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Impact of Modulation Methods on the Trade-Off between Investment and Operation Costs of a Medium-Voltage MMC-based STATCOM

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***Abstract*—The Modular Multilevel Converter (MMC) has become a preferred topology in HVDC applications due to its full controllability and the huge number of voltage steps. The excellent waveform generation, even at low switching frequencies, makes the MMC also very attractive for medium-voltage applications. In this context, both the converter design and the modulation methods need to be properly studied. Minimum switching frequencies are achieved by appropriate modulation, however, sufficient energy needs to be stored in the capacitors. This is particularly a challenge for STATCOM applications because the stored energy in the system needs to be controlled from the ac grid. In this paper different modulation methods with various capacitor designs are investigated for this application to find an optimum trade-off between capacitor design (investment costs) and switching frequency (operation costs). The appropriate MMC design and operation have been proven by simulation and experimental results showing excellent waveforms without additional filtering.**

I. Introduction

The Modular Multilevel Converter (MMC) especially profits by its scalability to different power and voltage levels by standard components and its multilevel waveform generation [1]. Particularly for HVDC transmission systems, the MMC has already become a competitive solution, being able to generate excellent waveforms even at fundamental switching frequencies [2]. The benefits of the MMC can be also exploited for medium-voltage applications as electrical drives where the topology is becoming more and more attractions [3], [4].

However, for STATCOM applications systematic studies are missing, although the potential of the MMC is equally promising in this area. The MMC in double-star configuration enables a very fast and flexible control even if the control of the capacitor energies is sophisticated [5]. Nevertheless, in contrast to single-star configuration, the energy transfer between the three legs can be directly controlled with the help of the circulating currents [6].

Beside the control, the selection of a suitable modulation method is of high importance because it directly influences waveform quality and power losses. However, the optimal selection of the modulation method can not be done without consideration of design aspects, since the capacitor voltage ripple is directly affected by switching pattern and frequency. For this reason, different modulation methods with tailored capacitance design will be investigated in this paper to find an optimum trade-off between capacitor design (investment costs) and switching frequency (operation costs). Since transient conditions are crucial for both, design and control, the performance will be evaluated in asymmetrical grid fault conditions by simulation and experimental results.

This paper is organized as follows. Section II introduces the MMC, whereas the modulation methods are described in Section III. Simulation studies are presented in Section IV and verified by experimental results in Section V. Finally, the conclusion is given in Section VI.

II. Modular Multilevel Converter

Conventional STATCOM applications, based on two-level or three-level voltage source inverters, have to be connected by a bulky transformer to the medium-voltage grid, as illustrated in Fig. 1a. In contrast, the MMC can be easily designed for a direct connection to the medium-voltage grid, enabling a very flexible control and significantly higher power ratings. The electrical circuit of the MMC in double-star configuration is depicted in Fig. 1b, whereas the submodules (SM) are designed as half-bridge cells. The ac grid current i_s can be controlled by the converter voltage according to equation (1).

$$v_\mathrm{conv} = \frac{v_\mathrm{n} - v_\mathrm{p}}{2} \tag{1}$$

The overall energy in the capacitors has to be controlled from the ac grid and equally distributed between the six arms by a proper circulating current control. However, the circulating current i_c can not be controlled independently for each phase due to the missing dc connection. Instead, the circulating currents can be expressed by equations (2)-(4).

