

Handling Ground Faults in Meshed MVDC Grids by Fast Redistribution of Power Flow

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Index Terms—Control strategy, Modelling, Modular Multilevel Converter, Power flow control, Stability, State-space model, Transmission of electrical energy.

Abstract—In case of ground faults, the power flows within multiterminal DC grids must be redistributed to drive the current in faulty lines to zero. This paper completes a previously presented method for generating such transitions by a central component, a new feedback control to correct undesirable deviations from the desired behavior.

I. INTRODUCTION

To reinforce existing medium-voltage distribution grids, meshed DC grids which are coupled to the existing AC grid(s) by Modular Multilevel Converters (MMCs) [1] have become the subject of intensive research in recent years. Such Medium Voltage Direct Current (MVDC) grids offer the ability to enhance power distribution capacity, improve operational flexibility, and increase power quality in distribution grids [2].

Since DC networks have a faster grid dynamics, and since the currents do not have natural zero crossings, the fault management, especially of ground faults, is a key issue [3]. Additional DC breakers to disconnect faulty sections require high investment costs and frequently cause additional losses. An alternative approach, which enables uninterrupted grid operation, is to move the power flow quickly but smoothly to the healthy parts of the grid and to drive the current in faulty lines to zero. For this purpose, the power flow controllers (PFCs) can be used, which are commonly located at grid nodes to control the power flow during normal operation.

When the DC midpoint at each MMC is grounded via a high impedance (see R_{high} in Fig. 1), a pole-to-ground fault in a single line (cable) does not lead to a short circuit, since no current will flow in the ground loop. This gives sufficient time to design the transition to a new power flow distribution in the grid, characterized by zero current in the faulty line. In [4], a feedforward control method has been proposed for generating smooth and fast transitions between steady states.

The continuous input signals designed by the feedforward control must be realized by the MMCs and PFCs by means of switching operations. This type of realization inevitably leads to discretization errors which, together with external disturbances, cause the controlled variables to deviate from their desired trajectories. Therefore, it is crucial to complete the feedforward control by a feedback loop. This is exactly the original contribution of this paper, namely to present a new feedback control which effectively corrects unwanted deviations from the desired trajectories for all relevant state variables of the DC grid. It should be noted that some parts of the proposed feedback control are inspired by [5], where a feedback control for a single MMC was introduced. However, the task of regulating a DC grid involves a whole host of further challenges, which have been solved here.

The method is demonstrated on the basis of an example network which is presented in Section II. It resembles the network in [4], but is equipped with 3 instead of 2 PFCs in order to increase its controllability.

II. DESCRIPTION OF THE DC GRID

A. Structure and variables

1) *Model of MMC*: Each MMC shown in Fig. 1 couples the DC grid with a 3-phase AC system with grid frequency $f_{AC} = \omega_{AC}/2\pi$. The space vectors representing symmetric AC voltages and currents are $\vec{u}_{AC}^T = (u_{AC,\alpha}, u_{AC,\beta})$ and $\vec{i}_{AC}^T = (i_{AC,\alpha}, i_{AC,\beta})$. Assuming a time scale long enough (in the magnitude of $\Delta t = 100\mu s$ [6]), all full-bridge submodules in each

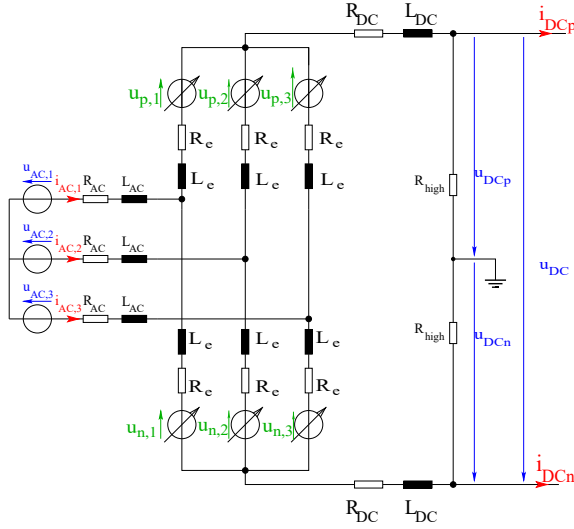


Fig. 1: Structure of Modular Multilevel Converter

of the 6 arms can be effectively considered as acting collectively as a controllable voltage source $u_{p,1}, \dots, u_{n,3}$. Therefore, considering these arm voltages, which form central input variables of the grid dynamics, as real-valued, continuous-time signals only makes sense for time scales slower than Δt . Consequently, all time scales of the control will be specified as multiples of Δt .

An important quantity is the total energy stored in all submodules of the MMC, denoted as $W_{\Sigma,0}$, since its dynamics is closely related to the power flows in the grid.

2) *DC grid configuration*: Fig. 2 depicts a DC grid configuration which is very similar to that presented in [4]. Three Modular Multilevel Converters (MMCs), called MMC1, MMC2, and MMC3, connect the grid to the respective AC networks. The DC lines that link the positive DC terminals of the MMCs create the p-ring, and in the same way, the n-ring is formed.

Each DC line in the grid is modeled by a resistance R and an inductance L , while the capacitance is neglected. Both rings are star-connected in the middle, offering a redundant path for power flow among the converters in case of faults. The hexagon-form grids, including the lines in the middle, are called the internal rings. MMC1&2 operate as AC-DC converters that inject power into the internal DC grid, while MMC3 serves as a DC-AC converter, providing power output to the external third AC system. All variables and notations relating to an MMC are labeled by the superscript (a) , with $a = 1, 2, 3$. At each terminal of the MMC, two internal currents are denoted by $i_{cw}^{(a)}$ and $i_{ccw}^{(a)}$. The subscript p/n

specifies whether the variable belongs to the p- or n-ring. The MMCs cannot control the current in the transmission lines of the internal rings, so the PFCs are needed for that task. In contrast to [4], three PFCs are inserted here to achieve better controllability of the power flow in the grid.

3) *Model of PFC*: The Power Flow Controller (PFC) shown in Fig. 3 is suitable for medium-voltage applications and consists of a single capacitance connected to the grid lines via six switches in full bridge topology. The capacitance voltage is called u_C , and the small internal resistance contribution can be neglected. Each PFC displays two independent line-to-line voltages denoted by $u_{F\alpha}$ and $u_{F\beta}$, serving as effective control inputs for the dynamics of the currents and PFC energies. The switching frequency is assumed to be high enough so that the signals $u_{F\alpha}$ and $u_{F\beta}$ can be considered as real-valued input signals at time scales of $\Delta t = 100\mu s$ and above.

In Fig. 2, in the p-ring, the PFC between MMC1&2 is called "PFC1 in the p-ring". Analogously, we have PFC2&3 in the p-ring. The line-to-line voltages of PFC1, PFC2 and PFC3 in the p-ring are denoted by $u_{F\alpha p}^{(a=1/2/3)}$ and $u_{F\beta p}^{(a=1/2/3)}$. The denotation of variables for the PFCs in the n-ring is completely analogous with the index p replaced by n .

