Direct multivariable control of Modular Multilevel Converters

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Abstract
While Modular Multilevel Converters (MMC) have become state of the art in many high power/high voltage applications like HVDC, other important future applications (i.e. multiterminal-DC-grids, wind parks, electric ships, ...) are still under development. The increased number of variables available for essentially improved control of MMC has to be made accessible and fully used by improved control concepts. Future progress in hardware, especially smaller submodule capacitors, is tightly interrelated to progress of control performance. The same applies to fully electronic fault management and protection at system level, which will be very valuable and important in future. A novel multivariable control concept for MMC, according to these requirements, is presented and explained. Its performance is investigated by extensive simulation results.

Introduction
High power voltage source converters (VSC) are key components for many important future applications, in particular: Grid infrastructure, multiterminal HVDC and MVDC, better exploitation of solar and wind power resources, electric ships and others. Modular Multilevel Converters (MMC) have become state of the art in these fields, because of several essential advantages [1], [2], [3], [4]. In addition, the elimination of large passive filters and - more important - the elimination of the central capacitors at the DC-Bus, has opened the way to fully electronic and very fast fault management, including DC-side fault blocking and controllable current limitation. Future progress will require closer “codevelopment” of the control system and the hardware of the converter. Reduction of submodule capacitor size and faster control of all essential variables of the converter are main issues. These important points are tightly interrelated: Slow and poor control performance leads to large deviations of the arm energies, especially under transient or fault conditions. In consequence, a high safety factor for the submodule capacitors must be chosen in order to keep resulting overvoltages in acceptable limits.

On the other hand, increasing the voltage ripple of the submodule capacitors from present typical design value of 10% towards 20% would allow to cut capacitor size in half. In contrast to conventional VSC, the increased voltage ripple does not necessarily impair the quality of the converter voltages. Unfortunately, present control schemes are unable to operate safely and stable under these conditions. One of the main problems is based on the fact, that the capacitor sorting algorithm produces severely disturbing low frequency components, which are “fed through” via the modulator and appear both in the circulating currents and the converter voltages.

“Purely hardware options” enabling reduced capacitor size are very limited. One excellent option for
large converters is double-connection [4], [5], [6], of two suitable submodules each. This measure enables submodule capacitances to be almost exactly cut in half. A suitable submodule topology, eliminating any problems of charge balancing or stray inductance of the interconnections, has been given in [4]. The potential of purely hardware optimization is getting more and more limited. In future, further development must be focussed on improved control schemes, as explained already. The low frequency ripple components, present in the arm energies of MMC, should be shifted to higher frequencies. This, however, requires a well controlled energy exchange between the arms of the MMC.

Basics of MMC control

Compared to conventional VSC, MMC offers additional degrees of freedom (Table II). The higher number of variables can be assigned to different control layers (Table I). The highest layer is related to control at system level. At this level, the converter is regarded as a simple functional block, which has to “deliver” the desired voltages, currents, real and reactive power at its terminals. This layer will not be covered in the present paper. The lowest layer - according to common understanding - is related to modulator function and gate signal generation, in general.

A lot of development work has been done to study modulation schemes and gate signal generation. First of all, there are Nearest-Level-Modulation (NLC) methods, [2]. The basic concept is to choose the number of inserted submodules such that the generated arm voltages are as close as possible to the desired arm voltages. The next group of modulation techniques are carrier based, [7], [8], [9], [10]. By comparing the reference voltage with carrier signals of different frequencies and phases, a number of needed submodules can be determined. Advanced approaches focus on lowering harmonics, improvements in submodule selection and equalized loss distribution. In [11] a tolerance band modulation scheme which limits capacitor voltage ripples and adjusts integrated voltage errors over time has been presented. Pulse-width modulated control strategies are presented in [12], [13]. In [14], [15], [16], space vector modulation (SVM) adapted to the multilevel structure of the MMC is used to generate the arm output voltages. The degrees of freedom of MMC modulation offer the possibility of decoupled capacitor voltage control [17].

Additionally, there are modulation techniques, which are based on predictive control [18], [19], [20], [21]. The assumption of steady state operation of the MMC at a stable fundamental frequency allows to implement predetermined switching angles and submodule selection. Sorting of the capacitors in the arms is closely related to the modulator function. Therefore, in many research papers both functions are studied in combination.