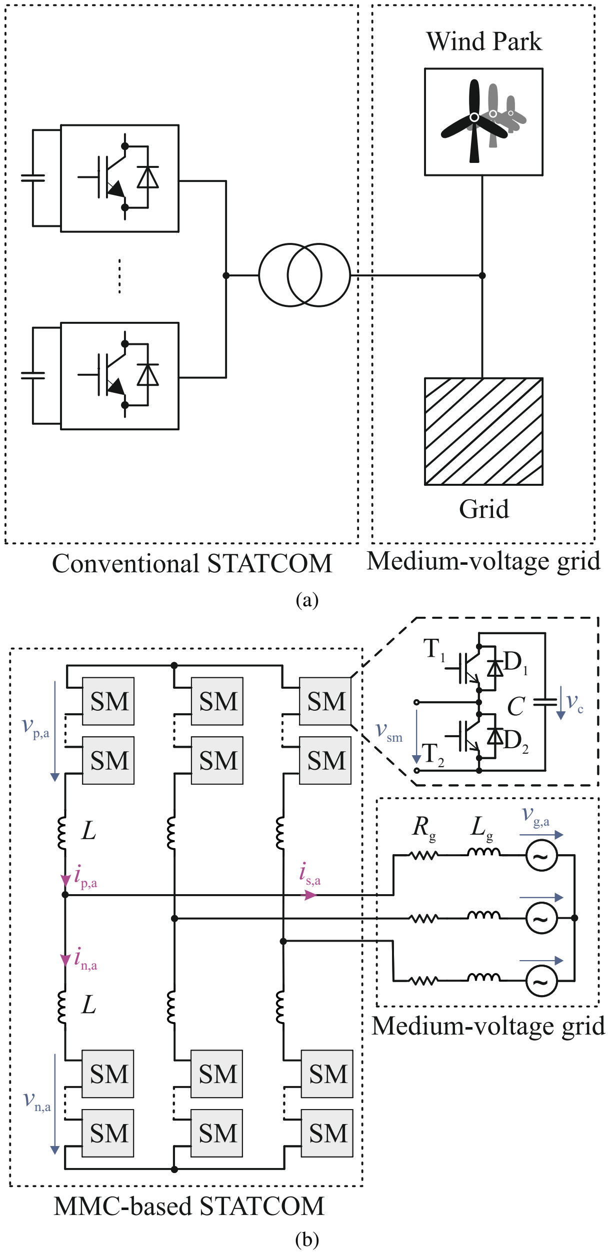


Fig. 1: STATCOM configurations for medium-voltage grid: a) conventional solution, b) MMC-based solution.

$$(v_{\mathrm{p,c}} + v_{\mathrm{n,c}}) - 2(v_{\mathrm{p,a}} + v_{\mathrm{n,a}}) + (v_{\mathrm{p,b}} + v_{\mathrm{n,b}}) = 12L \cdot \frac{\mathrm{d}i_{\mathrm{c,a}}}{\mathrm{d}t} \quad (2)$$

$$(v_{\mathrm{p,a}} + v_{\mathrm{n,a}}) - 2(v_{\mathrm{p,b}} + v_{\mathrm{n,b}}) + (v_{\mathrm{p,c}} + v_{\mathrm{n,c}}) = 12L \cdot \frac{\mathrm{d}i_{\mathrm{c,b}}}{\mathrm{d}t} \quad (3)$$

$$(v_{\mathrm{p,b}} + v_{\mathrm{n,b}}) - 2(v_{\mathrm{p,c}} + v_{\mathrm{n,c}}) + (v_{\mathrm{p,a}} + v_{\mathrm{n,a}}) = 12L \cdot \frac{\mathrm{d}i_{\mathrm{c,c}}}{\mathrm{d}t} \quad (4)$$

Consequently, both the grid currents and the circulating currents can be controlled by the arm voltages v_{p} and v_{n}.

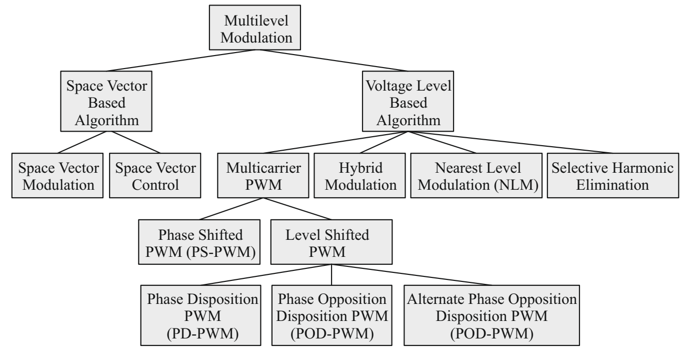


Fig. 2: Multilevel modulation classification.

