Comparison of 2.3-kV Medium-Voltage Multilevel Converters for Industrial Medium-Voltage Drives

Dietmar Krug, Steffen Bernet, Member, IEEE, Seyed Saeed Fazel, Kamran Jalili, and Mariusz Malinowski, Member, IEEE

Abstract—This paper compares the expense of power semiconductors and passive components of a (2.3 kV, 2.4 MVA) two-level, three-level neutral-point-clamped, three-level flying-capacitor, four-level flying-capacitor, and five-level series-connected H-bridge voltage source converter on the basis of the state-of-the-art 6.5-, 3.3-, 2.5-, and 1.7-kV insulated gate bipolar transistors for industrial medium-voltage drives. The power semiconductor losses, the loss distribution, the installed switch power, the design of flying capacitors, and the components of an LC sine filter for retrofit applications are considered.

Index Terms—Filter design, medium voltage, multilevel converters, power electronics.

I. INTRODUCTION

Today, there is a large variety of converter topologies for medium-voltage drives (MVDs) [1], [31]. Cycloconverters and load commutated converters (LCI) applying thyristors are used, particularly in applications with very high power demands (e.g., $S \geq 30$ MVA).

For low- and medium-power industrial applications (e.g., $S = 300–30$ MVA), the majority of the drive manufacturers offer different topologies of voltage source converters: two-level voltage source converters (2L-VSCs; e.g., Convertteam), three-level neutral-point-clamped voltage source converters (3L-NPC VSCs; e.g., ABB, Convertteam, Siemens, TMEIC), four-level flying-capacitor voltage source converters (4L-FLC VSCs; e.g., Convertteam), and series-connected H-bridge voltage source converters (SCHB VSCs; Siemens). One manufacturer (Allen Bradley) offers self-commutated current source inverters (CSI).

Whereas 4.5-, 6-, and 6.5-kV integrated gate commutated thyristors are mainly used in 3L-NPC VSCs and CISIs, respectively, 2.5-, 3.3-, 4.5-, and 6.5-kV medium-voltage insulated gate bipolar transistors (MV-IGBTs) are applied in 2L-VSCs, 3L-NPC VSCs, and 4L-FLC VSCs. In contrast, 1.2- and 1.7-kV low-voltage IGBTs (LV-IGBTs) are usually applied in SCHB VSCs. To derive specific converter characteristics, the modulation schemes, losses, and harmonic spectra of a 2L-VSC, a 3L-NPC VSC, a 3L-FLC VSC, and a 4L-FLC VSC were compared [2], [3].

This paper also includes the five-level SCHB VSCs (5L-SCHB VSCs) in the comparison. Thus, all available voltage source converter topologies for 2.3-kV industrial MVDs are compared regarding the expense of semiconductors and passive components, converter losses, modulation schemes, and harmonic spectra. It should be noted that the 2L-VSC (e.g., [1] and [4]–[6]), the 3L-NPC VSC (e.g., [1], [7], [8], [17], [24], and [25]), and the 3L/4L-FLC VSC (e.g., [9]–[13] and [33]) can be fed by identical grid side converters since they operate at one dc voltage link [Figs. 1(a) and 2]. In contrast, the 5L-SCHB VSC (e.g., [1], [8], [11], and [13]) requires six insulated dc voltage links (one per power cell), which are fed by a special multiwinding transformer and corresponding rectifiers [Figs. 1(b) and 2].

A retrofit application demanding an output voltage total harmonic distortion (THD) of less than or equal to 5% according to the standard IEEE 519-1999 is chosen to evaluate the quality of the output spectrum and the size of the passive components of an LC sine filter. State-of-the-art 6.5-, 3.3-, 2.5-, and 1.7-kV IGBTs are assumed. The design of semiconductors, flying capacitors, and passive components of an LC sine output filter is described. The calculation of losses and the expense of power semiconductors, gate units, capacitors, and inductors at medium and high switching frequencies are the basis for the converter comparison.

II. CONVERTER SPECIFICATION

Table I depicts the basic converter data and the conditions of a medium-voltage converter for the comparison. The converter ratings and conditions are closed to that of the commercially available medium-voltage converters.