B. Dynamics

1) *Defining the voltage level of the grid*: The voltage variables $u_{DCp}^{(a)}$ are described by the voltage loops from one entry point (MMC) to the next entry within each ring. Written as an example for the p-ring, this results in:

$$\begin{pmatrix} +1 & -1 & 0 \\ 0 & +1 & -1 \\ -1 & 0 & +1 \end{pmatrix} \begin{pmatrix} u_{DCp}^{(1)} \\ u_{DCp}^{(2)} \\ u_{DCp}^{(3)} \end{pmatrix} = \mathbf{L}_{cw} \frac{d}{dt} \vec{i}_{cwp} - \mathbf{L}_{e0} \frac{d}{dt} \vec{i}_{DCp} + \mathbf{R}_{cw} \vec{i}_{cwp} - \mathbf{R}_{e0} \vec{i}_{DCp} + \mathbf{M}_u \vec{u}_{Fp} \quad (1)$$

where $\vec{i}_{DCp}^T = (i_{DCp}^{(1)}, i_{DCp}^{(2)}, i_{DCp}^{(3)})$ and $\vec{i}_{cwp}^T = (i_{cwp}^{(1)}, i_{cwp}^{(2)}, i_{cwp}^{(3)})$. The vector of the control inputs is $\vec{u}_{Fp}^T = (u_{F\alpha p}^{(1)}, u_{F\beta p}^{(1)}, u_{F\alpha p}^{(2)}, u_{F\beta p}^{(2)}, u_{F\alpha p}^{(3)}, u_{F\beta p}^{(3)})$. The matrices in (1) are:

$$\mathbf{L}_{cw} = \begin{pmatrix} L_{cw}^{(1)} & L_{ccw}^{(2)} & 0 \\ 0 & L_{cw}^{(2)} & L_{ccw}^{(3)} \\ L_{ccw}^{(1)} & 0 & L_{cw}^{(3)} \end{pmatrix}; \quad \mathbf{L}_{e0} = \begin{pmatrix} 0 & L_{ccw}^{(2)} & 0 \\ 0 & 0 & L_{ccw}^{(3)} \\ L_{ccw}^{(1)} & 0 & 0 \end{pmatrix};$$

$$\mathbf{M}_u = \begin{pmatrix} +1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & +1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & +1 & -1 \end{pmatrix}.$$

The matrices $\mathbf{R}_{cw}$ and $\mathbf{R}_{e0}$ are obtained by replacing in $\mathbf{L}_{cw}$ and $\mathbf{L}_{e0}$ all inductances by the corresponding

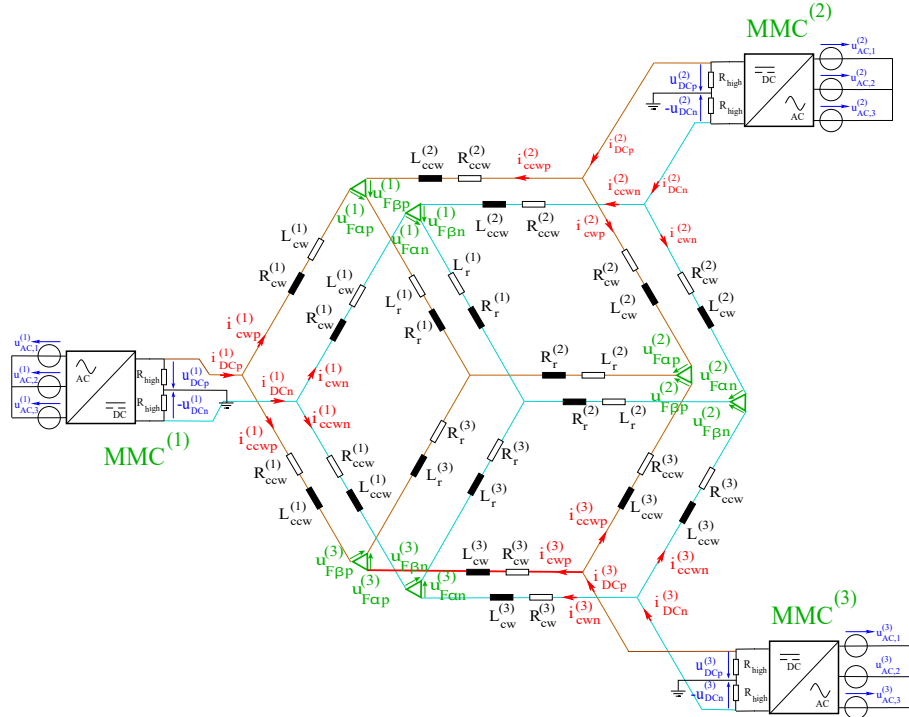


Fig. 2: The example DC grid configuration. The transmission line in which the ground fault occurs in Section V is highlighted in red.

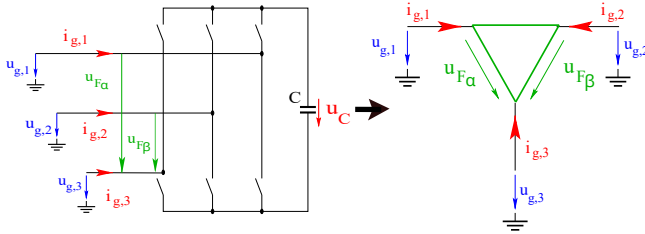


Fig. 3: Structure of Power Flow Controller (PFC)

where $R_{AC}'^{(a)} = R_{AC}^{(a)} + R_e^{(a)}/2$ and $L_{AC}'^{(a)} = L_{AC}^{(a)} + L_e^{(a)}/2$. The driving voltages of these AC currents are:

$$\begin{pmatrix} u_{\Delta,\alpha}^{(a)} \\ u_{\Delta,\beta}^{(a)} \end{pmatrix} = \begin{pmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} & -\frac{2}{3} & \frac{1}{3} & \frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} & 0 & -\frac{1}{\sqrt{3}} & \frac{1}{3} \end{pmatrix} \begin{pmatrix} u_{p,1}^{(a)} \\ u_{p,2}^{(a)} \\ u_{p,3}^{(a)} \\ u_{n,1}^{(a)} \\ u_{n,2}^{(a)} \\ u_{n,3}^{(a)} \end{pmatrix}$$

The dynamics for the DC currents from the MMCs ($a = 1, 2, 3$) read:

$$\frac{d}{dt} i_{DCp}^{(a)} = -\frac{R_{DC}'^{(a)}}{L_{DC}'^{(a)}} i_{DCp}^{(a)} - \frac{1}{L_{DC}'^{(a)}} \left(u_{\Sigma,0}^{(a)} + \frac{u_{DCp}^{(a)} + u_{DCn}^{(a)}}{2} \right) \quad (3)$$

resistances. It is worth noting that in (1) only two DC voltages are determined by the equation and one DC voltage can be freely chosen by the grid operator, defining the voltage level of the DC grid. Here, $u_{DCp}^{(1)}$ and $u_{DCn}^{(1)}$ are chosen for that role.

2) *Current dynamics*: The dynamics for the AC currents from MMC1,2&3 read [7]:

$$\frac{d}{dt} i_{AC,\alpha/\beta}^{(a)} = -\frac{R_{AC}'^{(a)}}{L_{AC}'^{(a)}} i_{AC,\alpha/\beta}^{(a)} - \frac{1}{L_{AC}'^{(a)}} \left(\frac{1}{2} u_{\Delta,\alpha/\beta}^{(a)} - u_{AC,\alpha/\beta}^{(a)} \right) \quad (2)$$

where $R_{DC}'^{(a)} = R_{DC}^{(a)} + R_e^{(a)}/3$, and $L_{DC}'^{(a)} = L_{DC}^{(a)} + L_e^{(a)}/3$. As can be seen in (3), the average voltage of all MMC's arms, $u_{\Sigma,0}^{(a)} = \frac{1}{6} (u_{p,1}^{(a)} + u_{p,2}^{(a)} + u_{p,3}^{(a)} + u_{n,1}^{(a)} + u_{n,2}^{(a)} + u_{n,3}^{(a)})$, is the driving voltage of the $i_{DCp}^{(a)}$ dynamics. The DC current of the MMC3 is a dependent variable: $i_{DCp}^{(3)} = - (i_{DCp}^{(1)} + i_{DCp}^{(2)})$, since the whole DC grid can be considered as a node.