Particularly during asymmetrical grid faults, the circulating currents need to be properly controlled to balance the energies between the three legs. The reference voltages, being generated by the modulator, are adjusted by both the circulating current control and the grid current control [7].

III. Modulation Methods

In Fig. 2 the standard multilevel modulation methods are summarized according to [8], categorized in space vector and voltage level based algorithms. The space vector based algorithms are not further considered in this paper due to the excessive computation effort for high numbers of SMs [9]. Among the voltage level based algorithms, there is no real benefit for selective harmonic elimination and hybrid modulation because the waveform generation is already excellent due to the high number of voltage steps. These are the reasons why the comparison will be concentrated on nearest level modulation (NLM) [10] and the multicarrier PWM methods [11]. The modulation methods are applied to each arm voltage [12], whereas the modulation range has been extended by third harmonic injection [13].

IV. Simulation Results

The simulation model is implemented according to the mathematical model of the MMC [7], whereas the simulation parameters are summarized in Table I. The MMC is designed for a 30 MVA STATCOM application, oriented to the design procedure in [14], [15]. For this study case, the 1700 V IGBT module FF600R17KE3_B2 from Infineon has been selected, rated for a dc-collector current of 600 A.

The electrical waveforms in Fig. 3 are generated by NLM. According to Fig. 6, the energies in the capacitors are properly controlled between all six arms and all capacitor voltages are kept within the limits by the embedded sorting algorithm. Despite of switching frequencies of only 88 Hz, the NLM achieves an excellent performance with $\mathrm{THD_i}$ values of 0.4 % and non-significant harmonics, as illustrated in Fig. 4. Occurring semiconductor power losses are highlighted in Fig. 5, derived from the datasheet characteristics according to [16]. It becomes clear that the conduction losses are dominant

TABLE I: MMC simulation parameters.

Description	Parameter	Value	Unit
SMs per arm	N	40	
SM's capacitance	C	14...30	mF
Arm inductor	L	3	mH
Arm resistance	R	17	mΩ
Capacitor voltage reference	v_c^*	955	V
Capacitor voltage limit	$v_{c,max}$	1050	V
Grid voltage (rms)	$V_{g,ll}$	20	kV
Grid inductance	L_g	1.13	mH

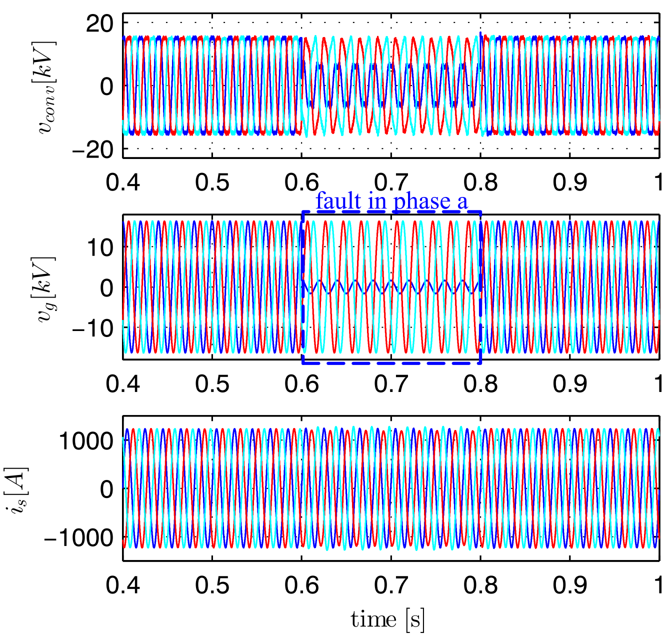


Fig. 3: Converter voltages, grid voltages and grid currents during a grid fault in phase a (NLM).

due to the minimized switching frequency. However, the low switching frequency needs to be paid by bulky capacitors (30 mF), increasing system costs and volume. On the other hand, smaller capacitors would enforce undesired switching events due to protection, resulting in higher losses and operation costs.