The minimum dc-link voltage to achieve an output line-to-line voltage of 2.3 kV using space vector modulation or a natural sampled sine-triangle modulation with one-sixth added third harmonics can be calculated by

$$V_{dc, min} = \sqrt{2} \times V_{ll,1, rms} = \sqrt{2} \times 2.3 \text{ kV} = 3252.7 \text{ V}. \quad (1)$$

To determine the nominal dc-link voltage of the converter, a dc-link voltage reserve of 4% is required to cover the voltage drop across the filter inductor, i.e.,

$$V_{dc, n} = 1.04 \times V_{dc, min} = 1.04 \times 3252.7 \text{ V} = 3382.8 \text{ V}. \quad (2)$$
III. POWER SEMICONDUCTOR UTILIZATION FOR CONSTANT CONVERTER POWER AND SWITCHING FREQUENCY

Considering the nominal device voltage $V_{com}$ at 100 FIT of IGBTs and diodes, where a cosmic ray withstand capability of 100 FIT (1 FIT is equivalent to 1 failure in $10^9$ operation hours) is guaranteed, 6.5-, 3.3-, 2.5-, and 1.7-kV IGBTs/diodes have to be applied in the 2L-VSC, the 3L-NPC/FLC VSC, the 4L-FLC VSC, and the 5L-SCHB VSC, respectively.

Table II summarizes the design of the power semiconductors for the converter specification of Table I, assuming a carrier
frequency of $f_C = 750$ Hz and a sine-triangle modulation with one-sixth added third harmonics [3], [32].

The constant ratio of commutation voltage $V_{\text{com}}$ and nominal IGBT/diode voltage $V_{\text{com}}$ at 100 FIT ($V_{\text{com}}/V_{\text{com}}$ at 100 FIT = 0.94) shows that the different converters feature the same semiconductor voltage utilization.

To determine the semiconductor current rating, the IGBT and diode ON-state voltages $V_{\text{CE},n,x}$ and the switching losses $E_{\text{sw},x}$ of a device $x$ given in the data sheets are approximated by

$$V_{\text{CE},F,x} = V_{o,x} + A_{\text{cond},x} \cdot i(t) B_{\text{cond},x} \quad (3)$$

$$E_{\text{sw},x} = A_{\text{sw},x} \cdot i(t) B_{\text{sw},x} \quad (4)$$

where $i$ is the instantaneous value of the device current, $V_{o,x}$ and $A_{\text{cond},x}$ are the ON-state voltage parameters (threshold voltage, ON-state resistance), and $B_{\text{cond},x}$, $A_{\text{sw},x}$, and $B_{\text{sw},x}$ denote the fitting constants of the ON-state voltage and switching losses, respectively [14], [15].

The fitting parameters and thermal resistance of the semiconductors being considered can be taken from Table III, where the abbreviations T (IGBT) and D (diode) are used for a device $x$.

An accurate loss simulation model, which is described in detail in [14], enables the determination of the semiconductor losses and junction temperatures. The accuracy of the loss and junction temperature calculation and the thermal model being applied is evaluated in [24]. To calculate the ideal current rating $I_{C,n}(I_{F,n})$, an ideal parallel connection of commercially available IGBT or diode modules is assumed. It is obvious that ON-state and switching losses are adapted to the ideal rated current and the corresponding silicon area. Furthermore, also the thermal resistance $R_{\text{th,je}}$ (thermal resistance of IGBT/diode from junction to case) and $R_{\text{th,ch}}$ (thermal resistance of IGBT/diode from case to heat sink) are adjusted to the rational number of ideally parallel connected modules according to the silicon area and the module size. The calculated ideal rated IGBT/diode currents $I_{C,n}/I_{F,n}$ (Table II) guarantee that the junction temperature of the mostly stressed IGBT or diode reaches a value of $T_j = 125$ °C in one worst case operating point of the four-quadrant operation. The temperature of the heat sink is supposed to be constant ($T_h = 80$ °C).

It is interesting that the required ideal current rating $I_{C,n}/I_{F,n}$ to enable a converter output current of $I_{\text{ph},1,\text{rms}} = 600$ A is very different for the considered topologies (Table II).

To determine the design of the flying capacitors for sinusoidal output voltages and currents, the flying capacitor voltages and device blocking voltages, effective switching frequencies, and semiconductor loss distributions, which are caused by the different circuit structures and modulations. Compared to the 5L-SCHB VSC, the installed switch powers of the 2L-VSC, 4L-FLC VSC, and both 3L VSCs are increased by about 55%, 28%, and 4%, respectively.

Although the semiconductor utilization is a very important value to evaluate medium-voltage topologies due to the high share of semiconductor costs in medium-voltage converters, it must be considered that the output voltage spectrum of the topologies is very different at constant carrier frequency [3]. To eliminate the influence of the different output voltage spectra, Section V contains a comparison of active (semiconductors, gate units) and passive (inductors, capacitors) power part components if all converters realize an output voltage THD of less than or equal to 5%.