The mesh equations for the internal closed loops for the p-ring can be summarized as:

$$\mathbf{L}_{rcw} \frac{d}{dt} \vec{i}_{cwp} = \mathbf{L}_{re0} \frac{d}{dt} \vec{i}_{DCp} - \mathbf{R}_{rcw} \vec{i}_{cwp} + \mathbf{R}_{re0} \vec{i}_{DCp} + \mathbf{M}_{pf} \vec{u}_{Fp} \quad (4)$$

The matrices $\mathbf{L}_{rcw}$, $\mathbf{L}_{re0}$ and $\mathbf{M}_{pf}$ in (4) are:

$$\begin{aligned} \mathbf{L}_{rcw} &= \begin{pmatrix} L_{cw}^{(1)} + L_{ccw}^{(1)} & 0 & 0 \\ 0 & L_{cw}^{(2)} + L_{ccw}^{(2)} & 0 \\ 0 & 0 & L_{cw}^{(3)} + L_{ccw}^{(3)} \end{pmatrix} \\ &+ \begin{pmatrix} L_r^{(1)} + L_r^{(3)} & -L_r^{(1)} & -L_r^{(3)} \\ -L_r^{(1)} & L_r^{(2)} + L_r^{(1)} & -L_r^{(2)} \\ -L_r^{(3)} & -L_r^{(2)} & L_r^{(3)} + L_r^{(2)} \end{pmatrix}; \\ \mathbf{L}_{re0} &= \begin{pmatrix} L_{ccw}^{(1)} + L_r^{(3)} & -L_r^{(1)} & 0 \\ 0 & L_{ccw}^{(2)} + L_r^{(1)} & -L_r^{(2)} \\ -L_r^{(3)} & 0 & L_{ccw}^{(3)} + L_r^{(2)} \end{pmatrix}; \\ \mathbf{M}_{pf} &= \begin{pmatrix} -1 & 0 & 0 & 0 & 0 & +1 \\ 0 & +1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & +1 & -1 & 0 \end{pmatrix}. \end{aligned}$$

3) *Energy dynamics*: The total energy stored in the capacitances of the MMC, $W_{\Sigma,0}^{(a)}$, is of primary interest. Since the power flows across the MMC describe the energy dynamics, the magnetic energy stored in the adjacent line inductances must be considered. Therefore, a component energy is defined, denoted by $W_{\Sigma,0}'^{(a)}$, which includes $W_{\Sigma,0}^{(a)}$ and the magnetic energies in all adjacent lines. All ohmic losses are disregarded in the following equation for simplification but could be easily included. Three component energies corresponding to three MMCs and their dynamic equations ($a = 1, 2, 3$) read:

$$\begin{aligned} W_{\Sigma,0}'^{(a)} &= W_{\Sigma,0}^{(a)} + \frac{L_{DC}^{(a)}}{6} \left(i_{DCp}^{(a)} \right)^2 + \frac{L_{AC}^{(a)}}{8} \left(\vec{i}_{AC}^{(a)} \right)^T \left(\vec{i}_{AC}^{(a)} \right), \\ \frac{dW_{\Sigma,0}'^{(a)}}{dt} &\approx \frac{1}{4} \left(\vec{u}_{AC}^{(a)} \right)^T \left(\vec{i}_{AC}^{(a)} \right) - \frac{i_{DCp}^{(a)}}{6} \left(u_{DCp}^{(a)} + u_{DCn}^{(a)} \right). \end{aligned} \quad (5)$$

For the PFC shown in Fig. 3, the dynamics of the energy stored in the PFC's capacitance with neglect of small ohmic losses reads (with $i_{g,1} + i_{g,2} + i_{g,3} = 0$):

$$\begin{aligned} \frac{d}{dt} W_{PFC} &\approx i_{g,1} u_{g,1} + i_{g,2} u_{g,2} + i_{g,3} u_{g,3} \\ &= i_{g,1} (u_{g,1} - u_{g,3}) + i_{g,2} (u_{g,2} - u_{g,3}) \\ &= i_{g,1} u_{F,\alpha} + i_{g,2} u_{F,\beta} \end{aligned}$$

Thus, the energy dynamics of PFC1 in the p-ring is:

$$\frac{d}{dt} W_{Cp}^{(1)} \approx i_{cwp}^{(1)} u_{F\alpha p}^{(1)} + \underbrace{\left(i_{DCp}^{(2)} - i_{cwp}^{(2)} \right)}_{=i_{ccwp}^{(2)}} u_{F\beta p}^{(1)} \quad (6)$$

The energy dynamics of other PFCs are analogous.

III. THE FEEDFORWARD CONTROL

A. The method of generating fast transitions

Faults can make it necessary to quickly transfer the DC grid to a new steady state, for instance one, where

the current of a faulty transmission line is set to zero. In [4], a method has been developed for designing smooth and fast trajectories that connect two steady states of the grid without exciting oscillatory modes.

In the DC grid dynamics, all variables that need to be controlled are: $\vec{x}^T = \left(i_{DCp}^{(a=1,2)}, i_{cwp/n}^{(a=1,2,3)}, i_{AC,\alpha/\beta}^{(a=1,2,3)}, W_{\Sigma,0}^{(a=1,2,3)}, W_{Cp/n}^{(a=1,2,3)} \right)$ (altogether $2 + 6 + 6 + 3 + 6 = 23$ variables). These variables are driven by the control inputs, $\vec{u}^T = \left(u_{\Sigma,0}^{(a=1,2)}, u_{\Delta,\alpha/\beta}^{(a=1,2,3)}, u_{F\alpha/\beta p}^{(a=1,2,3)}, u_{F\alpha/\beta n}^{(a=1,2,3)} \right)$ (altogether $2 + 6 + 6 + 6 = 20$ components).

The main variables whose trajectories must be designed are the currents for the following reasons: The driving voltages are obtained by differentiating the current trajectories, see (2), (3) and (4). The required changes in the converter energies are generated by means of power flows, which also depend on current trajectories, see (5), (6).

The main idea for designing suitable current trajectories is to form them as a sum of a smooth, s-shaped transition term and a hump-shaped term, as shown in Fig. 4. The amplitudes of those hump terms are determined by the condition that, at the end of the transition interval, all converter energies have to hit the values desired (and in principle freely chosen) by the grid operator.

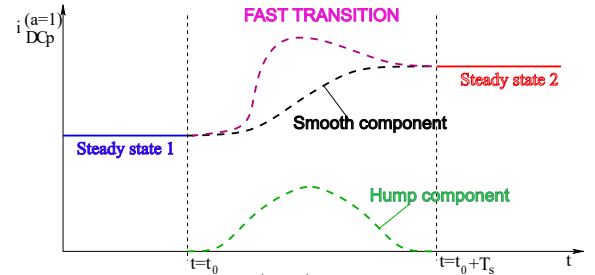


Fig. 4: The current $i_{DCp}^{(a=1)}$ is the sum of a smooth component and a hump-shaped component.

This amounts to solving a linear system of equations, which allows the current trajectories to be determined computationally efficiently.

B. Handling ground faults in the internal rings of the DC grid

Without PFCs, the currents within the DC grid would be distributed solely according to the line impedances. Any power flow distribution deviating from this must be actively controlled by the PFCs. A ground fault within the internal DC grid requires a serious redistribution of the power flows. Due to the relatively large inductances of long internal DC transmission lines, this redistribution

is associated with a major change in the magnetic energies stored in the lines. This change is particularly large if the current of a line, which carries the grid's highest internal current, has to be driven to zero due to a ground fault occurring there. In the scenario of the example DC grid, in the p-ring, these would be the currents $i_{cwp}^{(a=3)}$ and $i_{ccwp}^{(a=3)}$, which are of the same magnitude as the DC currents $i_{DCp}^{(a=1,2)}$. Managing this energy change poses a serious challenge for the PFCs due to their limited energy content in their capacitance.

To facilitate the workload of the PFCs and to prevent the voltage of their capacitances from falling below a threshold value, the relevant current will be gradually reduced to zero in several consecutively executed transitions.

