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Energy balancing in modular multilevel converter systems

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Abstract. The modular multilevel converter (MMC) is a well-known solution for medium and high voltage high power converter systems. This paper deals with energy balancing of MMCs. The analysis includes multi-converter systems. In order to provide clear view, the MMC control system is divided into hierarchical levels. Details of control and balancing methods are discussed for each level separately. Finally, experimental results, based on multi-converter test setup, are presented.

Key words: MMC, multilevel converters, energy balancing, control of power electronic converters.

1. Introduction

The modular multilevel converter, also-called MMC, M2LC or chain link converter, is a widely used solution for medium and high voltage high power converter systems. MMC provides a number of advantages, including high quality and multilevel waveforms of terminal voltage, even for low switching frequency applied to each semiconductor. High reliability of the system is ensured thanks to redundancy applied already on the cell level. The converter might be easily scaled in voltage, just by series connection of additional cells. In many cases fault blocking capability is a major requirement, which is fulfilled by some of MMC topologies. Using the same modules connected into different topologies and using different control schemes, various functions might be realized, including voltage source, current source, STATCOM, active filter and many others.

However, MMC requires more sophisticated control in comparison with standard converters, e.g. two-level voltage source inverter. The key challenge is to keep local DC-links in all cells equally charged (balanced) under various operation conditions, including fault conditions. A number of publications have dealt with balancing methods for MMC. A basic control scheme for MMC was proposed in [1] for AC-DC conversion and in [2] for direct AC-AC conversion. Balancing and stabilizing MMC branches is described in [3]. Balancing the whole converter was discussed in [4] on the example of series and parallel connection. Stable and reliable operation of MMC is also ensured by proper design of the power circuit, often done by numerical simulations based on an averaged model. This topic is addressed in [5].

In this paper, energy balancing of the modular multilevel converters system is discussed. In Section 2, a short overview on MMC topologies is provided. Section 3 describes control levels of MMC. Each level is described in detail, with focus on balancing methods applied on a specific control level. The experimental setup is described in Section 4 and the experimental results obtained for the multi-converter system are discussed in Section 5. Finally, the summary is presented in Section 6.

2. Basic MMC topologies

The basic concept of MMC has been described more than a decade ago by Lesnicar and Marquardt [1]. In that paper, a three-phase to one-phase AC-DC-AC MMC was presented. Since intermediate DC stage was used, one may consider it as connection of two AC-DC converters. The AC-DC converter consists of a number of so-called branches, connecting each input phase with positive and negative output terminal. Each branch is composed of sub-modules or cells. In this approach, MMC is similar to so-called cascaded converters presented earlier [6, 7]. The key differences are in how those converters are supplied and how cell voltage is controlled. Cascaded converters (AC-DC-AC) use multiple winding transformer to feed each cell individually. Cell voltage is determined by transformer secondary voltage. MMC (AC-DC-AC) cells are not supplied from external source. Cells voltages are actively regulated by proper control algorithms in the general case.

A direct AC-AC converter was introduced later by Marquardt [2]. This topology was somehow similar to Matrix converter in the way that each input phase is directly connected with each of output phases. The direct converter is based on so-called full-bridge cells (Fig. 3). Those cells may generate bipolar voltage at cell terminals. An interesting three-phase direct AC-AC topology, so-called Hexverter, is presented by Baruschka [8]. This converter only has six branches and potentially, fewer modules are needed as compared to direct AC-AC solutions with nine branches described by Marquardt [2] and Oates [9].

Based on these basic topologies, various modifications were proposed, especially for DC-DC conversion. One of the most typical solutions for the DC-DC conversion system is based on indirect DC-AC-DC conversion scheme. The AC link is

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equipped with transformer for galvanic insulation between input and output. This solution is presented by Kenzelmann [10], Luth [11] and Baruschka [12].

One of the possible modifications in AC-DC-AC indirect converter is the replacement of DC-link by the AC-link. It allows for implementation of galvanic insulation and connection of different voltages and currents at the input and the output (implementation of a transformer's turn to turn ratio). The transformer construction can be one-phase [10] or three-phase [12]. The so-called reduced MMC is introduced in [12]. Back to back connection of two reduced converters leads to obtaining a DC-DC converter with transformer isolation. The so-called three-string architecture DC-MMC [13] and polyphase cascaded cell [14] are good examples of direct DC-DC conversion using MMC submodules. The so-called triangular MMC, a non-isolated DC-DC converter utilizing MMC submodules, is presented in [15]. Yet another direct DC-DC converter is discussed in [16] and [17], with double wye or T connected branches enabling conversion without the intermediate stage. Figure 1 presents the overview of selected MMC topologies cited in the introduction. A more detailed overview of existing MMC topologies is provided in [18] and [19].

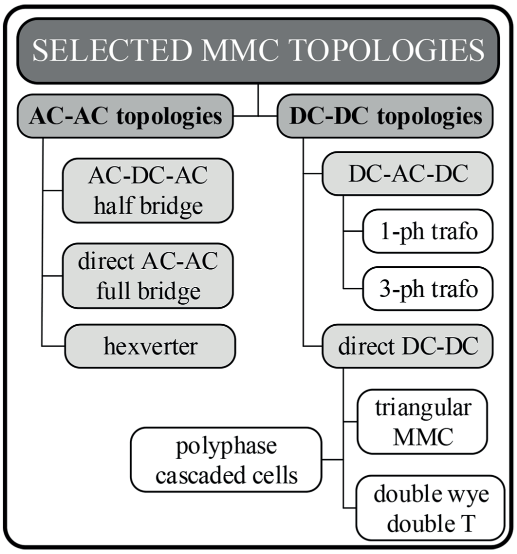

Fig. 1. The classification of selected MMC topologies

3. Balancing levels

MMC control system can be divided into several layers. For each layer, a separate balancing module is required. At the A-level, the cell balancing module is responsible for keeping voltages of every cell capacitor in the branch on the same level. At the B-level, the branch energy balancing is implemented. As a result, stabilization of the average value of voltages of cell capacitors in the branch is achieved. For the C-level, a converter energy balancing responsible for keeping nominal energy at required level. For the top D-level, a system energy balancing is required – if the system is built with more than one converter.