### IV. Design of Passive Components

#### A. Design of Flying Capacitors

Assuming a constant dc output current and reference signal of the modulation, the equation

$$C = \frac{I_{\text{dc}}}{p \cdot \Delta V_C \cdot f_c} \quad (5)$$

where $I_{\text{dc}}$ is the dc output current, $P$ is the number of series-connected flying capacitor cells, $\Delta V_C$ is the maximum voltage ripple across the flying capacitors, and $f_c$ is the carrier frequency, enables the design of the flying capacitors for a given converter structure and a specified capacitor voltage ripple [16]. For sinusoidal converter output voltages (sinusoidal reference signals) and currents, (5) can be used as an approximation if the amplitude of the maximum phase current $I_{\text{ph},\text{rms}}$ is applied, i.e.,

$$C = \frac{i_{\text{ph},\text{rms}}}{p \cdot \Delta V_C \cdot f_c} \quad (6)$$

To determine the design of the flying capacitors for sinusoidal output voltages and currents, the flying capacitor voltages and currents were simulated during one period of the reference signal for the (2.3 kV, 2.39 MVA) 3L-FLC VSC and 4L-FLC VSC (Figs. 7 and 8). The maximum capacitor voltage ripple $\Delta V_{C,max}$ was specified to 7.5% of the dc-link voltage $V_{dc}$. A sine triangle modulation with added third harmonics [3] was chosen to ensure a natural balancing of the flying capacitor voltages within one period of the reference signal.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>BASIC CONVERTER DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converter line-to-line voltage $V_{l1,1,\text{rms}}$</td>
<td>2.3 kV</td>
</tr>
<tr>
<td>Phase current $I_{p,1,\text{rms}}$</td>
<td>600 A</td>
</tr>
<tr>
<td>Apparent converter output power $S_C$</td>
<td>2.39 MVA</td>
</tr>
<tr>
<td>Converter output frequency $f_o$</td>
<td>0 Hz - 100 Hz</td>
</tr>
<tr>
<td>Converter efficiency $\eta$</td>
<td>99%</td>
</tr>
<tr>
<td>Output limit filter</td>
<td>LC sine filter</td>
</tr>
<tr>
<td>THD of output voltage $v_m$ according to IEEE 519-1990</td>
<td>5%</td>
</tr>
<tr>
<td>Nominal dc-link voltage $V_{d,k,n}$</td>
<td>3383 V</td>
</tr>
<tr>
<td>Modulation</td>
<td>Natural sampled sine-triangle modulation with 1/6 added third harmonics</td>
</tr>
<tr>
<td>Carrier frequency $f_C$</td>
<td>275 Hz – 4580 Hz</td>
</tr>
<tr>
<td>Maximum junction temperature $T_{j,\text{max}}$ (IGBT, diode)</td>
<td>125 °C</td>
</tr>
<tr>
<td>Heat sink temperature $T_h$</td>
<td>80 °C</td>
</tr>
</tbody>
</table>
TABLE II
CONVERTER VOLTAGE AND SEMICONDUCTOR SPECIFICATIONS FOR CONSTANT CONVERTER POWER AND CARRIER FREQUENCY

<table>
<thead>
<tr>
<th></th>
<th>2L-VSC</th>
<th>3L-NPC VSC</th>
<th>3L-FLC VSC</th>
<th>4L-FLC VSC</th>
<th>5L-SCHB VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal dc-link voltage $V_{dc,n}$</td>
<td>3382.8 V</td>
<td>3382.8 V</td>
<td>3382.8 V</td>
<td>3382.8 V</td>
<td>845.7 V</td>
</tr>
<tr>
<td>Commutation voltage $V_{com}$</td>
<td>3382.8 V</td>
<td>1601.4 V</td>
<td>1601.4 V</td>
<td>1127.6 V</td>
<td>845.7 V</td>
</tr>
<tr>
<td>Rated device voltage $V_{ce,n}$</td>
<td>6.5 kV IGBT</td>
<td>3.3 kV IGBT</td>
<td>3.3 kV IGBT</td>
<td>2.5 kV IGBT</td>
<td>1.7 kV IGBT</td>
</tr>
<tr>
<td>$V_{com}/V_{com}@100{\text{FIT}}$</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>Rated IGBT / diode current $I_{Cn}$</td>
<td>990 A</td>
<td>656 A</td>
<td>672 A</td>
<td>710 A</td>
<td>611 A</td>
</tr>
<tr>
<td>$S_{c}(S_{c}=V_{ce,n}I_{Cn})$</td>
<td>38.61 MVA</td>
<td>25.98 MVA</td>
<td>26.61 MVA</td>
<td>31.95 MVA</td>
<td>21.92 MVA</td>
</tr>
</tbody>
</table>

