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On Energy Storage Requirements in Alternate Arm Converters and Modular Multilevel Converters

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«Multilevel converters», «Voltage source converter (VSC)», «HVDC», «Energy storage»

Abstract

In this paper, a comparison of the energy storage requirements is performed for the modular multilevel converter (MMC) with half-bridge and full-bridge submodules as well as for the alternate arm converter (AAC). Concerning the AAC, the operational mode with overlap period is taken into account and an analytical relation between the overlap angle and the modulation index is presented. This ensures that the net energy exchange for the converter arms is zero over each half cycle.

Introduction

The modular multilevel converter (MMC), first presented by Marquardt et al. [1–4], has been identified as one of the prime converter candidates for high-voltage direct current (HVDC) supergrids [5, 6]. In dc grid applications, however, it is essential to be able to handle dc-side short circuits efficiently. This calls for dc circuit breakers [7], but also for converter topologies that can handle dc-side short circuits [8]. Two of such converters are the MMC with full-bridge submodules and the alternate arm converter (AAC).

During operation of the converter, the energy stored in the capacitors varies around the time average. Since these capacitive energy storages are a driving factor of the size, weight and cost of the converter [9], their capacitance must be kept minimal while limiting the voltage fluctuation caused by the current passing periodically through these capacitors. In [10], a comparison of the MMC with half-bridge submodules and the AAC was performed and it was found that the necessary amount of capacitors was significantly lower for the AAC than for the MMC. However, the comparison was performed in an operating point where the AAC was operating in the so-called *sweet spot*. In this operating point the complete energy exchange is achieved between the ac and the dc grid and no overlap period when both upper and lower switches are closed is needed to balance the arm energies. The question is, what would be the result of the comparison in case the AAC operates in an operating point considerably different from the *sweet spot*. Another interesting issue to bring into this comparison is to include the MMC with full-bridges, as this converter has the full capability to handle dc-side short circuits. From this analysis a fair comparison between the AAC and the MMC with half-bridge and full-bridge submodules can be made. The analysis can also be helpful in the design process of an AAC, especially for the case when operating with overlap angle [11, 12].

Operating principles and terminology

Case of MMC

The operation principles of an MMC and its energy fluctuation has been intensively studied in literature before [9] and is therefore deliberately kept concise here. The voltage reference for the upper arm is given by

$$v_{\text{arm}} = V_d - mV_d \cos(\omega t) \quad (1)$$

with the modulation index $m = \hat{V}_s/V_d$, where $\hat{V}_s$ is peak value of the alternating voltage imposed by the converter and V_d is the dc-link voltage. The current reference can be expressed as

$$i_{\text{arm}} = \frac{\hat{I}_s}{2} \left(\frac{m}{2} \cos(\varphi) + \cos(\omega t - \varphi) \right) \quad (2)$$

where $\hat{I}_s$ is the peak value of the ac-side current. The analysis is made on a per-phase basis. Accordingly, the arm energy fluctuation can be found to be

$$e_{\text{arm}} = \int v_{\text{arm}} i_{\text{arm}} dt \quad (3a)$$

$$e_{\text{arm}} = \frac{S}{m\omega} \sin(\omega t - \varphi) - \frac{Sm}{2\omega} \cos(\varphi) \sin(\omega t) - \frac{S}{4\omega} \sin(2\omega t - \varphi) \quad (3b)$$

with S corresponding to the apparent power per phase.

Case of AAC

A schematic diagram of an AAC is shown in Fig. 1. It is a hybrid topology which combines features of the two-level and multilevel converter topologies [13]. Each phase of the converter consists of two arms, each with a stack of H-bridge cells, a so-called *director switch* and a small arm inductor. The basic mode of operation of a phase leg is such that the director switches operate alternately, each conducting the output current during half of the fundamental cycle. The upper switch conducts during the positive half-cycle and during this interval the upper submodule string provides the ac-side emf.

Fig. 1: Schematic diagram of the AAC

The voltages that each stack of cells will have to generate will be higher than half the direct voltage because of the overlap period during which the director switches of the upper and lower arms are conducting simultaneously [14]. During such a period (see Fig. 2), a current flows through the entire phase leg thus exchanging energy between the upper and lower arm submodule strings and the dc terminal. From Fig. 2 it is found that the duration of the overlap period corresponds to an angle of 2α .