In order to achieve a smaller capacitor design, the inherent switching frequency of the modulator needs to be increased. For this purpose, the carrier-based modulation methods are considered by application of carrier frequencies of 5 kHz and 10 kHz for PD-PWM, POD-PWM and APOD-PWM. It is worth noting that the APOD-PWM is equivalent to the PS-PWM since the individual submodules are selected by a centralized capacitor voltage balancing [17]. The obtained switching frequencies between 134 Hz and 319 Hz are summarized in Fig. 7, whereas the capacitance selection is optimized for each study case.

The smallest capacitors can be selected for APOD-PWM due to the homogeneous switching profile. Both, the PD-PWM and APOD-PWM achieve reduced switching frequency

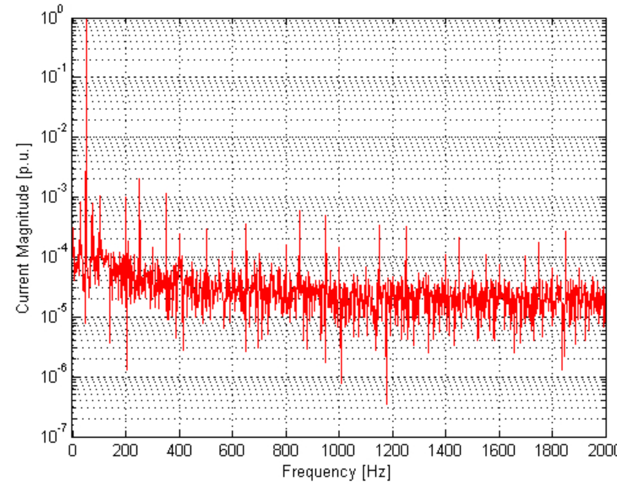


Fig. 4: Grid current spectrum normalized to nominal current $(\hat{i}_s^{50\,\mathrm{Hz}} = 1225\,\mathrm{A})$ (NLM).

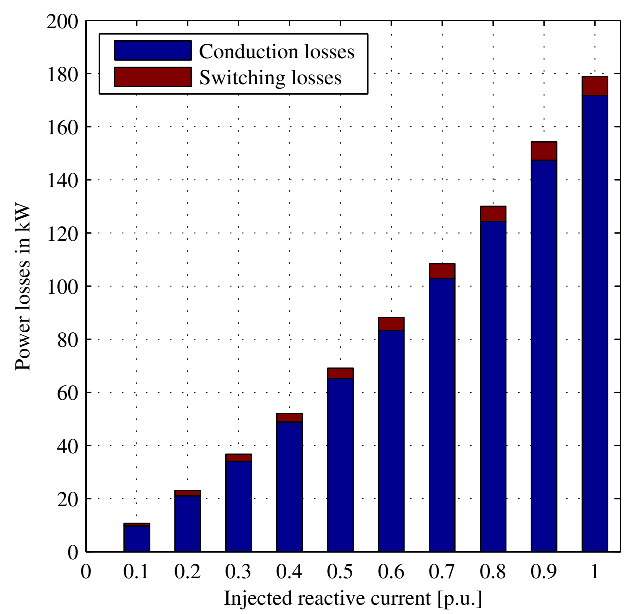


Fig. 5: Conduction and switching losses of all semiconductors (NLM).

due to the high number of voltage steps. Compared to this, the POD-PWM needs significantly more switching operations to follow the voltage references. Consequently, POD-PWM provides increased switching frequencies, leading to higher switching losses. Unlike the conduction losses, the switching losses can be significantly influenced by the selected modulation. In Fig. 8 the switching losses are summarized for all study cases at nominal power. Accordingly, a reduction in the capacitance from 30 mF to 15 mF by PWM requires an increase of switching losses from around 7 kW to more than 22 kW, leading to increased operation costs.