Table I: Control layers of the MMC.

| Layer | Description                        |
|-------|------------------------------------|
| 3     | Control of the total converter energy |
| 2     | Control of the arms energy distribution |
| 1     | Multivariable control (see table II) |
| 0     | Capacitor sorting                  |

Table II: Variables of the MMC.

| Quantity | Notation | Quantity | Notation |
|----------|----------|----------|----------|
| AC-voltage 1 | $v_{a,12}$ | DC-voltage | $v_d$ |
| AC-voltage 2 | $v_{a,23}$ | Circular current 1 | $i_{cc,1}$ |
| Common-mode voltage | $v_{cm}$ | Circular current 2 | $i_{cc,2}$ |
| Δ components | $\Sigma$ components | | |
side effect in most cases. In order to design a new control scheme for MMC, however, it is advisable and valuable to consider all six variables, as stated in Table II.

Circulating current control

At first glance, including the circular currents does not seem mandatory. More detailed investigations, however, clearly show, that it is extremely valuable to include them. One major reason is, that a fast and precise control of the circulating currents generates a reliable basis for controlling the arm energy distribution in the converter (Layer 2). Additional studies have shown, that implementing the circular current control in higher layers of the control system impairs the dynamics and precision, severely. (Note, that the system of circular currents \(i_{cc,1}, i_{cc,2}\) will be expressed as a space vector, too, in the following.) Similar to the AC-voltage space vector \(\vec{v}_a\) the third variable \(i_{cc,3}\) is not an independent variable. Combined with a controllable common mode voltage \(v_{cm}\), the circulating current control enables to establish fast and direct control of instantaneous arm powers and - in consequence - the distribution of arm energies inside the converter.

Several definitions for the circulating current are used in literature. Sometimes the associated current loops are including external components, like the DC-Bus ([9], [11],[18]) or other network branches. These definitions are possible, but may cause misleading interpretations. Figure 4 shows the definition of the current loops, which are restricted to the internal circuit of the MMC. Obviously, the circulating currents can not be measured directly, but they can be computed on line based on the measurements of the arm currents [22]. The most straightforward explanation starts with the DC-current. It can be computed by adding all six measurement values of the arm currents:

\[
i_d = \frac{1}{2} (i_{p,1} + i_{p,2} + i_{p,3} + i_{n,1} + i_{n,2} + i_{n,3}) .\tag{1}
\]

Next, the circular current components can be found by computing

\[
i_{cc,1} = \frac{1}{2} (i_{p,1} + i_{n,1}) - \frac{1}{3} i_d ,
\]

\[
i_{cc,2} = \frac{1}{2} (i_{p,2} + i_{n,2}) - \frac{1}{3} i_d ,
\]

\[
i_{cc,3} = -i_{cc,1} - i_{cc,2} .\tag{2}
\]

Note, that in the following explanations of the direct multivariable control system, the flux of the arm inductors \(\Phi_{cc}\) has been taken, instead of the current. As well known, the flux of an inductance is directly proportional to current ripple. The scaling factor for conversion of current ripple to flux is simply the inductance of the current loop, containing the arm inductors \(L_e\). The effective inductance for \(i_{cc,1}\) or \(i_{cc,2}\) is \((3L_e)\) in the MMC. The reason for choosing flux in the following is to enable a direct insight and comparison of the tolerance bands of all six variables (Table II). For a technical realisation of the multivariable control system, circulating current control based on arm current measurement is advisable and well feasible according to equations (1), (2).

Boundary conditions and objectives of the new multivariable control

Figure 1 shows the known basic structure of MMC. A number of \(n = 16\) submodules of bipolar type (Fullbridge-SM or Double-Zero-SM) have been defined for the following simulations. The arm inductors \(L_e\) are essential components, to be considered, while the arm resistors \(R_e\) have no considerable influence on the control performance. Definition of all terminal voltages of MMC is given in figure 2. Figure 3 emphasizes the fact, that the external impedances and counter voltages are not of main concern for the actual scope of work. The six variables (Table II), which will be controlled fast and independently - according to the objectives - are voltages and internal currents. As long as the dynamics of the external currents is orders of magnitude slower than the internal dynamics, the external currents “seem to be impressed and given” for the considered control system. Of course, the external currents have been adjusted to the actual values by corrective actions of the supervisory control (Table I, layer 3), and they
will be slowly adjusted to other values, in future. In consequence, fast adjustments of the instantaneous power can be performed by fast adjustment of the converter voltages, mainly.