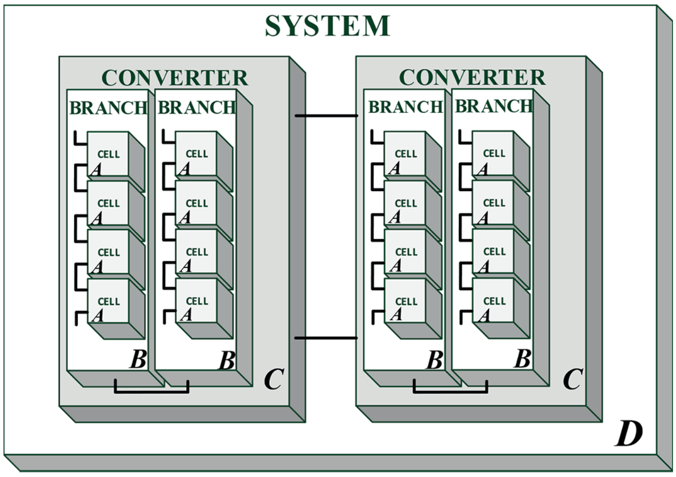

Fig. 2. Control levels in the MMC converter system. A – cell level, B – branch level, C – converter level, D – system level

Each of the balancing modules is described in this section.

3.1. Cell energy balancing. The fundamental building block of every MMC topology is a single cell (Fig. 3). Typically it comprises an inverter stage, based on half-bridge or full-bridge topology, which is connected with the capacitor C. For the half bridge only zero and positive voltage can be generated. Full bridge also allows to generate the negative voltage, therefore it can be used e.g. for direct AC-AC conversion, where the voltage between the terminals can be either positive or negative.

Cells connected in series create a branch which is able to generate a multilevel voltage (Fig. 4). Common modulation

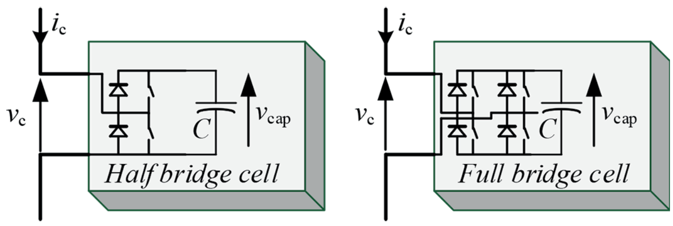

Fig. 3. Simplified internal structure of the single cell

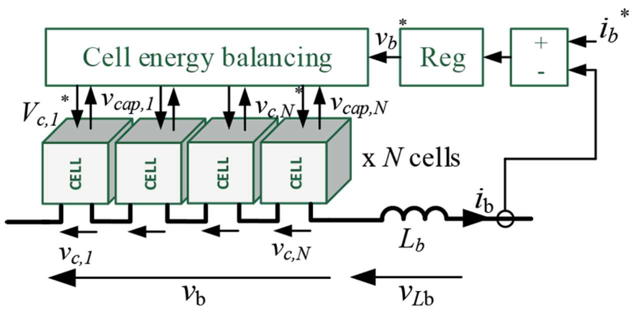

Fig. 4. Simplified structure of the single branch

strategy for such structure is PS-SPWM [20], where carriers between the cells are phase shifted by the certain value, which depends on the number of cells in the branch. Another common technique is called the nearest level modulation (NLM). This method is suitable for MMC with a large number of cells in the branch, and functionally, it is an equivalent of one-dimensional space vector modulation [21].

Branch current controllability is achieved by introducing the connected branch inductor L_b in series. Current controller tracks the reference value of the branch current i_b^* by the control of the value of the branch voltage v_b^*.

In steady state, the average value of the capacitor voltage v_{cap} in every cell in the branch should be stabilized at the same reference value. In MMC topologies, DC-links of the cells are not supplied from the external power supply. It means that voltages of the DC-link capacitors are controlled only by changing the branch current and output voltages of cells in the branch.

The basic balancing strategy has been presented by Marquardt [1] and can be used to determine which modules should be turned on in a specific time stamp. It works well for so-called direct-switching MMC. However, for high frequency switching systems, instead of using sorting algorithm, a "continuous" control loop can be applied [22].

From the analysis of the energy balance of the single cell, it may be concluded that in order to keep capacitor average voltage at constant level, output active power of the cell P_c must be equal to the total power losses $P_{c\,loss}$ of the cell (1).