IV. FEEDBACK CONTROL FOR COMPENSATION OF DEVIATIONS

A. Overview of the control concept

In this article, the feedforward control outlined in Section III is supplemented by a feedback loop. Fig. 5 shows the schematic of the control loop of the system. The desired values of $\vec{x}$ are provided by the grid operator. They are the desired steady-state values that must be achieved at the end of the transition period. The feedforward control computes suitable transition trajectories for all variables, denoted by $\vec{x}^{(ref)}$, as well as the input variable trajectories, $\vec{u}^{(ref)}$. The input signals $\vec{u}^{(ref)}$ are then applied to the system dynamics. However, these continuous input signals can only be approximately realized by the converters. Together with external disturbances, this causes deviations $\delta\vec{x}$ of the state variables from their desired values. Correcting these deviations through input corrections, denoted by $\delta\vec{u}$, is the role of the feedback control, which will be discussed in the following subsections.

B. The dynamics of current and energy deviations

For a general state variable x deviating from the ideal designed trajectory denoted by $x^{(ref)}$, the deviation is denoted by $\delta x = x - x^{(ref)}$. We assume that this deviation is so small that only terms linear in that deviation have to be considered (and higher powers in δx neglected).

Since the current dynamics are linear, the dynamic equations for current deviations result from (2), (3) and (4), with $a = 1, 2, 3$:

$$\frac{d\delta i_{AC,\alpha/\beta}^{(a)}}{dt} = -\frac{R_{AC}^{(a)}}{L_{AC}^{(a)}} \delta i_{AC,\alpha/\beta}^{(a)} - \frac{1}{L_{AC}^{(a)}} \left(\frac{1}{2} \delta^* u_{\Delta,\alpha/\beta}^{(a)} - \delta u_{AC,\alpha/\beta}^{(a)} \right) \quad (7)$$

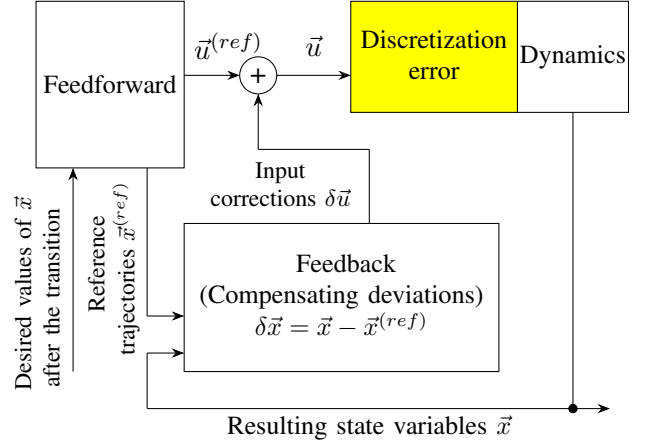


Fig. 5: The schematic of the control loop

$$\frac{d\delta i_{DCp}^{(a)}}{dt} = -\frac{R_{DC}^{(a)}}{L_{DC}^{(a)}} \delta i_{DCp}^{(a)} - \frac{1}{L_{DC}^{(a)}} \left(\delta^* u_{\Sigma,0}^{(a)} + \frac{\delta u_{DCp}^{(a)} + \delta u_{DCn}^{(a)}}{2} \right) \quad (8)$$

$$\mathbf{L}_{rcw} \frac{d}{dt} \delta \vec{i}_{cwp/n} = \pm \mathbf{L}_{re0} \frac{d}{dt} \delta \vec{i}_{DCp} - \mathbf{R}_{rcw} \delta \vec{i}_{cwp/n} \pm \mathbf{R}_{re0} \delta \vec{i}_{DCp} + \mathbf{M}_{pf} \delta^* \vec{u}_{Fp/n} \quad (9)$$

Here, $\delta^* u_{\Sigma,0}^{(a)}$, $\delta^* u_{\Delta,\alpha/\beta}^{(a)}$ and $\delta^* \vec{u}_{Fp/n}$ are the input corrections generated by the MMCs and PFCs. The aim of feedback control is to design these input signals in such a way that the deviations tend towards zero. In the deviation dynamics shown above, all terms that are multiplied by a resistance have the effect of reducing the deviation. They therefore do not need to be compensated, and their contribution in the deviation of MMC and PFC energies will be neglected.

The dynamics of the energy deviation for all MMCs are obtained from the power flow equations (5), with $a = 1, 2, 3$:

$$\begin{aligned} \frac{d}{dt} \delta W_{\Sigma,0}^{(a)} &\approx \frac{1}{4} \left(\delta \vec{u}_{AC}^{(a)} \right)^T \vec{i}_{AC}^{(a,ref)} + \frac{1}{4} \left(\vec{u}_{AC}^{(a,ref)} \right)^T \delta \vec{i}_{AC}^{(a)} \\ &- \frac{1}{6} \left(\delta u_{DCp}^{(a)} + \delta u_{DCn}^{(a)} \right) i_{DCp}^{(a,ref)} - \frac{1}{6} \left(u_{DCp}^{(a,ref)} + u_{DCn}^{(a,ref)} \right) \delta i_{DCp}^{(a)} \end{aligned} \quad (10)$$

The dynamic equation of the deviations in the energy stored in PFC1 in the p-ring is derived from (6) as follows:

$$\begin{aligned} \frac{d}{dt} \delta W_{Cp}^{(1)} &\approx \delta i_{cwp}^{(1)} u_{F\alpha p}^{(1,ref)} + \left(\delta i_{DCp}^{(2)} - \delta i_{cwp}^{(2)} \right) u_{F\beta p}^{(1,ref)} \\ &+ i_{cwp}^{(1,ref)} \delta^* u_{F\alpha p}^{(1)} + \left(i_{DCp}^{(2,ref)} - i_{cwp}^{(2,ref)} \right) \delta^* u_{F\beta p}^{(1)} \end{aligned} \quad (11)$$

where $\delta^* u_{F\alpha p}^{(1)}$ and $\delta^* u_{F\beta p}^{(1)}$ are the input corrections. For other PFCs, their dynamics of the energy deviations are analogous.

C. Feedback control for MMCs and the currents they control

MMC1 and MMC2 are considered first, as they each control independent DC currents. [5] introduced a new feedback control for the MMC, which enables fast compensation of deviations from any desired trajectory. This method can be directly applied to MMC1 and MMC2, but not to MMC3 (see later).

The input corrections $\delta^* u_{\Delta, \alpha/\beta}^{(a=1,2)}$ are used to correct the AC current deviations $\delta i_{AC, \alpha/\beta}^{(a=1,2)}$ within a fast time scale $\tau_{AC} = 5\Delta t$ ($\Delta t = 100\mu s$). This can be done by using the input corrections $\delta^* u_{\Delta, \alpha/\beta}^{(a=1,2)}$ to impose an exponential decay on the AC current deviations:

$$\frac{d}{dt} \delta i_{AC}^{(a=1,2)} = -\frac{1}{\tau_{AC}} \delta i_{AC}^{(a=1,2)} \quad (12)$$

The deviations in the DC currents, $\delta i_{DCp}^{(a=1,2)}$, and MMC energies, $\delta W_{\Sigma,0}^{(a=1,2)}$, are corrected simultaneously, using the input corrections $\delta^* u_{\Sigma,0}^{(a=1,2)}$ (see below). These corrections are carried out on a time scale that is at least one order of magnitude slower than the fast one, so that the control task on the faster time scale can be considered solved.

It is important to note that all deviations in the external voltages $(\delta u_{DCp}^{(a)} + \delta u_{DCn}^{(a)})$ and $\delta u_{AC, \alpha/\beta}^{(a)}$ ($a = 1, 2, 3$) are assumed to be random fluctuations with mean value zero. Their contributions therefore disappear when the dynamic equation (10) is integrated.

As a consequence of this assumption, the two underlined terms in equation (10) make no contribution on the slower time scale. If it is also assumed that for the AC current deviations $\delta i_{AC, \alpha/\beta}^{(a=1,2)} \rightarrow 0$ has already been achieved on the faster time scale, then on the slower time scale only the term proportional to $\delta i_{DCp}^{(a)}$ on the right-hand side of equation (10) remains relevant. So if it is possible to achieve $\lim_{t \rightarrow \infty} \delta W_{\Sigma,0}^{(a=1,2)} = 0$, then $\lim_{t \rightarrow \infty} \delta i_{DCp}^{(a=1,2)} = 0$, i.e. the asymptotically stable behavior of the DC current deviations, also follows.