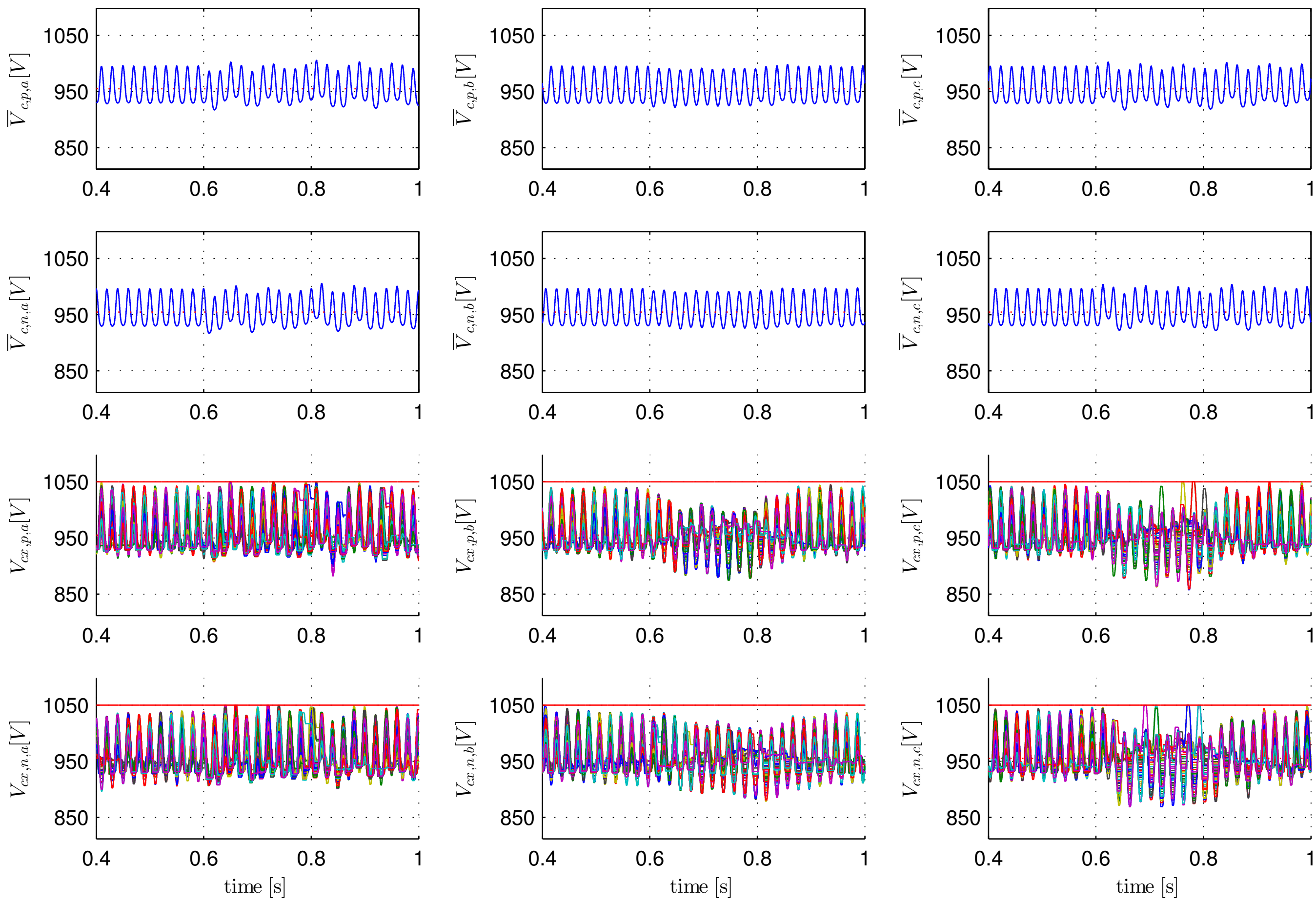


Fig. 6: Capacitor voltages in upper and lower arm, averaged and for each submodule (NLM).