TABLE III
FITTING PARAMETERS AND THERMAL RESISTANCE OF SEMICONDUCTORS

<table>
<thead>
<tr>
<th></th>
<th>FZ600R65K5F1 EUPEC 6.5 kV/600 A</th>
<th>FZ800R33K5F2C EUPEC 3.3 kV/800 A</th>
<th>FZ1000R25K5F1 EUPEC 2.5 kV/1000 A</th>
<th>FZ600R17K3E3 EUPEC 1.7 kV/600 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{CE}$</td>
<td>3600 V</td>
<td>1800 V</td>
<td>1200 V</td>
<td>900 V</td>
</tr>
<tr>
<td>$V_{o,T}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>$V_{o,D}$</td>
<td>0.5</td>
<td>0.8</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>$A_{on,T}$</td>
<td>0.010908105</td>
<td>0.000959466</td>
<td>0.000233997</td>
<td>0.00057942</td>
</tr>
<tr>
<td>$B_{on,T}$</td>
<td>1.001643596</td>
<td>1.115444805</td>
<td>1.284617945</td>
<td>0.9531</td>
</tr>
<tr>
<td>$A_{off,T}$</td>
<td>0.00437628</td>
<td>0.003771589</td>
<td>0.00177838</td>
<td>0.00066378</td>
</tr>
<tr>
<td>$B_{off,T}$</td>
<td>1.044655002</td>
<td>0.814860719</td>
<td>0.919017928</td>
<td>0.88671</td>
</tr>
<tr>
<td>$A_{on,D}$</td>
<td>0.039192228</td>
<td>0.059062305</td>
<td>0.04590942</td>
<td>0.0088387</td>
</tr>
<tr>
<td>$B_{on,D}$</td>
<td>0.574245428</td>
<td>0.422711861</td>
<td>0.38569705</td>
<td>0.43627</td>
</tr>
<tr>
<td>$A_{off,D}$</td>
<td>0.098574252</td>
<td>0.033603338</td>
<td>0.016146867</td>
<td>0.010357</td>
</tr>
<tr>
<td>$B_{off,D}$</td>
<td>0.591830287</td>
<td>0.687596711</td>
<td>0.744225321</td>
<td>0.79806</td>
</tr>
<tr>
<td>$R_{on,T}$</td>
<td>0.011</td>
<td>0.013</td>
<td>0.012</td>
<td>0.04</td>
</tr>
<tr>
<td>$R_{on,D}$</td>
<td>0.021</td>
<td>0.026</td>
<td>0.024</td>
<td>0.065</td>
</tr>
<tr>
<td>$R_{off,T}$</td>
<td>0.009</td>
<td>0.009</td>
<td>0.012</td>
<td>0.016</td>
</tr>
<tr>
<td>$R_{off,D}$</td>
<td>0.018</td>
<td>0.018</td>
<td>0.024</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Fig. 3. Flying capacitor voltage ripple of a 3L-FLC VSC as a function of modulation index and phase shift ($I_{ph,1,rms} = 600 A$, $f_c,3L$-FLC VSC = 1200 Hz, $C = 1393 \mu F$).

Fig. 4. Flying capacitor current of a 3L-FLC VSC as a function of modulation index and phase shift ($I_{ph,1,rms} = 600 A$, $f_c,3L$-FLC VSC = 1200 Hz, $C = 1393 \mu F$).

and the phase shift $\varphi$ between output voltage and current for the 3L-FLC VSC and the 4L-FLC VSC, respectively. The maximum voltage ripple $\Delta V_{C,max}$ and the current stress of the 3L-FLC VSC occur at a modulation index of $m = 0$ (Figs. 3 and 4). The maximum voltage ripple is identical to the corresponding value based on (6). The reason for the match of simulated and calculated capacitor voltage ripple is that the flying capacitor of the 3L-FLC VSC is stressed with 180° rectangular capacitor current parts of the load current [34], [35]. A carrier frequency of $f_c = 1200$ Hz was assumed since commercially available flying capacitor medium-voltage converters are operated at similar carrier frequencies.

Figs. 3–6 depict the voltage ripple $\Delta V_C$ and the current of the flying capacitors as a function of the modulation index

$$m = \frac{V_{ll,1,rms}}{\sqrt{3}} \cdot \frac{V_{dc}}{2}$$

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Fig. 5. Flying capacitor voltage ripple of a 4L-FLC VSC as a function of modulation index and phase shift \((I_{\text{ph,1,rms}} = 600 \text{ A}, f_{C,4L-FLC \text{ VSC}} = 1200 \text{ Hz}, C_{1,2} = 928 \mu \text{F})\).