$$P_c = \frac{1}{T}\int_0^T v_c \cdot i_c dt = P_{c\,loss} \tag{1}$$

Fulfilling requirement (1) for all cells in the branch cannot impact the generated output branch voltage v_b. It must be equal to the reference value v_b^* in order to keep the branch current regulator operating properly. Voltage v_b is equal to the sum of the voltages generated by all N cells in the structure:

$$v_b = \sum_{k=1}^{N} v_{c,\,k}. \tag{2}$$

It is desired that branch voltage is equally distributed among the cells. Then, reference value for k-cell output voltage equals:

$$v_{c,\,k}^* = \frac{1}{N} v_b^*. \tag{3}$$

Unfortunately, (3) is correct only in a converter with ideal and identical cells. In reality, losses of the cells are not equal to each other. Cells are connected in series, so they conduct the same branch current i_b. According to (1), it means that for different $P_{c,\,k\,loss}$, output voltages of particular cells must diverse. Reference output voltage of the k-cell may be written as a sum of two components:

$$v_{c,\,k}^* = \frac{1}{N} v_b^* + \Delta v_k \tag{4}$$

Reference $v_{c,\,k}^*$ with additional balancing voltage Δv_k, which differs for each cell, must fulfill requirement (1) for active power of the cell:

$$P_{c,\,k} = \frac{1}{T}\int_0^T \left(\frac{1}{N} v_b^* + \Delta v_k\right) \cdot i_b^* dt = P_{c,\,k\,loss}. \tag{5}$$

Based on (2), it can be concluded that total sum of Δv_k in the branch must be equal to zero:

$$\sum_{k=1}^{N} \Delta v_k = 0. \tag{6}$$

One of the methods for obtaining Δv_k values while fulfilling requirements (5) and (6) is based on the measurement of voltages of the cell capacitors v_{cap}:

$$\Delta v_k = K_p \cdot (v_{cap,\,k} - v_{cap\,avg}) \cdot sing(i_b). \tag{7}$$

Value of the Δv_k is proportional to the error between the k-cell capacitor voltage and average capacitor voltage, which is calculated for all cells in the branch. The sign of the voltage Δv_k depends on the branch current polarization. With such a method, quasi-distributed cell balancing is possible. Internal controller in the cell only needs information about average value of the DC-link voltages in the branch for proper balancing. Relationship (7) meets requirement (6):

$$\begin{aligned} \sum_{k=1}^{N} \Delta v_k &= K_p sing(i_b) \sum_{k=1}^{N} (v_{cap,k} - v_{cap\,avg}) = \\ &= K_p sing(i_b)\left(\sum_{k=1}^{N} v_{cap,k} - \sum_{k=1}^{N}\left(\frac{1}{N}\sum_{k=1}^{N} v_{cap,k}\right)\right) = \\ &= K_p sing(i_b)\left(\sum_{k=1}^{N} v_{cap,k} - N\frac{1}{N}\sum_{k=1}^{N} v_{cap,k}\right) = 0 \end{aligned} \tag{8}$$

3.2. Branch energy balancing. Cell energy balancing is a topology independent, i.e. for every topology the control is identical. For the branch level, the balancing is more challenging – depending on the topology different scenarios are valid. If the presented topology has independent internal current loops, the circulating current can be applied. Unfortunately, for some topologies loops do not exist (e.g. STATCOM star connection). In that case, branch energy balancing without affecting the terminal quantities is not possible – the only way to balance is to have influence on the common mode voltage.

The topology is crucial for the branch balancing. Operation mode (voltage source mode or current source mode) or function (active rectifier or inverter) are not taken into account. It means that e.g. branch energy balancing is defined for 3–2 topology (three terminals on one side, two on the other side of the electric circuit), and it can be used in every operation or functional mode of that topology.

In this paper, balancing for 3–2 topology is presented. Detailed description of the balancing method (including matrix transformations) can be found in [3].

The ideal branch energy balancing has no impact on the terminal voltages and currents. Therefore, in order to be able to balance the branch energy, an extra degree or degrees of freedom (DOF) are required. Each DOF can be treated as an independent current loop within the branches. For 3–2 topology, two loops can be distinguished, which may be proved graphically or by Kirchhoff's current law (KCL) by calculating number of nodes versus number of terminals [23]:

$$n_l = b - n + 1, \tag{9}$$

where n_l is number of independent loops, b is number of branches and n is number of nodes which is equal:

$$n_l = 6 - 5 + 1 = 2. \tag{10}$$

Therefore, 3–2 topology has two independent loops in which circulating current can be applied.

Additional DOF can be found in the voltage. If it is allowed to introduce common mode voltage, an extra DOF is present. However, in some application the common mode is not allowed and it should be controlled to stay at zero level.

The balancing approach is based on the theorem that average capacitor voltage stored in a branch correlates with the total energy stored in the capacitors.

The derivative of the energy is branch power [3]:

$$\dot{e_b} = p_b = v_b i_b. \tag{11}$$

It must be stated that fundamental power component is defined by v_b and i_b, which means it cannot be used for the balancing purpose – it is determined by voltages and currents on the converter's terminals. Luckily, there is some freedom in the branch references, which allows to create a feed-forward branch energy control using those references. For example, DC link current can be distributed equally within the branches, but it does not have to. That degree of freedom allows to construct v_b, i_b waveforms, provided that the branch energy is stable during the steady state. For that purpose, neglecting losses in the branch, v_b, i_b are chosen to satisfy the equation:

$$e_b = \int_0^T p_b = \int_0^T {v_b}^* \cdot {i_b}^* dt = 0. \tag{12}$$

Example references satisfying that constrain are:

$${v_b}^* = \left(\frac{1}{2} - \frac{m}{2}\sin(\omega t)\right) \cdot U_{nom} \tag{13}$$

$${i_b}^* = \frac{m\cos(\phi_u) + 2\sin(\omega t + \phi_u) + \cos(2\omega t + \phi_U)}{4} \cdot I_{nom} \tag{14}$$

where ${v_b}^*$ is a sinusoidal branch reference and ${i_b}^*$ is a current reference with sinusoidal, 2nd harmonic and DC component; m is a modulation index ($-1 \le m \le 1$), ω is a base angular frequency, ϕ_u is a phase shift between current and voltage and U_{nom}, I_{nom} are nominal values for voltage and current. Figure 5 presents voltage/current waveform and numerical integral of the accumulated power for those waveforms.

