can be operated with the technically possible number of voltage levels. With the FCC, fewer semiconductors are required for the same number of output voltage levels. Furthermore, the FCC can take advantage of fast switching semiconductors to reduce the capacity of the capacitors. Independently of this, the switching frequency of the FCC can be selected with Q2O in such a way that the efficiency and the output filter are optimized.

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