Fig. 6. Flying capacitor current of a 4L-FLC VSC as a function of modulation index and phase shift \((I_{\text{ph,1,rms}} = 600 \text{ A}, f_{C,4L-FLC \text{ VSC}} = 1200 \text{ Hz}, C_{1,2} = 928 \mu \text{F})\).

(Fig. 7). Thus, the rms capacitor current is identical to the rms load current. In contrast, the maximum capacitor voltage ripple \(\Delta V_{C,\text{max}}\) of the 4L-FLC VSC occurs at \(m = 0.808\) at a phase shift between output voltage and current of \(\varphi = 90^\circ\) (Figs. 5 and 6).

The maximum capacitor current of the 4L-FLC VSC is about 18% lower than that of the 3L-FLC VSC due to the occurring zero capacitor current states, which are caused by the three phase-shifted carrier signals of the modulation. The voltage ripple is about 30% higher compared to the calculated value according to (6) since maximum positive and negative capacitor voltages during one-half period of the reference modulation signal are not identical (Fig. 8). Obviously, the average capacitor voltage of the 4L-FLC VSC fluctuates during half cycles of the period of the reference signal.

This deviation between simulated and calculated capacitor voltage ripple is independent of the carrier frequency \(f_C\) if the frequency ratio of carrier frequency and frequency of the reference signal \(f_o\) is sufficiently large (e.g., \(f_C/f_o > 4, \ldots, 5\)). Thus, the value of the flying capacitors of the 4L-FLC VSC calculated on the basis of (6) has to be increased by about 30% to fulfill the specified maximum ripple voltage.

Table IV summarizes the design of the flying capacitors according to (6) and the simulation results of Figs. 3–8.

B. Design of an LC Sine Filter

Disadvantages of directly inverter-fed variable speed drives are the additional harmonic losses, a high insulation stress of the machine windings due to steep \(dv/dt\’s\) at the inverter output, and increased overvoltages at the machine windings if long cables are applied [17], [18]. These drawbacks can be avoided if the harmonics around the switching frequency and multiples of the switching frequency are reduced. In particular, for retrofit applications, MVDs usually apply a low-pass \(LC\) sine filter at the output (Fig. 9), which basically enables sinusoidal machine voltages and currents.

Minimum costs, losses, size, and weight are typical optimization criteria of the \(LC\) sine filters. For the converter comparison of Section V, the design and evaluation of the filters have been performed for the following two cases:

- converter operation at constant converter efficiency assuming a THD of the phase voltage \(v_M \leq 5\%\) according to the standard IEEE 519-1999;
- converter operation at maximum switching frequency at a THD of the phase voltage \(v_M \leq 5\%\).
The filter design was realized by MATLAB/Simulink simulations assuming an active damping control [19]. A machine leakage inductance of $L_M = 20\%$ (1.4 mH), which is typical for industrial induction machines, was assumed. The transfer functions of the harmonics are described by (8)–(10) [2], [21].

The inductance of the $LC$ filter should be chosen according to (11) to limit the converter current ripple [21]. For all topologies, the maximum current ripple $i_{\text{ripple,peak}}$ is specified to be equal to or less than 40% of the rated phase current amplitude, i.e.,

$$L_f = \frac{V_{\text{I}}}{2 \sqrt{6} \cdot f_{\text{cb}} \cdot i_{\text{ripple, peak}}}. \quad (11)$$

To set the resonance frequency to about 0.5 of the first carrier band frequency $f_{\text{cb}}$, the capacitor of the $LC$ filter (Y-connected) is described by the following [22]:

$$C_f = \frac{L_f + L_M}{4 \cdot \pi^2 \cdot f_{\text{rms}}^2 \cdot L_f \cdot L_M}. \quad (12)$$

V. CONVERTER COMPARISON

A. Comparison at Constant Efficiency

1) Losses and Semiconductor Loss Distribution: To enable an evaluation of the considered topologies for different applications, it was assumed for a first comparison that converter power ($S_C = 2.39$ MVA) and efficiency are constant ($\eta \approx 99\%$). The efficiency being selected is typical for state-of-the-art medium-voltage converters.

The carrier frequencies, the ideal rated IGBT/diode currents, and, thus, the installed switch powers were determined in an iterative simulation procedure to meet both the efficiency requirement at the specified converter power and a junction temperature of $T_j = 125\, ^\circ\text{C}$ in one worst case operating point. Table V depicts the resulting ideal rated currents, installed switch powers, carrier frequencies, and capacitance of the flying capacitors.