Atop of the fundamental references, a feedback controller input can be added. The simplest control is a P-controller which defines output power change as:

$$\Delta p_b = K \Delta e_b. \tag{15}$$

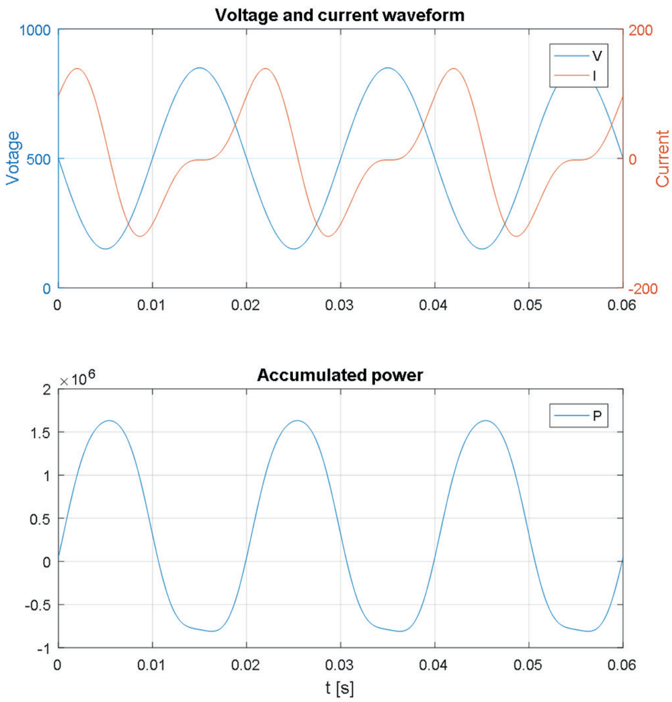

Fig. 5. Numerical integral of the accumulated power. Calculations based on equations (13) and (14) for: $m = 0.7$, $\omega = 2\pi \cdot 50$, $\phi = -30°$, $I_{max} = 200$, $V_{max} = 1000$

The Δe_b is a difference between branch energy and the average branch energy within the converters.

As it was already stated, the branch energy can be influenced by change of the voltage and the current:

$$\Delta\dot{e_b} = \Delta p_b = \Delta i_b \cdot u_b + i_b \cdot \Delta u_b + \Delta i_b \cdot \Delta u_b. \tag{16}$$

For $\Delta i_b \ll i_b$ and $\Delta u_b \ll u_b$, the last component can be ignored, which leads to:

$$\Delta\dot{e_b} = \Delta p_b = \Delta i_b \cdot u_b + i_b. \tag{17}$$

For proportional controller, feedback control changes are equal:

$$\Delta i_b = \frac{-K_i \Delta e_b}{u_b} \tag{18}$$

$$\Delta u_b = \frac{-K_u \Delta e_b}{i_b}. \tag{19}$$

That gives an infinite reference for $u_b = 0$ or $i_b = 0$, which is of course not possible to achieve and which breaks the assumption that $\Delta i_b \ll i_b$ and $\Delta u_b \ll u_b$.

Therefore, references are scaled by u_b^2 and i_b^2 coefficients respectively, which gives:

$$\Delta i_b = -K_i u_b \Delta e_b, \tag{20}$$

$$\Delta u_b = -K_u i_b \Delta e_b. \tag{21}$$

Unfortunately, this manipulation breaks the assumption that introducing Δi_b and Δu_b has no influence on the voltages and currents of the system terminal.

The next step is to map the branch references into a subspace of the branch voltages/currents which is orthogonal to the voltages and currents of the terminal, which has been described in [3]. In the mentioned paper, it is proved that balancing is possible to realize for the 3–2 topology even without common mode voltage introduction.

3.3. Converter energy balancing. Converter energy balancing, also known as converter energy control (CEC), is a control loop responsible for keeping defined energy set-point for the whole converter. Since the stored energy is proportional to the capacitor voltage, it might be stated that CEC is responsible for keeping capacitor voltages on a specific level.

CEC is crucial not only for steady state operation or for transients, but also for the charging sequence when the whole converter is charging up, which is realized by ramping up the reference voltage from zero to the nominal level.

The energy control module is realized by setting terminal current references. Depending on the control scenario, DC or AC active current is given as an output reference of the controller. Particularly for active rectifier mode, DC current is defined by the load. Therefore, energy controller is setting active current reference (positive for charging up the converter and negative for discharging). For an inverter mode, the AC current is defined by the load, so the energy controller is setting DC current reference to charge or discharge the converter.

Feedback for converter energy control is average capacitor voltage or total stored energy, which is compared with a nominal (set-point) voltage or energy. The error is given to PI controller which gives ΔE as the output. Next, ΔE is scaled either to active or DC link current reference. The crucial issue is to provide correct limits for the current. With no limitation, the grid can be altered easily. A good practice is to have two different limits – the first, for a charging when a big error on the controller input is expected. In this case, current should be limited to the value which can be drained from the grid in a long time ($>$1 s). The second limit is set for normal operation, when expected error is quite low, but the expected dynamics is much higher than during the charging. Charging can be a slow process, but time response in the nominal operation should be very fast (e.g. to provide fault current limiting) [24].

The reference given as a voltage is more intuitive due to the fact that the rating of a converter can be easily related to the cell's nominal voltage and number of cells.

Cell nominal voltage can vary during the operation on the system. It might be required to decrease the converter nominal rating to limit the voltage ripple. For example for 1 kV/cell, a 1 kV voltage ripple in the output is visible. If the nominal voltage is decreased twice, the ripple will be two times lower as well. Unfortunately, in that case the maximum voltage on the output terminals is limited as well. This operation mode is named limited cell voltage.