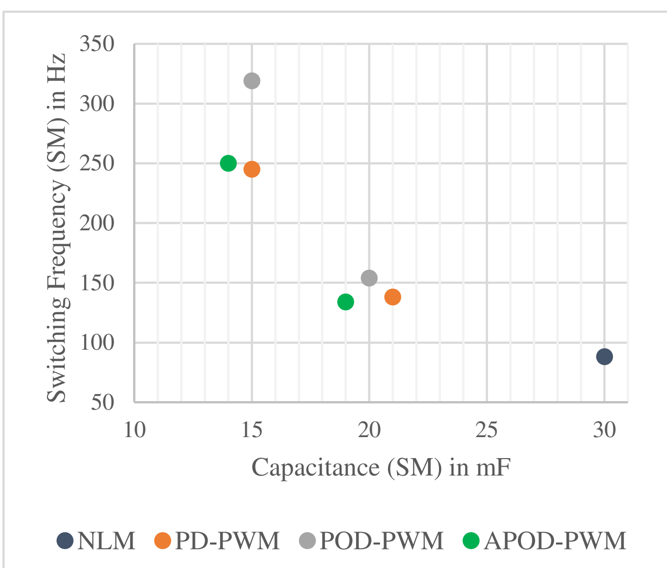


Fig. 7: Trade-off between capacitance and switching frequency by comparison of NLM and carrier-based PWM methods.

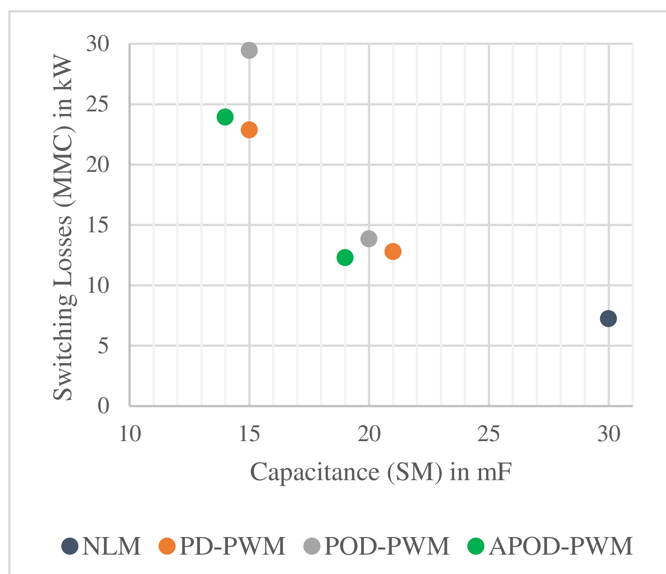
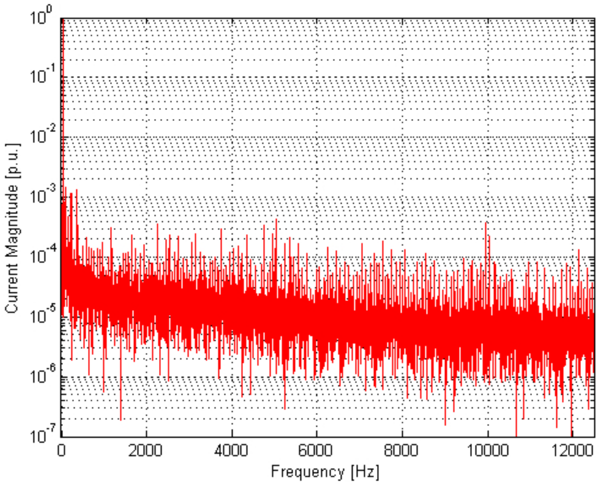
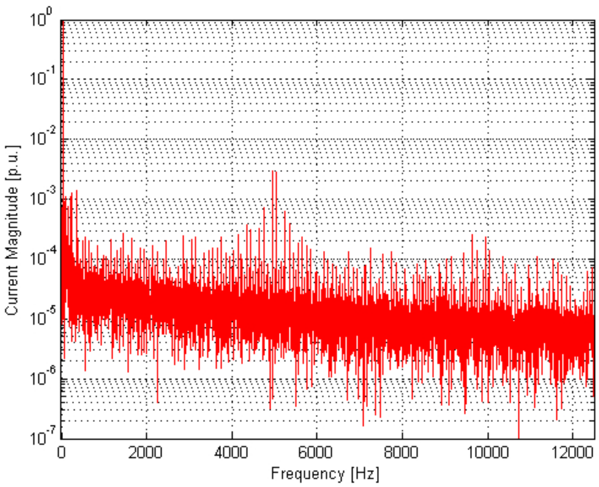