The core of the iterative simulation procedure is the loss simulation model described in Section III. In a first step, the carrier frequencies for a converter efficiency of $\eta \approx 99\%$ ($n = 1.11$; $I_{\text{ph,1,rms}} = 600\, \text{A}; \cos \varphi = 0.9$) were determined assuming an installed switch power of $S_S = 38.61$ MVA (Table II) in all topologies. In a second step, the rated semiconductor currents were calculated for the new carrier frequencies to achieve a maximum junction temperature of $T_j = 125\, ^\circ\text{C}$ in one worst case operating point of the converter. Since the change of the semiconductor current rating influences the converter efficiency, a new carrier frequency and new rated semiconductor currents are calculated during a second iteration. The iterations are repeated until a converter efficiency of about $\eta \approx 99\%$ and a maximum junction temperature of $T_j = 125\, ^\circ\text{C}$ are achieved. The semiconductor current ratings, carrier frequencies, efficiencies, and installed switch powers are shown in Table V.

The relative installed switch power $S_{SR}$ is calculated by normalizing the installed switch power of a certain converter topology to the installed switch power of the 3L-NPC VSC, i.e.,

$$S_{SR} = \frac{S_S}{S_{S,3L-NPC\,\text{VSC}}} \times 100. \quad (13)$$

Fig. 10 depicts the corresponding loss distribution of the converters being considered. Although the installed switch powers of the 2L-VSC and the 3L-NPC VSC are comparable, the

<table>
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<th>TABLE IV</th>
<th>FLYING CAPACITOR DESIGN ($V_{\text{I}}, V_{\text{rms}} = 2.3, \text{kV}, I_{\text{ph,1,rms}} = 600, \text{A}, f_C = 1200, \text{Hz}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design according to Equation (5)</td>
<td>Design according to simulation results (Fig. 7 / Fig. 8)</td>
</tr>
<tr>
<td>Specified capacitor voltage ripple $AV_C$</td>
<td>Capacity of flying capacitors</td>
</tr>
<tr>
<td>3L-FLC VSC</td>
<td>254 V</td>
</tr>
<tr>
<td>4L-FLC VSC</td>
<td>254 V</td>
</tr>
</tbody>
</table>
installed switch powers of the 3L-FLC VSC ($f_C = 500$ Hz), the 4L-FLC VSC, and the 5L-SCHB VSC are reduced by 21%, 6%, and 16%, respectively, in comparison to the 3L-NPC VSC. Although the 3L-FLC VSC is operated at half of the carrier frequency of the 3L-NPC VSC, the losses of both converters are not identical. The reason for this is the lower ideal current rating of the semiconductors in the 3L-FLC VSC, which is caused by a symmetrical loss distribution in the 3L-FLC VSC in contrast to the unsymmetrical loss distribution in the 3L-NPC VSC [31], [23], [25]. The conduction losses ($P_{\text{cont}}/D$: conduction losses of IGBTs/diodes) of the 4L-FLC VSC are drastically higher compared to those of the other topologies since there are always three conducting medium-voltage devices in the current path due to the three series-connected commutation cells. On the other hand, the switching losses ($P_{\text{onT}}$: turn-on losses of IGBTs; $P_{\text{offT}}/D$: turnoff losses of IGBTs/diodes) of the 2.5-kV IGBTs/diodes of the 4L-FLC VSC are very small. Also, in the case of the 5L-SCHB VSC, the on-state losses clearly dominate due to the very low switching losses of the 1.7-kV IGBTs/diodes. The 6.5-kV IGBTs/diodes of the 2L-VSC realize low conduction but very high switching losses even at the low carrier frequency of $f_C = 450$ Hz.

2) **LC Sine Filter:** The values of the LC filter components of the five topologies for a converter efficiency of about $\eta = 99\%$ and a THD of the machine phase voltages of THD, $V_M \leq 5\%$ are given in Table VI.

The 2L-VSC realizes a very low frequency $f_{1cb}$ of the first harmonic band. To eliminate the low-frequency current harmonics, an extremely large inductor in the LC filter must be used, which results in a high voltage drop across the inductor and finally a substantially increased dc-link voltage to deliver the nominal power to the motor. However, an increase in the dc-link voltage is not possible to ensure a high reliability of the semiconductors ($V_{\text{dc,max}} \leq V_{\text{com}}$ at 100 FTT). Obviously, the 2L-VSC applying 6.5-kV IGBTs/diodes is not a useful medium-voltage converter topology for industrial medium-voltage applications if a high efficiency ($\eta = 99\%$) and a low THD of the machine voltage (THD, $V_M \leq 5\%$) are required since a reasonable LC sine filter design cannot be achieved. The 3L-NPC VSC and the 3L-FLC VSC realize an identical output voltage spectrum, which leads to an identical filter design of both converters, if the condition $f_C,3\text{L-FLC VSC} = 0.5f_C,3\text{L-NPC VSC}$ is fulfilled, and a comparable modulation is applied.