The converter's nominal voltage can also be increased, e.g. to increase the operation range (maximum output voltage). This feature can also be used to provide redundancy in the system (when one converter is out of order, others will increase their rating to keep the system's power range on the same level).

Apart from the feedback control, a feed forward can be applied. Feed forward loop uses AC or DC link measurements and references to calculate the power or energy required for this specific operation point. For example in active rectifier voltage source mode, DC link current measurement and DC link voltage reference defines the power which would be transferred from the converter to the DC side. To keep the converter stable, the same amount of energy should be drained from AC link, so AC active current reference (for feed-forward path) is equal:

$$I_{a,FF} = \frac{2}{3} \cdot \frac{(V_{DC} \cdot I_{DC})}{V_d}. \tag{22}$$

A similar approach can be used to implement a feed-forward control for the inverter operation mode.

3.4. System energy balancing. For multi-converter operation (more than one separate MMC unit with its own control system and its own balancing on levels A, B, C), a master controller is required. One of its functions is to share the references between all converters to achieve the specified set-point. Sharing does not have to be symmetrical, and this phenomenon is used to implement power sharing between modules.

Depending on the system-level topology and operation mode, balancing of the system might be required. Even if it is not required for some topology or operation mode combinations, it is implemented for all to provide control system integrity.

The information whether the balancing is required is presented in the Table 1.

Table 1
Operation mode / system configuration matrix specifying if the balancing is required, *Ns*-converters in series, *Np*-converters in parallel

Operation mode system configuration	Voltage source mode	Current source mode
Single unit	no	no
$Ns > 1, Np = 1$	no	yes
$Np > 1, Ns = 1$	yes	no
$Ns > 1, Np > 1$	yes	yes

System energy control for the rectifier-inverter system can also be applied. It is not required, but its presence increases the system dynamic behavior (lower voltage dip/sag on DC link is visible during the transient as the reference change).

System energy balancing is quite similar to the low-level cell energy balancing, however its dynamics is much lower (time constant $>$1 s), the used controller has integral part (PI) and it must support series/parallel connections.

In the balancing algorithm, the converter's voltage is compared with the average converter's voltage in the branch (reference). The error is send to PI controller. The critical issue is to define which converter belongs to which branch.

For more than one converter in series $(Ns > 1)$ and more than one converter in parallel $(Np > 1)$ in series-parallel configuration, a cascaded control is required. First the energy is shared between parallel branches. Next, each parallel branch is treated separately in a reference distribution (series connected converters). The schematic of $Ns = 2$, $Np = 2$ configuration is shown in Fig. 6. In that example, a system works in current source with parallel energy sharing. The energy is shared between the branches and within a branch by using specific references for series and parallel balancing [25]. A simplified energy sharing algorithm is presented in Fig. 7. The upper part shows references calculated for Converter 1 and 3 (one of parallel branches), and the bottom part shows references calculated for second parallel branch (Converter 2 and 4). Upper PI controller calculates $\Delta V/\Delta I$ (depending on whether the system works in voltage or current source mode). This quantity balances voltage between two converters in series. The lower PI controller is responsible for current sharing between two parallel branches.

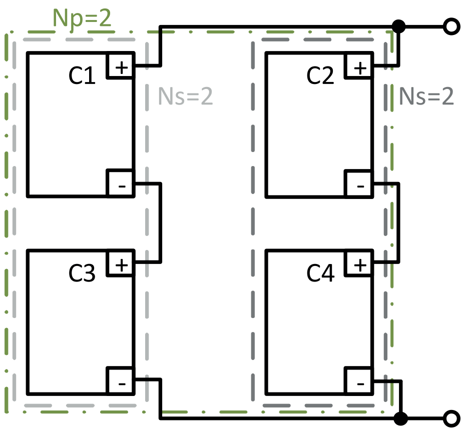

Fig. 6. Series parallel configuration of the MMS converters

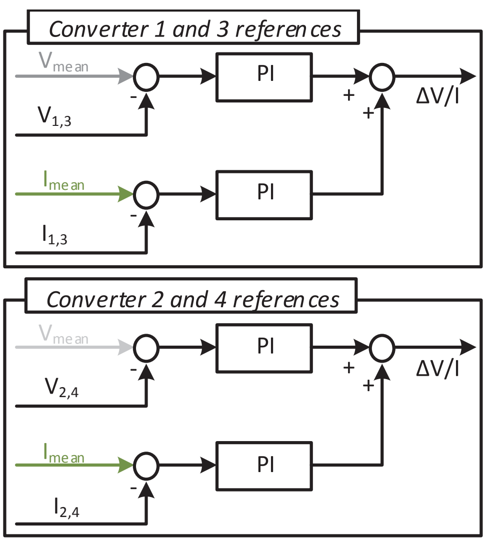

Fig. 7. Energy sharing workflow

The total output, which is a sum of two PI controller outputs, is finally added to a fundamental reference, which is given (for symmetric power sharing) as:

$$V_{ref,\ fun} = \frac{V_{ref}}{n_s} \tag{23}$$

$$I_{ref,\ fun} = \frac{I_{ref}}{n_p}, \tag{24}$$

where (23) is valid for voltage source mode, and (24) is valid for current source mode; V, $I_{ref,\ fun}$ are fundamental references depending on external references which define required terminal voltage or current and the number of series or parallel converters in the system.