Fig. 2: Voltage waveforms of the AAC with overlap period

The voltage reference for the upper arm can be divided into two parts depending on the state of the director switch. Accordingly,

$$v_{\text{arm,on}} = V_d - mV_d \cos(\omega t), \quad -\frac{\pi}{2} - \alpha \leq \omega t \leq \frac{\pi}{2} + \alpha \quad (4a)$$

$$v_{\text{arm,off}} = V_d + mV_d \sin(\alpha), \quad \text{otherwise.} \quad (4b)$$

By defining the nominal voltage V_{nom} as the voltage that the full-bridge submodules have to deliver for a given overlap angle

$$V_{\text{nom}} = V_d + mV_d \sin(\alpha), \quad (5)$$

the arm voltage reference can be formulated as

$$v_{\text{arm}} = V_{\text{nom}} f \quad (6)$$

with

$$f = \frac{1 - m \cos(\omega t)}{1 + m \sin(\alpha)}, \quad -\frac{\pi}{2} - \alpha \leq \omega t \leq \frac{\pi}{2} + \alpha \quad (7a)$$

$$f = 1, \quad \text{otherwise.} \quad (7b)$$

The current reference is also a function of the overlap angle. In the simplest approach a linear current transition between the two arms of a phase leg can be assumed during the overlap period. This is depicted in Fig. 3. Hence, the arm current can be written as

$$i_{\text{arm,on}} = \hat{I}_s \cos(\omega t - \varphi), \quad -\frac{\pi}{2} + \alpha \leq \omega t \leq \frac{\pi}{2} - \alpha \quad (8a)$$

$$i_{\text{arm,overlap1}} = i_{\text{arm}} t, \quad -\frac{\pi}{2} - \alpha \leq \omega t \leq -\frac{\pi}{2} + \alpha \quad (8b)$$

$$i_{\text{arm,overlap2}} = i_{\text{arm}}(1 - t), \quad \frac{\pi}{2} - \alpha \leq \omega t \leq \frac{\pi}{2} + \alpha \quad (8c)$$

$$i_{\text{arm,off}} = 0, \quad \text{otherwise.} \quad (8d)$$

Fig. 3: Arm current reference of the AAC with overlap period

By making use of the symmetry properties of the trigonometric functions the arm energy fluctuation can be found to be

$$e_{\text{arm}} = 2 \left(\int_{-\frac{\pi}{2}-\alpha}^{-\frac{\pi}{2}+\alpha} v_{\text{arm}} i_{\text{arm}} dt + \int_{\frac{\pi}{2}-\alpha}^{\frac{\pi}{2}+\alpha} v_{\text{arm}} i_{\text{arm}} dt \right). \quad (9)$$

Relation between modulation index and overlap angle

It is stated in previous publications on the AAC [10, 13] that the converter has to be operated with a modulation index of $m = 4/\pi$ in order to achieve inherent energy balance of a phase leg. However, this holds only for an operation without overlap period. An expression is derived in the following that relates the modulation index to a certain overlap angle in order to achieve the same inherent energy balancing. To start with, the power balance between ac and dc sides is

$$V_d I_{\text{arm,avg}} = \frac{m V_d \hat{I}_s}{4} \cos(\varphi) \quad (10)$$

with $I_{\text{arm,avg}}$ referring to the average arm current that is given by

$$I_{\text{arm,avg}} = \frac{1}{T} \int_0^T i_{\text{arm}} dt. \quad (11)$$

After inserting the expressions for the arm current presented in (8a)-(8d) into (11) and evaluating the integral contained therein, the average arm current is found to be

$$I_{\text{arm,avg}} = \frac{\hat{I}_s \cos(\varphi)}{\pi} \frac{\sin(\alpha)}{\alpha}. \quad (12)$$

Finally, substituting $I_{\text{arm,avg}}$ in (10) and solving for m leads to

$$m = \frac{4}{\pi} \frac{\sin(\alpha)}{\alpha}, \quad (13)$$

which is an analytical expression (in the following called " m - α relation") that relates the modulation index to any overlap angle (see Fig. 4).

Fig. 4: m - α relation for the AAC

The arm energy fluctuation given in (9) is plotted in Fig. 5 for active power transfer and different overlap angles. In Fig. 5a the modulation index is kept according to the *sweet spot*, while the m - α relation presented in (13) is taken into account in Fig. 5b. A drift in the arm energy can be observed in the first case, whereas the arm energy is not drifting when the modulation index is controlled to fulfil the m - α relation. This applies without exception to any power factor. However, it has to be noted that only small changes in the output voltage are possible using this method.