Both first carrier band frequencies $f_{1cb}$, and stored energy in the LC filter are in the same range for the 3L-NPC VSC, the 3L-FLC VSC, and the 4L-FLC VSC. However, the very high frequency of the first carrier band $f_{1cb}$ of the 5L-SCHB VSC compared to the other topologies causes a drastic reduction of the filter values. Despite comparable carrier frequencies, the 5L-SCHB VSC enables a reduction of the stored energy of the LC sine filter components by about 84% compared to both 3L-VSCs and the 4L-FLC VSC. Furthermore, the 5L-SCHB VSC causes the minimum THD of the converter current.

Figs. 11–13 present the simulation results of the inverter phase voltage $v_I$, the machine phase voltage $v_M$, the inverter current $i_I$, and the machine current $i_M$.

### B. Comparison at Maximum Switching Frequency

1) **Losses and Semiconductor Loss Distribution:** To extend the converter evaluation to high switching frequency applications, a second converter comparison is realized for the maximum switching frequency of each converter. Additional to the converter data of Table I, a constant installed switch power of $S_S = 38.61$ MVA is assumed.

The maximum carrier switching frequency of a converter is achieved if one of the semiconductors reaches the maximum junction temperature $T^\circ_{j,\text{max}} = 125 ^\circ$C in one worst case operating point of the four-quadrant operation. Table VII summarizes the corresponding carrier frequencies, the frequencies of the first harmonic band $f_{1cb}$, and the converter efficiencies. The

---

**TABLE V**

<table>
<thead>
<tr>
<th>TABLE V</th>
<th>CARRIER FREQUENCY AND CAPACITY OF FLYING CAPACITORS FOR A CONVERTER EFFICIENCY OF 99%</th>
<th>(V_{\text{dc,1rms}} = 2.3 kV, I_{\text{ph,1rms}} = 600 A, S_C = 2.39 MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed switch power $S_S$</td>
<td>29.25 MVA</td>
<td>30.096 MVA</td>
</tr>
<tr>
<td>Relative installed switch power $S_R$</td>
<td>97.2%</td>
<td>100%</td>
</tr>
<tr>
<td>Nominal IGBT / diode voltage</td>
<td>6.5 kV</td>
<td>3.3 kV</td>
</tr>
<tr>
<td>Rated IGBT / diode current $I_{\text{CS,1}} = I_{\text{CE,1}}$</td>
<td>750 A</td>
<td>760 A</td>
</tr>
<tr>
<td>Converter efficiency $\eta$</td>
<td>99.06%</td>
<td>99.06%</td>
</tr>
<tr>
<td>Carrier frequency $f_C$</td>
<td>450 Hz</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>First carrier band $f_{1cb}$</td>
<td>450 Hz</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>Capacity of flying capacitor</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
TABLE VI

<table>
<thead>
<tr>
<th>Topology</th>
<th>( f_{C}[\text{Hz}] )</th>
<th>( f_{C5}[\text{Hz}] )</th>
<th>( L_{C}[\mu\text{H}] )</th>
<th>( C_{f} [\mu\text{F}] )</th>
<th>THD_{L/I} [%]</th>
<th>THD_{V_M} [%]</th>
<th>( W_{T} [\text{J}] )</th>
<th>( W_{t} [\text{J}] )</th>
<th>( W_{ext} [\text{J}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2L-VSC</td>
<td>450</td>
<td>450</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3L-NPC VSC</td>
<td>1000</td>
<td>1000</td>
<td>3 \times 800</td>
<td>3 \times 375</td>
<td>10.8</td>
<td>4.7</td>
<td>1424</td>
<td>-</td>
<td>1424</td>
</tr>
<tr>
<td>3L-FLC VSC</td>
<td>500</td>
<td>1000</td>
<td>3 \times 800</td>
<td>3 \times 375</td>
<td>10.8</td>
<td>4.7</td>
<td>1424</td>
<td>3344</td>
<td>14351</td>
</tr>
<tr>
<td>4L-FLC VSC</td>
<td>275</td>
<td>825</td>
<td>3 \times 800</td>
<td>3 \times 370</td>
<td>9.8</td>
<td>4.2</td>
<td>1411</td>
<td>5269</td>
<td>50259</td>
</tr>
<tr>
<td>5L-SCHB VSC</td>
<td>985</td>
<td>3940</td>
<td>3 \times 240</td>
<td>3 \times 47</td>
<td>6.9</td>
<td>3.1</td>
<td>232</td>
<td>-</td>
<td>232</td>
</tr>
</tbody>
</table>

* Assumption: converter without dc-link capacitors

Fig. 11. Simulation results of 3L-NPC/FLC VSC (\( f_{C,3L-NPC-VSC} = 1000 \text{ Hz}, f_{C,3L-FLC-VSC} = 500 \text{ Hz} \)). (a) Phase voltage \( v_I \) (inverter side). (b) Inverter current \( i_I \). (c) Phase voltage \( v_M \) (machine side). (d) Machine current \( i_M \).