Since this control is relatively slow (time constant defined in seconds), it was stated that PI controller has the same settings for voltage and current source mode, and only a simple scaling has been provided to obtain the same dynamics for voltage or current reference:

$$k_{scale} = \frac{V_{nom}}{I_{nom}} = \frac{6000\ V}{200\ A} = 30\ \frac{V}{A}. \tag{25}$$

It must be highlighted that this control is non time-critical and it is suitable only for steady state operation. During transients, symmetric power sharing is not as critical as the system dynamics.

4. Experimental setup

Energy balancing methodology was verified in the prototype multi-converter MMC system (Fig. 8). The system was built with two 1.25 MW active rectifier MMC units in 3–2 topology, which are connected back-to-back. Converters are supplied from three-phase MV/LV transformer with converter start-up unit (resistors for passive charging of cell capacitors).

With this setup, power may circulate between the converters, and power losses must be provided only from the supply grid. Single active rectifier consists of six branches, each with six full bridge cells connected in series. Reference voltage for cell capacitor voltage equals 1000 V. Single unit is able to generate +/−6 kV DC voltage. DC output current of the converter may reach 210 A.

Cells switch with 2 kHz frequency, which gives effectively 12 kHz per branch. Due to this fact, current control dynamics are on the level which is not reachable by the classical two or three level MV converters. Additionally, the switching frequency can be increased up to 4 kHz/cell, which gives 24 kHz output frequency. To limit the switching losses, switching fre-

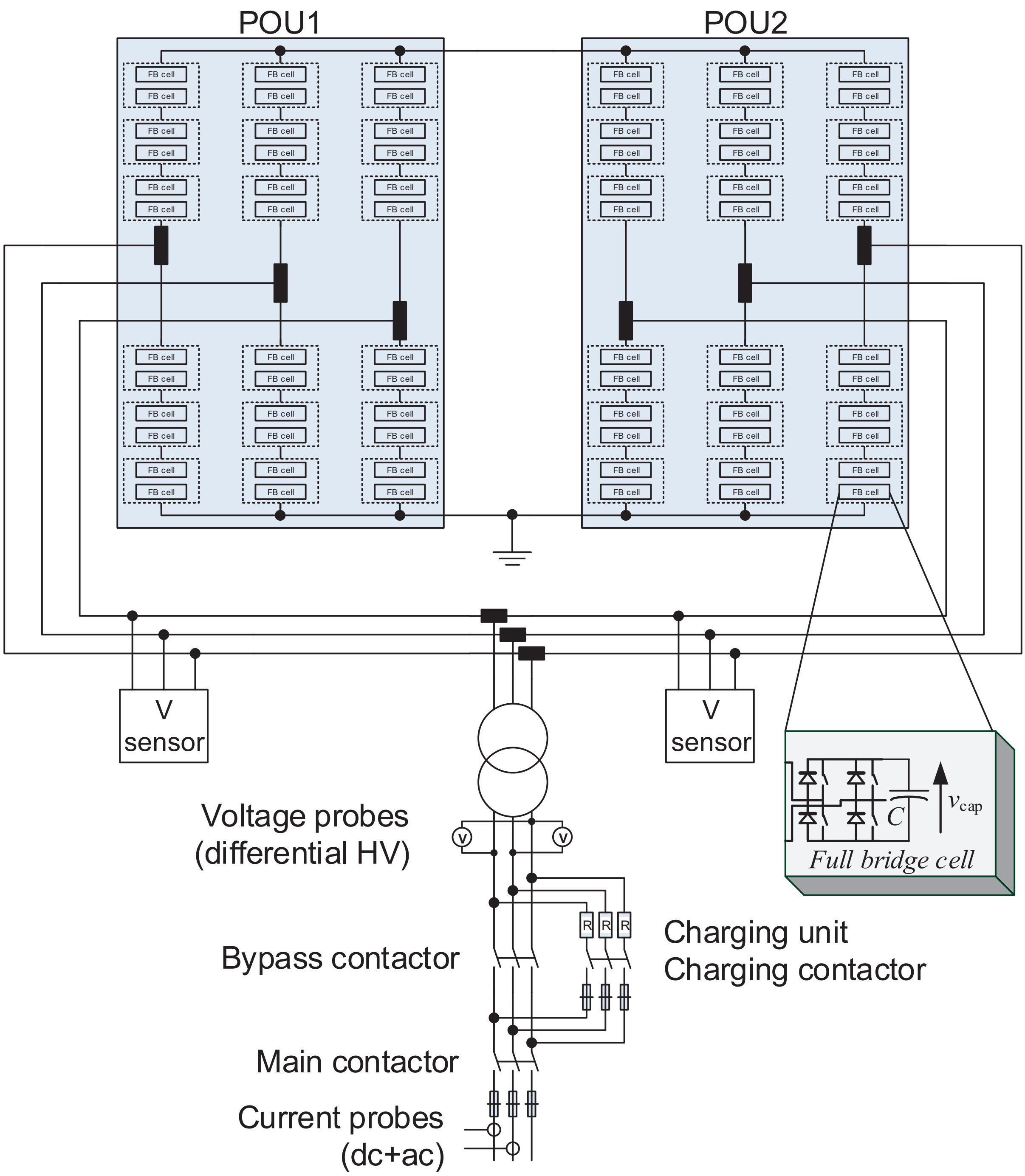

Fig. 8. PLCRC Test Stand block schematic. Back-to-back configuration

quency can also be reduced. 1 kHz operation point has been tested.

The main control system of the converter was implemented in the industrial controller based on PowerPC + FPGA and supporting automated code generation.

On the cell level, the control is realized with Texas Instruments TMS320F28069 DSP processor.

There are two laboratory setups built with those types of converters: a two-unit setup located in ABB Corporate Research Center, Poland (PLCRC) and a four-unit setup located in Florida State University, Center for Advanced Power Systems (FSU CAPS), USA.