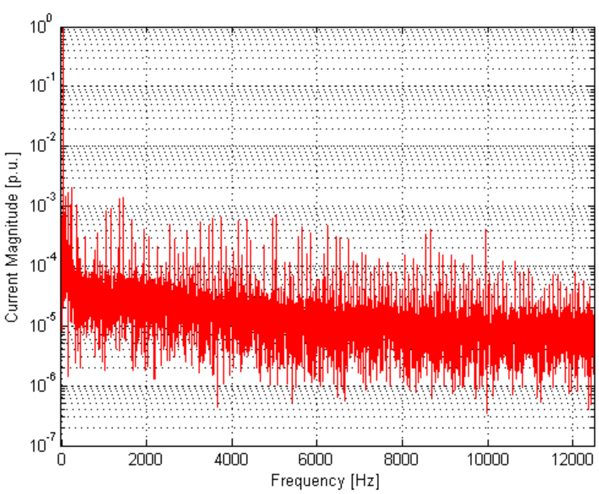
Fig. 8: Trade-off between capacitance and switching losses by comparison of NLM and carrier-based PWM methods.



(a)



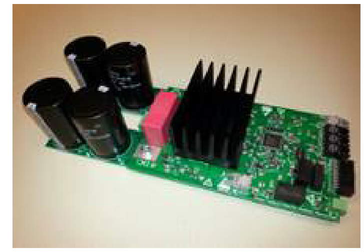
(b)



(c)

Fig. 9: Grid current spectrum normalized to nominal current: a) PD-PWM, b) POD-PWM, c) APOD-PWM.

(a)



(b)

Fig. 10: Experimental setup: a) cabinet, b) submodule board.

TABLE II: Experimental data.

Parameter	Value	Unit
N	4	
L	20	mH
C	4	mF
v_{c}^{*}	25	V
$V_{\mathrm{g,ll}}$	$\sqrt{3} \cdot 30$	V

The harmonic performance is excellent for all modulation methods due to the high number of voltage levels, as illustrated in Fig. 4 for NLM and in Fig. 9 for the PWM methods. Except from both, the size of capacitors (investment costs) and the switching losses (operation costs), the system costs are not significantly influenced by the modulation method. Consequently, the proper modulation method needs to be selected by a trade-off between dc capacitance and switching losses. This trade-off is very individual for each application, strongly depending on the expected mission profile, the local energy costs, the capacitor costs and the available space.

V. Experimental Results

The MMC performance in STATCOM operation will be evaluated by a downscaled setup depicted in Fig. 10, whereas the experimental data are summarized in Table II. Each of the 24 SM boards has an own FPGA as control unit for blanking time generation, capacitor voltage measurement processing as well as protection for overcurrent, overvoltage and overtemperatures. The duty cycles are centrally generated by a dSPACE system (DS1006 processor board), whereas the communication is realized by optic fiber.