If equation (10) - with the approximations justified above - is differentiated with respect to time and the dynamics of $\delta i_{DCp}^{(a=1,2)}$ and $\delta i_{AC, \alpha/\beta}^{(a=1,2)}$ are inserted according to (8) and (12), the input corrections $\delta^* u_{\Sigma,0}^{(a=1,2)}$ become

visible as the driving inputs for the dynamics of the energy deviations $\delta W_{\Sigma,0}^{(a=1,2)}$:

$$\begin{aligned} \frac{d^2}{dt^2} \delta W_{\Sigma,0}^{(a)} &= +\frac{1}{4} \left(\bar{u}_{AC}^{(a,ref)} \right)^T \frac{d}{dt} \delta i_{AC}^{(a)} \\ &- \frac{1}{6} \left(u_{DCp}^{(a,ref)} + u_{DCn}^{(a,ref)} \right) \frac{d}{dt} \delta i_{DCp}^{(a)} + \dots \\ &= \frac{\left(\bar{u}_{AC}^{(a,ref)} \right)^T}{4} \left(-\frac{\delta i_{AC}^{(a)}}{\tau_{AC}} \right) + \frac{\left(u_{DCp}^{(a,ref)} + u_{DCn}^{(a,ref)} \right)}{6L_{DC}^{(a)}} \delta^* u_{\Sigma,0}^{(a)} + \dots, \end{aligned} \quad (13)$$

with $a = 1, 2$. These input corrections are now determined by enforcing asymptotically stable dynamics of the energy deviations $\delta W_{\Sigma,0}^{(a)}$ (with $a = 1, 2$):

$$\frac{d^2}{dt^2} \delta W_{\Sigma,0}^{(a)} = -\frac{1}{\tau_{DC}} \frac{d}{dt} \delta W_{\Sigma,0}^{(a)} - \frac{1}{\tau_{DC}^2} \delta W_{\Sigma,0}^{(a)}, \quad (14)$$

where τ_{DC} denotes the time scale for the exponential decay of $\delta W_{\Sigma,0}^{(a=1,2)}$. The time scale τ_{DC} is chosen to be (at least) one order of magnitude higher than the fast time scale τ_{AC} , i.e. $\tau_{DC} = 10\tau_{AC} = 50\Delta t$. Equating the right-hand sides of (13) and (14) yields the required voltage corrections¹ ($a = 1, 2$):

$$\begin{aligned} \delta^* u_{\Sigma,0}^{(a)} &= \frac{6L_{DC}^{(a)}}{u_{DCp}^{(a,ref)} + u_{DCn}^{(a,ref)}} \left\{ \frac{1}{6} \left(\delta u_{DCp}^{(a)} + \delta u_{DCn}^{(a)} \right) \frac{d}{dt} i_{DCp}^{(a,ref)} \right. \\ &+ \frac{1}{6} \delta i_{DCp}^{(a)} \frac{d}{dt} \left(u_{DCp}^{(a,ref)} + u_{DCn}^{(a,ref)} \right) \\ &+ \frac{i_{DCp}^{(a,ref)}}{6\tau_{DC}} \left(\delta u_{DCp}^{(a)} + \delta u_{DCn}^{(a)} \right) + \frac{\delta i_{DCp}^{(a)}}{6\tau_{DC}} \left(u_{DCp}^{(a,ref)} + u_{DCn}^{(a,ref)} \right) \\ &\left. - \frac{\left(u_{DCp}^{(a,ref)} + u_{DCn}^{(a,ref)} \right)}{12L_{DC}^{(a)}} \left(\delta u_{DCp}^{(a,ref)} + \delta u_{DCn}^{(a,ref)} \right) - \frac{1}{\tau_{DC}^2} \delta W_{\Sigma,0}^{(a)} \right\}. \end{aligned} \quad (15)$$

The situation is different for MMC3.

As the whole DC grid can be considered as a node, the sum of three DC current deviations is equal to zero: $\delta i_{DCp}^{(a=1)} + \delta i_{DCp}^{(a=2)} + \delta i_{DCp}^{(a=3)} = 0$. Therefore, in case of $a = 3$, equation (8) only provides an algebraic constraint for $\delta^* u_{\Sigma,0}^{(3)}$:

$$\sum_{a=1}^3 \frac{1}{L_{DC}^{(a)}} \delta^* u_{\Sigma,0}^{(a)} = -\sum_{a=1}^3 \frac{\delta u_{DCp}^{(a)} + \delta u_{DCn}^{(a)}}{2L_{DC}^{(a)}} - \sum_{a=1}^3 \frac{R_{DC}^{(a)}}{L_{DC}^{(a)}} \delta i_{DCp}^{(a)}.$$

Hence, the input correction $\delta^* u_{\Sigma,0}^{(3)}$ of MMC3 depends on the input corrections $\delta^* u_{\Sigma,0}^{(a=1,2)}$ of MMC1&2 and cannot be used for the feedback control of MMC3. Instead, in the case of MMC3, the input corrections $\delta u_{\Delta, \alpha/\beta}^{(a=3)}$ are used to compensate for the energy deviation

¹To simplify equation (15), it was assumed that the AC powers injected into MMC1 and MMC2 are constant, which means $\delta u_{AC, \alpha/\beta}^{(a=1,2)} = 0 = \delta i_{AC, \alpha/\beta}^{(a=1,2)}$.

$\delta W_{\Sigma,0}'^{(a=3)}$ and the AC current deviations $\delta i_{AC,\alpha/\beta}^{(a=3)}$ at the same time.

For MMC3, the DC current deviation $\delta i_{DCp}^{(a=3)} = -(\delta i_{DCp}^{(a=1)} + \delta i_{DCp}^{(a=2)})$ tends to zero, as $\delta i_{DCp}^{(a=1,2)}$ are compensated by the MMC1&2. Therefore, according to (10), an asymptotically stable behavior of the energy deviation, $\lim_{t \rightarrow \infty} \delta W_{\Sigma,0}'^{(a=3)} = 0$, would also result in the asymptotically stable behavior of the AC current deviations, $\lim_{t \rightarrow \infty} \delta i_{AC}^{(a=3)} = \vec{0}$.

In contrast to MMC1 and MMC2, the deviations of the AC currents at MMC3 are not regulated on the fast time scale τ_{AC} , but on the slower timescale τ_{DC} . If you therefore write down the second derivative of MMC3's energy deviation $\delta W_{\Sigma,0}'^{(a=3)}$, the control task for $\delta i_{AC}^{(a=3)}$ cannot be regarded as already solved, but the input corrections $\delta^* u_{\Delta,\alpha/\beta}^{(a=3)}$ appear explicitly:

$$\begin{aligned} \frac{d^2}{dt^2} \delta W_{\Sigma,0}'^{(a=3)} &= +\frac{1}{4} \left(\bar{u}_{AC}^{(a=3,ref)} \right)^T \frac{d}{dt} \delta i_{AC}^{(a=3)} \\ &\quad - \frac{1}{6} \left(u_{DCp}^{(a=3,ref)} + u_{DCn}^{(a=3,ref)} \right) \underbrace{\frac{d}{dt} \delta i_{DCp}^{(a=3)}}_{= -\frac{d}{dt} (\delta i_{DCp}^{(a=1)} + \delta i_{DCp}^{(a=2)})} + \dots \\ &= -\frac{u_{AC,\alpha}^{(a=3,ref)}}{8L_{AC}'^{(a=3)}} \delta^* u_{\Delta,\alpha}^{(a=3)} - \frac{u_{AC,\beta}^{(a=3,ref)}}{8L_{AC}'^{(a=3)}} \delta^* u_{\Delta,\beta}^{(a=3)} \\ &\quad - \frac{(u_{DCp}^{(a=3,ref)} + u_{DCn}^{(a=3,ref)})}{6} \left(\frac{\delta^* u_{\Sigma,0}^{(a=1)}}{L_{DC}'^{(1)}} + \frac{\delta^* u_{\Sigma,0}^{(a=2)}}{L_{DC}'^{(2)}} \right) \\ &\quad + \dots, \end{aligned} \quad (16)$$