5. System energy balancing study

To prove that balancing leads to stable operation, laboratory tests of prototype converter were performed.

Each single converter passed functional tests before system-level testing. On the system level, different series-parallel configurations were tested.

5.1. Branch energy balancing. Branch balancing mode is active since the converter starts switching. Therefore, the first check can be performed during the active charging of the system. Fig. 9 presents the beginning of the active charging sequence.

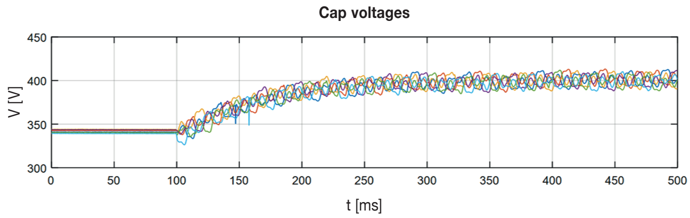

Fig. 9. Cell capacitors voltages. Active charging sequence

As shown, during the charging branch voltages follow each other, which proves that balancing works correctly.

Another operation point to be checked is a steady state with nominal capacitor voltage and defined operation point. For that purpose, two converters were connected (back-to-back). The system is stable for zero and non-zero power flow. Additionally, it can be said that for non-zero power flow, the voltage ripple is lower.

Finally, dynamic performance of the controller was checked by applying reference step changes, e.g. 50 A steps for 3 kV on DC link.

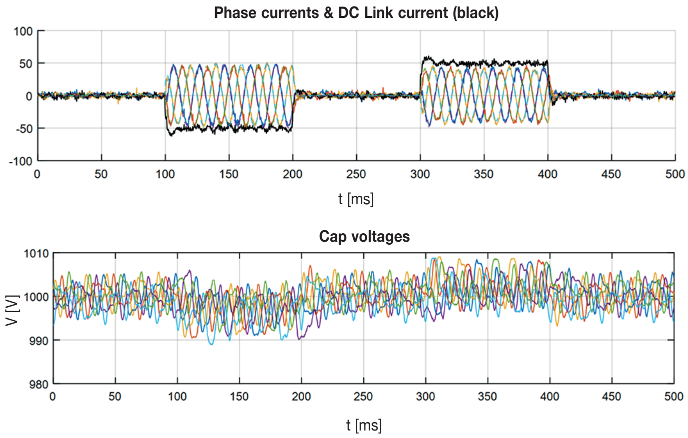

Fig. 10. Dynamic performance check of the converter. AC and DC (black) currents on the top graph. Average branch capacitor voltage during the test for defined nominal voltage equal 1000 V

As shown in Fig. 10, the system is stable and even during the transients, capacitor voltages follow each other. This proves that energy balancing gain is tuned correctly.

5.2. System energy balancing. The system energy balancing was tested on FSU CAPS test field. Test results were published in [25]. In this paper only an extraction of lab measurements is presented.

One of the tested configurations was two-converter setup (either in series or in parallel) described in [4].

In the first stage of tests, energy balancing was disabled. For the $Np = 2$, voltage source configuration imbalance was visible for voltages >1 kV (Fig. 11).

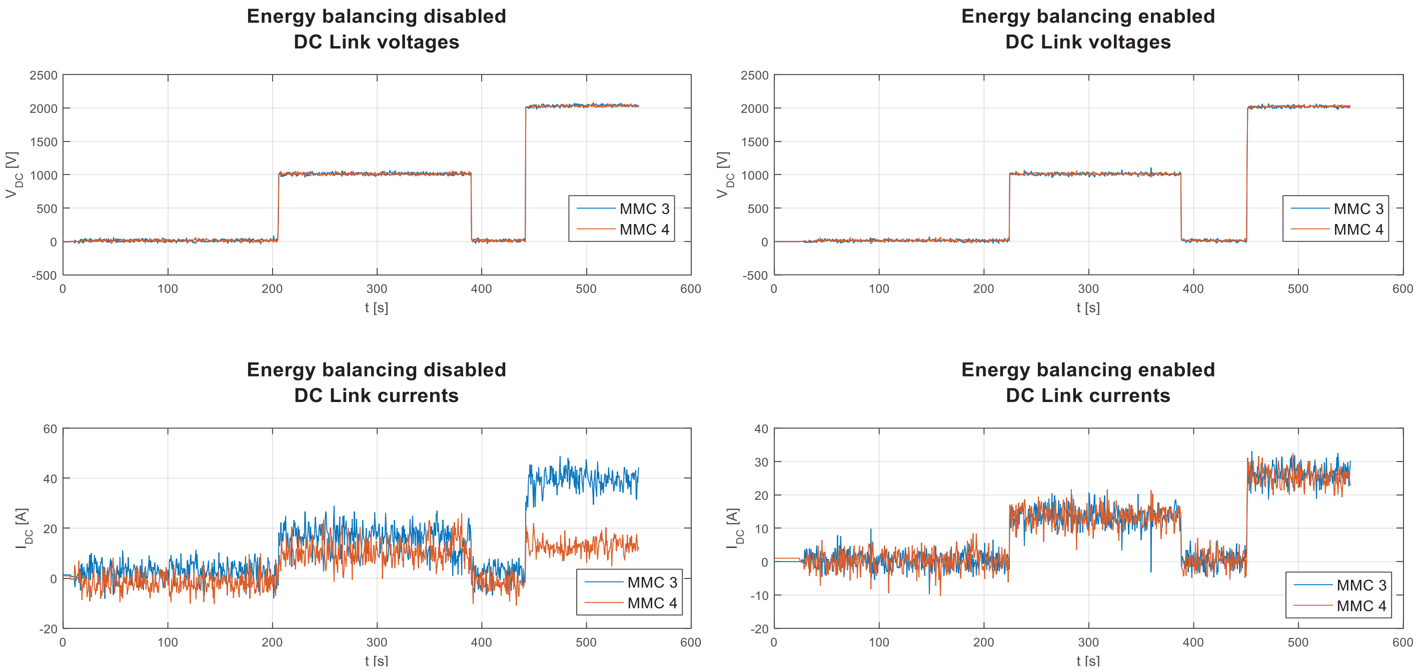

Fig. 11. Energy balancing disabled (left) versus enabled (right) for two converters in parallel in voltage source mode operation mode. Top – output DC link voltage; bottom – two converter DC link current