Fig. 5: Arm energy fluctuation of an AAC for active power transfer

Energy storage requirements

The energy storage requirements do not only depend on the voltage limit of the semiconductors and the peak-to-peak energy deviation, but also on the time average of the stored energy in the submodules which can be controlled. It has been shown for the MMC that even if the time average of the available voltage has been reduced the converter can still operate without entering the region of overmodulation [9]. However, the time average of the available voltage must be chosen such that the requested voltage is available in the submodule capacitors at all times. The method presented here is calculating the required energy storage per transferred VA based on those limits.

Case of MMC

The nominal energy in a half- or full-bridge MMC can be written as follows

$$E_{\text{nom}} = \frac{C}{2N} V_d^2 (1+m)^2. \quad (14)$$

The minimum voltage must be greater than the reference voltage, while the maximum voltage must not exceed the rated voltage of the submodules. This leads to the following equation that defines the limits of the stored energy in each arm

$$\frac{C}{2N} V_{\text{arm}}^2 \leq E_0 + e_{\text{arm}} \leq \frac{C}{2N} k_{\text{max}}^2 V_d^2 (1+m)^2. \quad (15)$$

Dividing (15) by (14) leads to (16)

$$\begin{aligned} \frac{(1 - m \cos(\omega t))^2}{(1+m)^2} \leq \frac{E_0}{E_{\text{nom}}} + \frac{1}{E_{\text{nom}}/S} \left(\frac{1}{m\omega} \sin(\omega t - \varphi) - \frac{m}{2\omega} \cos(\varphi) \sin(\omega t) \right. \\ \left. - \frac{1}{4\omega} \sin(2\omega t - \varphi) \right) \leq k_{\text{max}}^2, \end{aligned} \quad (16)$$

where E_0 represents the time average of the energy stored in each arm. The required nominal energy storage E_{nom}/S can be found from (17) and (18) by increasing the power S until the maximum amount of energy that can be stored in each arm is reached.

$$\left(\frac{E_0}{E_{\text{nom}}} \right)_{\min} = \max \left[\frac{(1 - m \cos(\omega t))^2}{(1+m)^2} - \frac{1}{E_{\text{nom}}/S} \left(\frac{1}{m\omega} \sin(\omega t - \varphi) - \frac{m}{2\omega} \cos(\varphi) \sin(\omega t) \right. \right. \\ \left. \left. - \frac{1}{4\omega} \sin(2\omega t - \varphi) \right) \right] \quad (17)$$

$$\left(\frac{E_0}{E_{\text{nom}}} \right)_{\max} = \max \left[\left(\frac{E_0}{E_{\text{nom}}} \right)_{\min} + \frac{1}{E_{\text{nom}}/S} \left(\frac{1}{m\omega} \sin(\omega t - \varphi) - \frac{m}{2\omega} \cos(\varphi) \sin(\omega t) \right. \right. \\ \left. \left. - \frac{1}{4\omega} \sin(2\omega t - \varphi) \right) \right] \leq k_{\text{max}}^2 \quad (18)$$

Case of AAC

The nominal energy in an AAC can be written as

$$E_{\text{nom}} = \frac{C}{2N} V_{\text{nom}}^2. \quad (19a)$$

Again, the minimum voltage must be greater than the reference voltage and lower than the rated voltage of the submodules. Accordingly,

$$\frac{C}{2N} v_{\text{arm}}^2 \leq E_0 + e_{\text{arm}} \leq \frac{C}{2N} k_{\text{max}}^2 V_{\text{nom}}^2. \quad (20)$$

The required nominal energy storage E_{nom}/S can be found from (20) using the same method as for the MMC by substituting e_{arm} in (21a) and (21b) with (9).

$$\left(\frac{E_0}{E_{\text{nom}}}\right)_{\min} = \max \left[f^2 - \frac{e_{\text{arm}}}{E_{\text{nom}}} \right] \quad (21a)$$

$$\left(\frac{E_0}{E_{\text{nom}}}\right)_{\max} = \max \left[\left(\frac{E_0}{E_{\text{nom}}}\right)_{\min} + \frac{e_{\text{arm}}}{E_{\text{nom}}} \right] \leq k_{\max}^2 \quad (21b)$$

Plotting (18) and (21b) produces the plots shown in Fig. 6. They differ considerably from the shape of the peak-to-peak energy deviation presented in [10].