Figure 4 shows an equivalent circuit of the MMC in order to explain the control scheme and the definition of the control variables. Note, that neither the arm currents nor the external currents are to be controlled at control layer 0 and 1, where the new multivariable controller is operating. Solely, the circulating currents are to be considered. The speed achievable, here, is only limited by the available control voltages and the chosen internal inductances $L_e$.

Equation (3) shows, that an ideal decoupled control of all six variables could be realized by strictly using sum ($\Sigma$) and difference ($\Delta$) components of the controllable arm voltages. (The sum of voltages of the positive and the negative arm of each phase is called $\Sigma$-component here. The difference of the arm voltages of each phase is called $\Delta$-component here.) This ideal control scheme, however, would lead to simultaneously switching in many arms, in most cases. A high average switching frequency of the converter would result.

Further investigations showed, that a somewhat contrary approach leads to better results: For each of the six variables a tolerance band is defined, which can be freely chosen according to the requirements. Solely one corrective switching in the whole converter is executed if one of the six variables touches the limit of its tolerance band. It can be shown, that a single voltage step of minimal amplitude ($+v_c$ or $-v_c$) in one of the arms is sufficient to “kick back” the corresponding variable into its tolerance band, in general. Solely, if SM-capacitor voltage ripple is very high, the required amplitude of the voltage step may be $2|v_c|$. This very seldom case is covered in the presented control scheme by a sequential execution of two voltage steps. (This behaviour is inherent in the present implementation as a “natural” feature.) In order to realize a complete multivariable control system, based on this state of knowledge, several additional decisions had to be made. These are explained in the following.
Definition of control errors and voltages

The underlying basic function of the new control system is straightforward: The desired voltage values (see table II) are converted to target values of arm voltages. This is done by a simple Nearest-Level-Control-Scheme. After this procedure small voltage errors will remain, which are in the range of \( \pm 0.5 \Delta v_c \), in general (see figure 4, error voltages \( v_e \)). These voltage errors are expressed as an “error space vector” \( v_{e,医} \) with respect to the desired AC-voltage space vector and a second “error space vector” \( v_{e,cc} \) with respect to the desired circulating current space vector. The second error vector is causing an unwanted drifting of the current space vector in one of the six discrete directions (see figure 5 and the explanations). The multivariable controller has to switch appropriate control voltages \( v_m \). The remaining two scalar voltages \( v_d \) and \( v_cm \) are suffering from similar voltage errors, which have to be considered, too.

Next the definition of the tolerance bands and the corrective switching actions of the multivariable controller have to be considered: An important objective of the new control system is to keep all six variables (Table II) in defined tolerance bands. The width of the tolerance band can be selected separately for each variable. In order to be consistent and to enable comparisons all six tolerance bands are defined as flux error bands. This values can be compared with each other and may be transformed to current ripple values by taking into account the actual inductances of the corresponding branches. With respect to the internal currents \( i_{cc,医}, i_{cc,2} \) this has been explained, already, in the previous section “circulating current and control”. The corrective switching actions of the multivariable control system will finally result in a discrete decision for switching one voltage step in one of the converter arms, every time one of the tolerance bands is hit. This decision process is explained in the next chapter. With respect to the detection of the tolerance band limits, there are two options: One option is to do the limit detection on the space vector variables (2 variables). The other is to do the detection on the original three phase variables (For instance: \( i_{cc,医}, i_{cc,2}, i_{cc,3} \)). The last mentioned case is slightly easier to implement. Therefore, it has been chosen.

In consequence, the tolerance bands limits in the space vector diagrams are appearing in form of a hexagon. The exact form, however, is of minor importance.