In Fig. 11 and 12 the electrical performance of the MMC is shown for NLM. A phase-to-phase grid fault is emulated by the connected ac source for 0.2 s. During the fault the reactive current has been controlled to 5 A for grid voltage stabilization. The currents are properly generated even by NLM and the capacitor voltages are kept within the limits ($\pm 10\,\%$) by the embedded sorting algorithm.

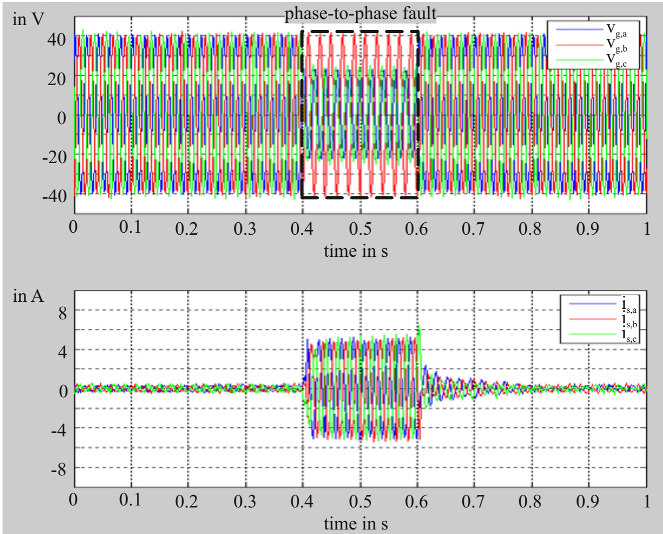


Fig. 11: Grid voltages and grid currents during phase-to-phase fault.

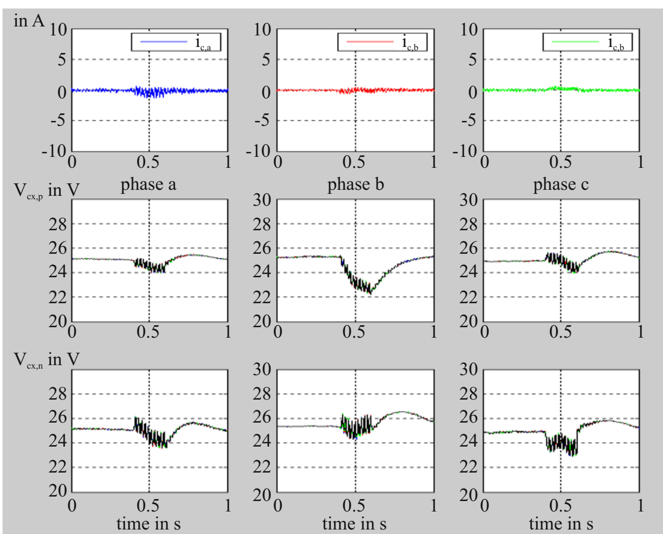


Fig. 12: Circulating currents and capacitor voltages during phase-to-phase fault.

VI. Conclusion

In this paper, different modulation methods have been studied for an MMC-based STATCOM application. It has been shown that the nearest level modulation provides excellent waveforms at switching frequencies lower than 100 Hz, even without additional filters. However, the low switching losses require bulky and expensive capacitors to provide the energy during long and inhomogeneous insertion times. With the help of carrier-based pwm methods, the insertion times can be reduced and more equalized, paid by higher switching losses. By accepting three times higher switching losses at switching frequencies of around 250 Hz, a capacitance reduction of more than 50 % has been demonstrated. Consequently, an individual trade-off has to be done between the submodule capacitance (investment costs) on the one hand and the submodule switching frequency (operation costs) on the other hand.

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