with $\delta^* u_{\Sigma,0}^{(a=1,2)}$ already determined in (15). Demanding an asymptotically stable behavior of the energy deviation $\delta W_{\Sigma,0}'^{(a=3)}$ on the time scale τ_{DC} , analogously to (14), results in the following equation for the input corrections $\delta^* u_{AC,\alpha/\beta}^{(a=3)}$ of MMC3:

$$d_0 + d_\alpha \delta^* u_{\Delta,\alpha}^{(a=3)} + d_\beta \delta^* u_{\Delta,\beta}^{(a=3)} = 0 \quad (17)$$

with:

$$\begin{aligned} d_0 &= \delta W_{\Sigma,0}'^{(3)} + \tau_{DC} \left[\left(\frac{\bar{u}_{AC}^{(3,ref)}}{4} \right)^T \delta i_{AC}^{(3)} + \left(\frac{\delta \bar{u}_{AC}^{(3)}}{4} \right)^T \bar{i}_{AC}^{(3,ref)} \right] \\ &\quad - \frac{1}{6} \left(u_{DCp}^{(3,ref)} + u_{DCn}^{(3,ref)} \right) \delta i_{DCp}^{(3)} - \frac{1}{6} \left(\delta u_{DCp}^{(3)} + \delta u_{DCn}^{(3)} \right) i_{DCp}^{(3,ref)} \\ &\quad + \tau_{DC}^2 \left[\frac{1}{4} \left(\frac{d}{dt} \bar{u}_{AC}^{(3,ref)} \right)^T \delta i_{AC}^{(3)} + \frac{1}{4L_{AC}'} \left(\bar{u}_{AC}^{(3,ref)} \right)^T \delta \bar{u}_{AC}^{(3)} \right] \\ &\quad + \left(\frac{\delta \bar{u}_{AC}^{(3)}}{4} \right)^T \frac{d}{dt} \bar{i}_{AC}^{(3,ref)} - \frac{\delta i_{DCp}^{(3)}}{6} \frac{d}{dt} \left(u_{DCp}^{(3,ref)} + u_{DCn}^{(3,ref)} \right) \end{aligned}$$

$$\begin{aligned} & - \frac{(\delta u_{DCp}^{(3)} + \delta u_{DCn}^{(3)})}{6} \frac{d}{dt} i_{DCp}^{(3,ref)} \\ & - \frac{(u_{DCp}^{(3,ref)} + u_{DCn}^{(3,ref)})}{6L_{DC}'^{(1)}} \left(\delta^* u_{\Sigma,0}^{(1)} + \frac{\delta u_{DCp}^{(1)} + \delta u_{DCn}^{(1)}}{2} \right) \\ & - \frac{(u_{DCp}^{(3,ref)} + u_{DCn}^{(3,ref)})}{6L_{DC}'^{(2)}} \left(\delta^* u_{\Sigma,0}^{(2)} + \frac{\delta u_{DCp}^{(2)} + \delta u_{DCn}^{(2)}}{2} \right) \Bigg]; \\ d_{\alpha/\beta} &= -\frac{\tau_{DC}^2}{8L_{AC}'^{(3)}} u_{AC,\alpha/\beta}^{(3,ref)}. \end{aligned}$$

d_0 contains the deviations to be corrected, namely $\delta W_{\Sigma,0}'^{(a=3)}$ and $\delta i_{AC}^{(a=3)}$, and two input corrections already determined, $\delta^* u_{\Sigma,0}^{(a=1)}$ and $\delta^* u_{\Sigma,0}^{(a=2)}$. Due to the factor $u_{AC,\alpha/\beta}^{(3,ref)}$, the coefficients d_α and d_β in (17) have periodic zero crossings. This is taken into account by the following solution of (17), which provides the MMC3 feedback control in the form of the input corrections:

$$\delta^* u_{\Delta,\alpha/\beta}^{(3)} = -\frac{d_{\alpha/\beta}}{d_\alpha^2 + d_\beta^2} d_0 = \frac{8L_{AC}'^{(3)}}{\tau_{DC}^2} \frac{u_{AC,\alpha/\beta}^{(3,ref)}}{\bar{u}_{AC}^{(3)}} d_0$$

D. Feedback control for PFCs and the currents they control

The dynamics in the deviations of the energy stored in the PFCs in the p-ring (see (11)) can be summarized as follows:

$$\begin{aligned} \frac{d}{dt} \begin{pmatrix} \delta W_{Cp}^{(1)} \\ \delta W_{Cp}^{(2)} \\ \delta W_{Cp}^{(3)} \end{pmatrix} &\approx \underbrace{\begin{pmatrix} \delta i_{cwp}^{(1)} u_{F\alpha p}^{(1,ref)} + (\delta i_{DCp}^{(2)} - \delta i_{cwp}^{(2)}) u_{F\beta p}^{(1,ref)} \\ \delta i_{cwp}^{(2)} u_{F\alpha p}^{(2,ref)} + (\delta i_{DCp}^{(3)} - \delta i_{cwp}^{(3)}) u_{F\beta p}^{(2,ref)} \\ \delta i_{cwp}^{(3)} u_{F\alpha p}^{(3,ref)} + (\delta i_{DCp}^{(1)} - \delta i_{cwp}^{(1)}) u_{F\beta p}^{(3,ref)} \end{pmatrix}}_{:=\tilde{m}} \\ &\quad + \underbrace{\begin{pmatrix} i_{cwp}^{(1,ref)} & 0 & 0 \\ 0 & i_{cwp}^{(2,ref)} & 0 \\ 0 & 0 & i_{cwp}^{(3,ref)} \end{pmatrix}}_{:=M2} \begin{pmatrix} \delta^* u_{F\alpha p}^{(1)} \\ \delta^* u_{F\alpha p}^{(2)} \\ \delta^* u_{F\alpha p}^{(3)} \end{pmatrix} \\ &\quad + \underbrace{\begin{pmatrix} i_{DCp}^{(2,ref)} - i_{cwp}^{(2,ref)} & 0 & 0 \\ 0 & i_{DCp}^{(3,ref)} - i_{cwp}^{(3,ref)} & 0 \\ 0 & 0 & i_{DCp}^{(1,ref)} - i_{cwp}^{(1,ref)} \end{pmatrix}}_{:=M3} \begin{pmatrix} \delta^* u_{F\beta p}^{(1)} \\ \delta^* u_{F\beta p}^{(2)} \\ \delta^* u_{F\beta p}^{(3)} \end{pmatrix} \end{aligned} \quad (18)$$

When the dynamics of the DC grid performs a transition from one steady state to another, certain internal DC currents may change direction and pass through zero. For any PFC, this will lead to situations where, at certain times, only one of the two input corrections, $\delta^* u_{F\alpha}^{(a)}$ or $\delta^* u_{F\beta}^{(a)}$, is effective in influencing this PFC's energy deviation dynamics. If this input were then used to compensate for current deviations, the possibility of regulating the PFC's energy would be lost at that moment.

To avoid this problem, a control strategy for the PFCs is developed which allows to select one of the

three currents entering a PFC for feedback control. At the same time, feedback control will be ensured for the energy of all three PFCs regardless of possible zero crossings of DC grid currents during transition phases.