Multivariable control

The objective of multivariable control is to keep the flux within defined tolerance bands. In order to achieve that, the influence of the switching options on the control variables is analysed (Tables III, IV). Here, the number of displayed variables seems to be 8, because the third circular current \( i_{cc,3} \) and AC-voltage \( u_{a,31} \) are included. With the help of these tables, possible switching operations to “kick back” the
corresponding flux into its tolerance band, can be determined. Out of the pool of twelve switching options (a positive and negative switching operation per arm), six can always be used to redirect the specific flux. In the case of AC-flux control, the number is lowered to four useful operations. This means, by ensuring adjustment of the first priority flux (the one which triggered the switching operation) with the selected pool of switching options, the impact on the other variables can be taken into account. The best suitable switching option is the one, which keeps all fluxes as long as possible within the defined tolerance bands. The limited possible options, in combination with the small time interval between two successive switching operations, compared to the AC-period ($T_{sw} \ll T_1$), enables the predictive calculation of the flux changes. The prediction is solely used for deciding the next switching state. Therefore, it must not be precise and it can be performed without knowing the actual capacitor voltages. The decisions can be further improved by predictive calculation of more than one ($k > 1$) switching operations. Note, that the total number of options $p$ would raise considerably in this case: $p = 6^k$.

The columns (single switching operation influences of specific arms) in tables III, IV are transformed into space vector diagrams shown in figures 6, 7.

$$\vec{v} = \begin{pmatrix} v_{cc} \\ v_d \\ v_a \\ v_{cm} \end{pmatrix}^T, \quad \vec{\Phi} = \begin{pmatrix} \Phi_{cc} \\ \Phi_d \\ \Phi_a \\ \Phi_{cm} \end{pmatrix}^T.$$  

Here, the control voltages $\vec{v}$ determine the directions and velocity of changes of their fluxes $\vec{\Phi}$. The six possible directions of $\vec{v}_{cc}$ and $\vec{v}_a$ form a tolerance band in hexagonal shape, as explained already. Voltages $\vec{v}_d$ and $\vec{v}_{cm}$ and their tolerance band are real valued scalars, so their adjustment is simple compared to the others. An important fact is, that the angular relation between $\vec{v}_{cc}$ and $\vec{v}_a$ is always $30^\circ$ and $210^\circ$, which gives a $180^\circ$ difference. This provides an excellent controllability of the fluxes with every single switching operation.

Fig. 5: Example case of the selection scheme used by the multivariable control scheme.

**Example**

Figure 5 visualizes an example case for the decision process. In this example, the error voltages $v_{e,cc}$ and $v_{e,a}$ have led to the current state of the fluxes $\Phi_{cc}$ and $\Phi_a$, in which the CC-flux reached the limit and triggered the switching operation. The options to adjust the error voltage directions and stay within the tolerance band are the grey vectors $\Delta v_{p,n,123}$ (Figures 6, 7). Obviously, three directions are useful to correct the actual error of $\Phi_{cc}$. These are labelled as relevant voltages $v_{rel}$. Since each of these can be set by two different switching operations, the number of possible directions to control the AC-flux is doubled (6 directions). Finally, the decision process chooses the switching operation $\Delta v_{n,3} = -\bar{v}_c$, because it will keep the flux in the tolerance band for the longest time.

**Simulation results**

A simulation model has been used to verify the proposed control scheme. Table V employs the related parameters. Noteworthy are the values of installed inductive $L_e$ and capacitive $C$ energy of the converter.
Table III: Impact of a positive voltage step \((+\bar{v}_c)\) on the control voltages.

| Control | Arms | \(\Delta v_{cc,1}\) | \(\Delta v_{cc,2}\) | \(\Delta v_{cc,3}\) | \(\Delta v_{cm,1}\) | \(\Delta v_{cm,2}\) | \(\Delta v_{cm,3}\) |
|---------|------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| voltages | \(v_p\) | \(p_1\) | \(p_2\) | \(p_3\) | \(n_1\) | \(n_2\) | \(n_3\) |
| \(\frac{\Delta v_{cc,1}}{\bar{v}_c}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(-\frac{1}{2}\) | \(-\frac{1}{2}\) | \(-\frac{1}{2}\) |
| \(\frac{\Delta v_{cc,2}}{\bar{v}_c}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(-\frac{1}{2}\) | \(-\frac{1}{2}\) | \(-\frac{1}{2}\) |
| \(\frac{\Delta v_{cc,3}}{\bar{v}_c}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(-\frac{1}{2}\) | \(-\frac{1}{2}\) | \(-\frac{1}{2}\) |
| \(\frac{\Delta v_{cm,1}}{\bar{v}_c}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) |
| \(\frac{\Delta v_{cm,2}}{\bar{v}_c}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) |
| \(\frac{\Delta v_{cm,3}}{\bar{v}_c}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) | \(+\frac{1}{2}\) |