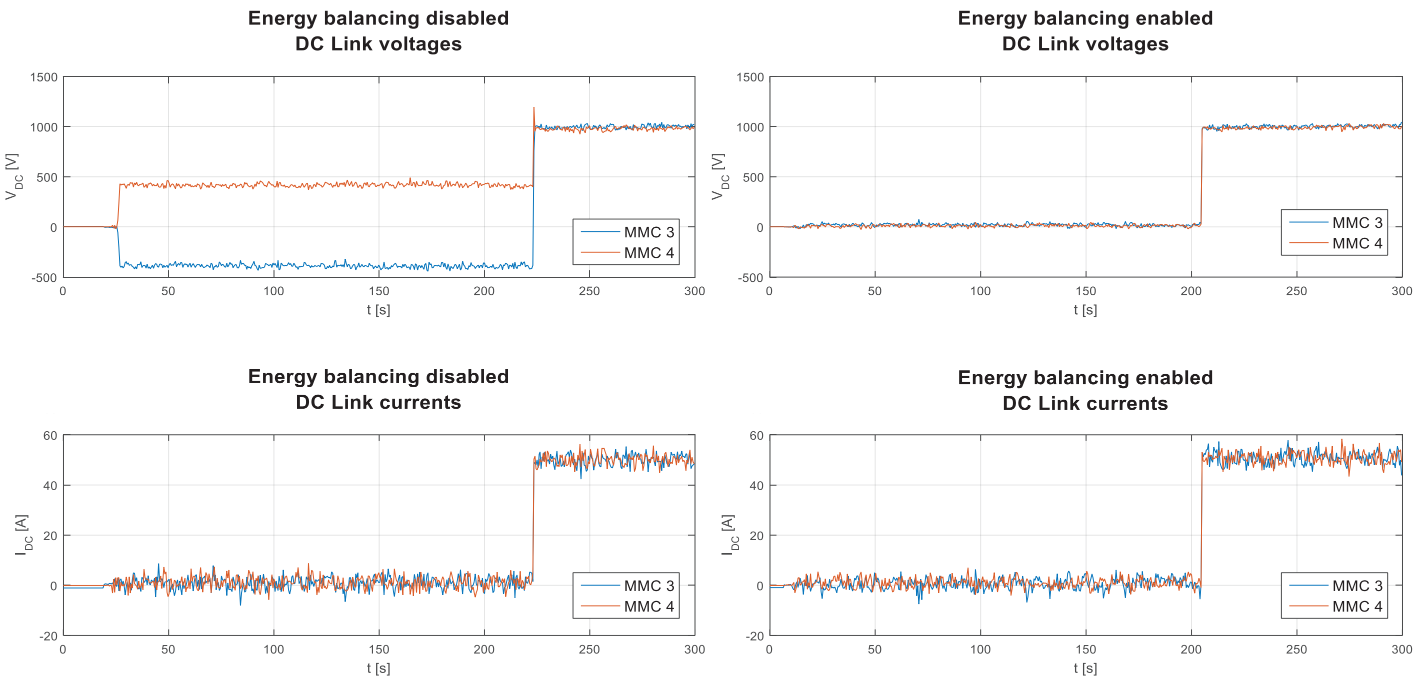

Fig. 12. Energy balancing disabled (left) versus enabled (right) for two converters in series in current source mode operation mode. Top – output DC link voltage; bottom – two converter's DC link current

In the $Ns = 2$ current source configuration, the situation is the opposite – the imbalance is visible for low current (Fig. 12).

The reason might be that the converter has current measurement offset, which leads to imbalance for near-zero reference but it might be neglected for higher current references (as 40 A).

At the same time, on voltage measurement path, the problem does not concern the measurement offset, but the gain which leads to higher error for higher references.

It should be emphasized that applying the energy balancing resolved the problem of imbalance in both cases investigated (Fig. 10 and Fig. 11, right side).

6. Summary

In this paper, the energy balancing aspects of MMC were discussed. The control is divided into several levels. Starting from the smallest functional unit of MMC, the cell, the following control levels are discerned: A – cell level, B – branch level, C – converter level and D – system level. This kind of structured approach is valid for energy balancing control and for other control algorithms as well.

As discussed in Section 3.1, the primary task of A – cell level control is to keep cell energy at desired level. Usually, output voltage reference of a cell is modified to achieve balancing. It is important that it is independent of MMC topology or function. There are two main ways to achieve the balance – direct cell switching based on cell selection algorithm or modulating index modification in each cell.

Applied B – branch level control scheme, described in Section 3.2, depends on MMC topology and realized function or operating mode. It is important to realize what DOFs are available for a given topology and if it allowed to affect terminal quantities, e.g. by introducing common mode voltage.

In C – converter level control, also-called converter energy control, the applied scheme depends on operating mode in most cases, since different reference values and load dependent values are present in different operating modes.

Optionally, D – system level energy balancing control may be used in multi converter systems. System level control is used to ensure equal power sharing or to improve dynamic behavior of the system.

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