For each PFC, one input correction is used to compensate for the deviation in its energy, while the other is used to compensate for the deviation in one internal current entering it. Without loss of generality, we will consider the case where the three internal current deviations $\delta i_{cwp}^{(a=1,2,3)}$ are selected for feedback control. The two tasks of PFC control are solved in two different time scales: 1) On the faster time scale, three internal current deviations $\delta i_{cwp}^{(a=1,2,3)}$ are compensated by three input corrections $\delta^* u_{F\alpha p}^{(a=1,2,3)}$. 2) On the slower time scale, three energy deviations in the PFCs are compensated by $\delta^* u_{F\beta p}^{(a=1,2,3)}$.

The two tasks and time scales will now be discussed in detail:

1) On the faster time scale τ_d , three input corrections $\delta^* u_{F\alpha p}^{(a=1,2,3)}$ are determined such as to impose an exponential decay on the current deviations ($a = 1, 2, 3$):

$$\frac{d}{dt} \delta i_{cwp}^{(a)} = -\frac{1}{\tau_d} \delta i_{cwp}^{(a)} \quad (19)$$

τ_d is chosen to match the time scale for the feedback control of the AC currents, i.e. $\tau_d = \tau_{AC}$. Combining (9) and (19) results in the feedback control for the currents:

$$\begin{aligned} \begin{pmatrix} \delta^* u_{F\alpha p}^{(1)} \\ \delta^* u_{F\alpha p}^{(2)} \\ \delta^* u_{F\alpha p}^{(3)} \end{pmatrix} &= \left(\frac{1}{\tau_d} \mathbf{L}_{rcw} - \mathbf{R}_{rcw} \right) \delta \vec{i}_{cwp} + \mathbf{L}_{re0} \frac{d}{dt} \delta \vec{i}_{DCp} \\ &+ \mathbf{R}_{re0} \delta \vec{i}_{DCp} + \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} \delta^* u_{F\beta p}^{(1)} \\ \delta^* u_{F\beta p}^{(2)} \\ \delta^* u_{F\beta p}^{(3)} \end{pmatrix} \end{aligned} \quad (20)$$

Equation (20) still contains contributions of $\frac{d}{dt} \delta \vec{i}_{DCp}$ and $\delta \vec{i}_{DCp}$, because the current deviations $\delta \vec{i}_{DCp}$ have not yet been compensated in this time scale ($\tau_d < \tau_{DC}$).

The proposed separate feedback control of the internal currents on a fast time scale quickly brings the deviations of the internal currents close to zero. This is particularly necessary if, in the event of a ground fault, the faulty line is to be disconnected from the DC grid without the need for DC breakers.

2) The slower time scale is at least one order of magnitude larger than τ_d . Therefore, control task 1 can be considered solved and $\delta \vec{i}_{cwp} \rightarrow \vec{0}$ may be assumed. Three input corrections $\delta^* u_{F\beta p}^{(a=1,2,3)}$ serve now for the compensation of the deviations in the PFC energies. The PFC energy control should work robustly even if

the control of a single PFC energy fails for a short moment (see above). This is achieved by basing the feedback control on a Lyapunov function that includes the (squared) deviations of **all** PFC energies in the p-ring:

$$J(t) = \frac{1}{2} \left(\delta W_{Cp}^{(1)} \right)^2 + \frac{1}{2} \left(\delta W_{Cp}^{(2)} \right)^2 + \frac{1}{2} \left(\delta W_{Cp}^{(3)} \right)^2 \quad (21)$$

The time derivative of this Lyapunov function results from (18) and (20) as follows:

$$\begin{aligned} \frac{d}{dt} J(t) &= \underbrace{\begin{pmatrix} \delta W_{Cp}^{(1)} & \delta W_{Cp}^{(2)} & \delta W_{Cp}^{(3)} \end{pmatrix}}_{:= \delta \vec{W}_{Cp}^T} \frac{d}{dt} \begin{pmatrix} \delta W_{Cp}^{(1)} \\ \delta W_{Cp}^{(2)} \\ \delta W_{Cp}^{(3)} \end{pmatrix} \\ &\approx \delta \vec{W}_{Cp}^T \left(\vec{m} + \mathbf{M2} \begin{pmatrix} \delta^* u_{F\alpha p}^{(1)} \\ \delta^* u_{F\alpha p}^{(2)} \\ \delta^* u_{F\alpha p}^{(3)} \end{pmatrix} + \mathbf{M3} \begin{pmatrix} \delta^* u_{F\beta p}^{(1)} \\ \delta^* u_{F\beta p}^{(2)} \\ \delta^* u_{F\beta p}^{(3)} \end{pmatrix} \right) \\ &= \delta \vec{W}_{Cp}^T \left\{ \vec{m} + \mathbf{M2} \left[\mathbf{L}_{re0} \frac{d}{dt} \delta \vec{i}_{DCp} \right] \right\} \\ &+ \delta \vec{W}_{Cp}^T \left(\mathbf{M2} \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} + \mathbf{M3} \right) \begin{pmatrix} \delta^* u_{F\beta p}^{(1)} \\ \delta^* u_{F\beta p}^{(2)} \\ \delta^* u_{F\beta p}^{(3)} \end{pmatrix} \\ &= \underbrace{\delta \vec{W}_{Cp}^T \left\{ \vec{m} + \mathbf{M2} \left[\mathbf{L}_{re0} \frac{d}{dt} \delta \vec{i}_{DCp} \right] \right\}}_{:= c_0} \\ &+ \underbrace{\left[\delta W_{Cp}^{(1)} \left(i_{DCp}^{(2,ref)} - i_{cwp}^{(2,ref)} \right) + \delta W_{Cp}^{(2)} i_{cwp}^{(2,ref)} \right]}_{:= c_1} \delta^* u_{F\beta p}^{(1)} \\ &+ \underbrace{\left[\delta W_{Cp}^{(2)} \left(i_{DCp}^{(3,ref)} - i_{cwp}^{(3,ref)} \right) + \delta W_{Cp}^{(3)} i_{cwp}^{(3,ref)} \right]}_{:= c_2} \delta^* u_{F\beta p}^{(2)} \\ &+ \underbrace{\left[\delta W_{Cp}^{(3)} \left(i_{DCp}^{(1,ref)} - i_{cwp}^{(1,ref)} \right) + \delta W_{Cp}^{(1)} i_{cwp}^{(1,ref)} \right]}_{:= c_3} \delta^* u_{F\beta p}^{(3)} \end{aligned} \quad (22)$$

The input corrections $\delta^* u_{F\beta p}^{(a=1,2,3)}$ are determined in such a way that the derivative of the Lyapunov function has the following form:

$$\frac{d}{dt} J(t) = -\frac{1}{\tau_{DC}} J(t) = -\frac{1}{\tau_{DC}} \delta \vec{W}_{Cp}^T \delta \vec{W}_{Cp} \leq 0 \quad (23)$$

Here $\frac{d}{dt} J(t) = 0$ only if $\delta \vec{W}_{Cp} = \vec{0}$, i.e. if the control target is achieved. The time scale τ_{DC} for the decay of the Lyapunov function is chosen to be the same size as the time scale for the decay of the MMCs' energy deviations.

Since the deviations of the internal currents are compensated in the framework of task 1, the whole deviation dynamics will tend towards equilibrium

$(\delta \vec{W}_{Cp}^T, \delta \vec{i}_{cwp}^T) = \vec{0}^T$. Combining (22) and (23) results in:

$$c_0 + c_1 \delta^* u_{F\beta p}^{(1)} + c_2 \delta^* u_{F\beta p}^{(2)} + c_3 \delta^* u_{F\beta p}^{(3)} = -\frac{\delta \vec{W}_{Cp}^T \delta \vec{W}_{Cp}}{\tau_{DC}} \quad (24)$$

The following feedback control satisfies (24), while ensuring an equally shared control effort:

$$\delta^* u_{F\beta p}^{(1/2/3)} = \frac{-c_{1/2/3}}{c_1^2 + c_2^2 + c_3^2} \left(c_0 + \frac{1}{\tau_{DC}} \delta \vec{W}_{Cp}^T \delta \vec{W}_{Cp} \right) \quad (25)$$

V. SIMULATION RESULTS

To display the full potential of the method, one of the most challenging ground fault cases is chosen for the simulation, where the internal DC current $i_{cwp}^{(3)}$ - highlighted in red in Fig. 2 - must be driven to zero. In the following graphics, the designed and desired reference trajectories are the dashed lines, marked in the legend with (*ref*), while the resulting dynamic variables are displayed by the solid lines, marked in the legend with (*res*).