(a) Half- and full-bridge MMC vs. AAC ($\alpha = 0$)

(b) AAC operating 10% away from the *sweet spot* ($\alpha = 0$)

(c) AAC operating with overlap period acc. to m - α relation

Fig. 6: Required nominal energy storage in kJ/MVA

It is shown that operating the MMC with full-bridges ($m = \sqrt{2}$) reduces the energy storage requirements compared to half-bridge submodules (see Fig. 6a), while operating the AAC away from the *sweet spot* and without an overlap period increases the energy storage requirements of the AAC (see Fig. 6b). The amount of energy storage that is required if the AAC is controlled with different overlap angles and according to the m - α relation (13) is illustrated in Fig. 6c. The energy storage requirements are only marginally increased compared to the *sweet spot* for a 30° overlap period and slightly increased for a longer overlap of 60° . For all topologies the lowest energy storage is required when the converter is generating reactive power. In this case the current rating of the submodules and the maximum voltage at the ac terminals are the limiting factors and not the size of the capacitors as previously described in [9].

Simulation Results

Simulations in the software PSCAD/EMTDC are conducted to verify the analytical findings presented above. The AAC used for this study is modelled as a single-phase converter with one full-bridge submodule per arm, director switches and arm inductors according to Fig. 1. The submodule is switched very fast in the simulation such that only a small inductor is needed in order to get as close as possible to the simplified analytical model, where an ideal circuit without inductance and resistance is assumed. The grid is modelled as a resistive load such that always a current of 1 kA flows independent of the modulation index. The selected simulation parameters are summarized in Table I.

Table I: Specifications of the simulated system

Parameter	Value
Fundamental system frequency	50 Hz
DC-link voltage	1 kV (pole-ground)
Resistive load	m k Ω
Arm inductance	0.02 mH
Arm resistance	1 m Ω
Number of submodules	1 per arm
Submodule capacitance	5 mF
Submodule carrier frequency	100 kHz
Simulation time step	0.05 μ s
Proportional gain (Kp)	12

The converter control is implemented as depicted in Fig. 7. It consists of an inner current control loop (see Fig. 7a) and a feedforward voltage controller that calculates the voltage reference signal for the carrier-based pulse width modulation (PWM) of the full-bridge submodules (see Fig. 7b). The arm current reference I_{arm}^{ref} is created by multiplying the output current reference I_s^{ref} with a linear transition function during the overlap period. The error signal e is fed into a proportional controller with the gain Kp and added to the analytical voltage reference V_{sub}^{anal} given in (6). The output of the current controller is the voltage reference for the submodules V_{sub}^{ref} . It is divided by the actual available capacitor voltage v_{cap} in the voltage control block to obtain the PWM reference signal v_{sub}^{ref} .

Fig. 7: Control system of the AAC

The simulated arm energy waveforms are shown in Fig. 8. The same overlap cases as presented in Fig. 5 have been chosen. Comparing Fig. 8 and Fig. 5b it can be concluded that the simulation shows very good agreement with the calculated values.

The modulation index has been chosen to be the parameter that can be varied in order to control the arm energies. The respective operation points that ensure arm energy balance are illustrated in Fig. 9. The simulation results are very close to the analytical values. The maximum discrepancy is slightly more than one percent. This discrepancy can be explained by the fact that the simulated circuit contains inductors and resistors, which were omitted in the analysis. Furthermore, a switching submodule is used in the simulation, in contrast to an ideal voltage source that is used in the analysis.

Fig. 8: Simulated arm energy fluctuation of the AAC

Fig. 9: Comparison of the analytical m - α relation and simulation results

Conclusion

This paper presents a general analysis of the energy storage requirements in the MMC and AAC. Concerning the AAC, a relation between the modulation index and the overlap angle is introduced to match ac and dc energy quantities. The theoretical analysis indicates that the required energy storage is smaller in the AAC compared to the MMC. It is only marginally increased when operating the AAC with an overlap period provided that the converter is controlled according to the presented m - α relation. However, this control method only permits small changes in the output voltage. The theoretical findings were validated by simulation results.

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