The installed energy is small compared to the state of the art [3], [11]. Since the controlled fluxes are related to specific inductances, it is possible to directly define the bounds of the current ripples. As the modulation scheme is able to adjust multiple control fluxes with a single switching operation, it is reasonable to specify the flux limits in the same order. Basically, the flux limits can be chosen freely and separately from each other. But usually, it is preferred to have small arm inductors. So, the CC-flux may be the most demanding variable. Since the external dynamics are slow compared to the internal dynamics, DC-, CM- and AC-flux bands have been chosen wider. The following values have been chosen:

\[
\Phi_{cc,max} = 30 mV, \quad \Phi_{d,max} = 3 \cdot 3 \cdot \Phi_{cc,max}, \quad \Phi_{d,max} = 7 \cdot \Phi_{cc,max}, \quad \Phi_{em,max} = 7 \cdot \Phi_{cc,max}.
\]

Figure 8 shows the eight controlled voltages normalized to the average capacitor voltage \(\bar{v}_c\). The results of tables III and IV become visible. The resulting voltage steps for circular current (CC) control are approximately \(\frac{1}{2}\bar{v}_c\) and \(\bar{v}_c\), as expected. Line-to-line voltages (AC) seeing voltage steps of \(\frac{1}{2}\bar{v}_c\). In summary, the specification leads to an average submodule switching frequency of 151 Hz, only.

Figure 9 shows the control fluxes. The desired flux limits (dashed lines) of all control variables are met. Since the tolerance band of the AC-flux is small compared to its amplitude, figure 10 is used to display the errors of AC-flux, in an expanded scale.
For the sake of high resolution it was only possible to show 4 ms in figures 8, 9, 10. Fast Fourier Transformation (FFT) of all control fluxes is shown in (figure 11). There are no significant harmonics in any control flux. A noise floor is generated, which is advantageous in comparison to discrete harmonics. In fact, the set flux limits define the level of the noise floor. This can be seen, for example, by comparing CC-flux and DC-flux. In figure 12 the spectrum is shown once more, when an additional 100 Hz-component is desired for $i_{cc}$. According to the objectives, no disturbing low frequency components are present in the spectrum.

Figure 13 shows the capacitor voltages of all arms normalized by the average capacitor voltage $\bar{v}_c$. The predefined limits for the capacitor voltages are met, too.

Table V: Simulation parameters

| Quantity                   | Notation | Value       | Quantity                   | Notation | Value       |
|----------------------------|----------|-------------|----------------------------|----------|-------------|
| DC power                   | $P_d$    | 6.36MW      | Number of SM per arm       | $n$      | 16          |
| DC-voltage                 | $v_{id}$ | 10kV        | Arm resistance             | $R_e$    | 20m$\Omega$ |
| AC-voltage                 | $\dot{v}_{ia}$ | 7.07kV    | Arm inductance             | $L_e$    | 1mH         |
| AC-frequency               | $f_1$    | 50Hz        | SM capacitance             | $C$      | 2mF         |
| Desired circular current   | $i_{cc}^*$ | 0A         | Ind. energy of converter   | $E_{le}$ | 0.17 MW     |
| Desired CM voltage         | $v_{cm}^*$ | 0V         | Cap. energy of converter   | $E_c$    | 22 kJ       |

Fig. 8: Resulting voltages of all controlled variables (Time span of record shown: 4ms).

Fig. 9: Resulting fluxes of all controlled variables (Time span of record shown: 4ms).
Fig. 10: Errors of the AC fluxes (Time span of record shown: 4ms).

Fig. 11: Resulting spectrum (Flux) of all controlled variables (Time span of FFT analysis: 200ms).

Fig. 12: Resulting spectrum (Flux) of all controlled variables (Time span of FFT analysis: 200ms). Desired circular current: $\hat{i}_{cc} = 150A$, $f_{cc} = 100Hz$.

Fig. 13: Normalized submodule capacitor voltages of each arm ($\bar{v}_c = 1,2kV$).
Conclusion

A novel multivariable control scheme for MMC has been presented. It enables to keep all essential variables of the MMC in predefined tolerance bands. By selecting the individual tolerance bands, the switching frequency and the resulting noise floor of harmonics can be adjusted in a wide range. The multivariable control establishes a reliable basis for higher level control of the arm energies of the converter. Stable operation with essentially reduced submodule capacitors and low switching frequencies is achieved.

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