Consistent with section II, the timestep used for numerical integration of the dynamics is $\Delta t = 100\mu s$. In order to demonstrate the robustness of the feedback control, slightly overestimated values are used in this simulation for both the discretization errors of the converter voltages, which are caused by switching actions, and for the external disturbances. At every timestep, a discretization error of 4% is applied for the MMCs and 10% for the PFCs. Furthermore, the external voltages $u_{AC,\alpha/\beta}^{(a)}$ and $u_{DCp/n}^{(a)}$ ($a = 1, 2, 3$) are set to have a random fluctuation within a range of 2% of their original values at every timestep. The control time scales $\tau_{AC} = \tau_d = 5\Delta t = 0.5ms$ and $\tau_{DC} = 50\Delta t = 5ms$ are chosen for the simulation. Three internal currents $i_{cwp}^{(a=1,2,3)}$ are chosen to be controlled.

TABLE I: Simulation parameters

Parameter	Value	Parameter	Value
L_{DC}	5 mH	$\hat{u}_{AC}^{(1/2/3)}$	[9; 10; 11] kV
R_{DC}	50 mΩ	$\hat{i}_{AC}^{(1/2/3)}$	[2; 1.6; -2.31] kA
L_{AC}	10 mH	f_{AC}	50 Hz
R_{AC}	100 mΩ	$\cos(\varphi_{i,AC}^{(1/2/3)})$	[0.61; 0.78; 0.85]
L_e	1 mH	$u_{DCp/n}^{(1)}$	10 kV
R_e	10 mΩ	C in the PFC	3.5 mF

In Fig. 6, the internal current $i_{cwp}^{(3)}$ in the faulty line is driven gradually to zero. This is accomplished in five consecutively executed transitions, which take a total of 300ms. The start and end of the transition time are

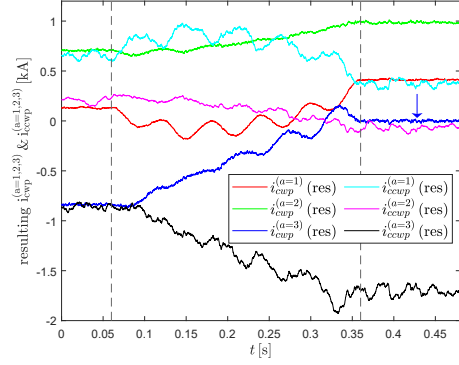


Fig. 6: The internal DC currents. The current $i_{cwp}^{(3)}$ is driven to zero and marked by an arrow.

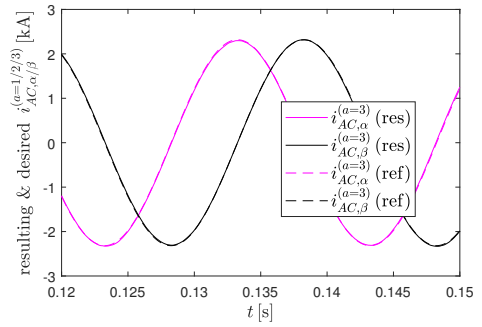


Fig. 7: The AC currents corresponding to MMC3

marked by dashed lines (in Fig. 6, 8, 9, 10). After this transition time, the desired value of zero is very precisely achieved for $i_{cwp}^{(3)}$ (see arrow). The effect of feedback control can be seen by comparing the deviations of the regulated currents with those of the unregulated currents. The internal currents $i_{cwp}^{(a=1,2,3)}$, which have been chosen for control, fluctuate within a narrow tolerance band between $-10A$ and $10A$. In contrast, the unregulated currents $i_{cwp}^{(a=1,2,3)}$ have higher deviations of $\pm 50A$.

As the AC currents at MMC1 and MMC2 are controlled on a fast time scale, the simulation does not show any difference between desired and resulting ('real') values. Fig. 7 therefore shows the 'most difficult' case of the AC currents at MMC3, which are controlled, together with MMC3's energy, at the slower time scale τ_{DC} . In order to make the difference between desired and resulting values visible, a short time interval [0.12s...0.15s] is shown enlarged. The AC currents at MMC3 closely follow their designed trajectories while at the same time ensuring the feedback control of the MMC3's energy in Fig. 9.

The simulation result in Fig. 8 shows the DC currents

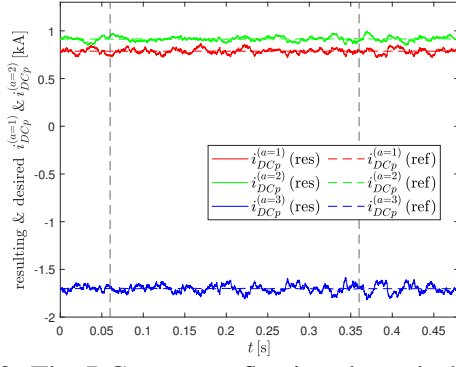


Fig. 8: The DC currents flowing through the MMCs

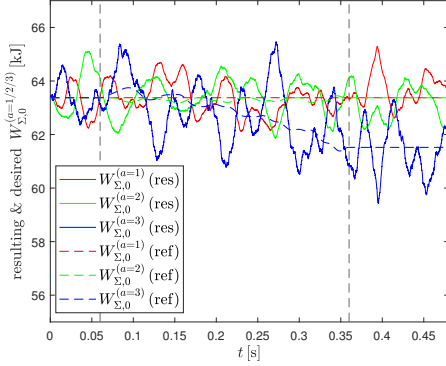


Fig. 9: The total energy stored in each MMC

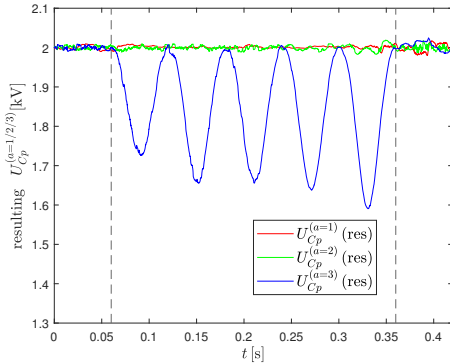


Fig. 10: The capacitor voltages of the PFCs in the p-ring

$i_{DCp}^{(a=1,2,3)}$ at the MMCs. Again, the resulting values fluctuate within a narrow band around the desired values.

Fig. 9 displays the energy content of the three MMCs. Due to the feedback control of these energies, all deviations are less than 5% of the desired energies.

When the current $i_{cwp}^{(3)}$ is driven to zero, the total magnetic energy in the grid increases as a result of the

new distribution of internal currents within the grid. The time course of the desired energy of MMC3 in Fig. 9 shows that MMC3 has been selected to accommodate this change in the magnetic energy of the DC grid.

Fig. 10 displays the capacitor voltages of the PFCs, which indicate their energy content. The effect of reducing the workload of the PFCs by splitting the transition into five partial transitions can be seen in this figure: The capacitor voltages of the PFCs show five oscillations. PFC3 has to work the hardest here, as it is adjacent to the line carrying $i_{cwp}^{(3)}$. Nevertheless, the capacitor voltage of PFC3 never drops below a value of $1.6kV$ during the entire transition, while a capacitor voltage of $0.7kV$ is completely sufficient to keep the PFC functional. The oscillation of the capacitor voltage can be reduced when the transition time is increased.

VI. CONCLUSION

In this paper, a previously presented method for the fast and smooth redistribution of power flows in meshed DC grids has been completed by a new feedback control. This very effectively corrects deviations of the currents and converter energies from the desired trajectories. The effectiveness of the method is demonstrated by a challenging ground fault scenario and the corresponding simulation results.

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