Fig. 12. Simulation results of 4L-FLC VSC (\( f_{C,4L-FLC-VSC} = 275 \text{ Hz} \)). (a) Phase voltage \( v_I \) (inverter side). (b) Inverter current \( i_I \). (c) Phase voltage \( v_M \) (machine side). (d) Machine current \( i_M \).
Fig. 13. Simulation results of 5L-SCHB VSC \( f_C = 4580 \) Hz. (a) Phase voltage \( v_I \) (inverter side). (b) Inverter current \( i_I \). (c) Phase voltage \( v_M \) (machine side). (d) Machine current \( i_M \).

Semiconductor loss distribution can be taken from Fig. 14. It is remarkable that the 3L-FLC VSC enables almost the same carrier frequency like the 3L-NPC VSC, which means that the resulting switching frequency at the converter output is almost doubled. This is because of a substantially more equal loss distribution of the semiconductors of one phase in the 3L-FLC VSC [23].

Whereas also the carrier frequencies of the 4L-FLC VSC \( f_C = 1500 \) Hz and the 5L-SCHB VSC \( f_C = 4580 \) Hz are remarkably high, the maximum carrier frequency of the 2L-VSC is very low \( f_C = 750 \) Hz due to the high switching losses of the 6.5-kV IGBTs/diodes. The maximum frequency of the first carrier band of the 4L-FLC VSC \( f_{1cb} = 4500 \) Hz is about 25% and 137% higher than that of the 3L-FLC VSC and the 3L-NPC VSC, respectively. The phase-shifted modulation of the series-connected H-bridges and the low switching losses of the 1.7-kV IGBTs/diodes cause an extremely high maximum first carrier band frequency of the 5L-SCHB VSC \( f_{1cb} = 18.3 \) kHz. This frequency is increased by factors of about 9.6 and 4 compared to the 3L-NPC VSC and the 4L-FLC VSC, respectively.

2) LC Sine Filter: Table VIII shows the values of the filter components for the maximum switching (carrier) frequencies.

The first harmonic carrier band of the 3L-NPC VSC occurs at the maximum carrier frequency of 1900 Hz. In contrast, the first harmonic carrier band of the 3L-FLC VSC is centered at around twice of its maximum carrier frequency \( f_{1cb} = 3600 \) Hz. Obviously, the components of the output filter of the 3L-FLC VSC are essentially smaller than those of the 3L-NPC VSC since the inductor values, as well as the capacitor values, decrease with increasing frequency of the first harmonic carrier band according to (11) and (12).

The four-level output voltage and the high frequency of the first harmonic band \( f_{1cb} = 4500 \) Hz are the reasons why the inductance value of the 4L-FLC VSC is about 35% and 67% lower than that of the 3L-FLC VSC and the 3L-NPC VSC, respectively. The capacitance value of the 4L-FLC VSC is about 34% and 70% lower than that of the 3L-FLC VSC and the 3L-NPC VSC, respectively.

The very high first carrier band frequency \( f_{1cb} \) of the 5L-SCHB VSC causes very small filter components and stored energies. It becomes clear from Table VIII that the increase in the number of voltage levels enables smaller LC filter values and a decrease in the THDs of the machine phase voltages and the inverter currents.

Simulated waveforms of the inverter phase voltage \( v_I \), the machine phase voltage \( v_M \), the inverter current \( i_I \), and the machine current \( i_M \) are depicted in Figs. 15–17.

C. Practical Considerations

1) Modularity and Maintenance of the Converters: A modular design of medium-voltage converters is an important requirement, which enables a platform based on development, manufacturing, and service of converter systems. Usually, one inverter phase leg depicts one power electronic building block in 3L-NPC VSCs and 4L-FLC VSCs, respectively [8], [27], [28].

In the case of a 2.3-kV IGBT 3L-NPC VSC, a modular phase leg design can be achieved by three power cards containing two 3.3-kV IGBT/diode modules including gate units on one heat sink (Fig. 18) [27]. The standardization of the power cards enables a simple assembly of the inverters. Furthermore, the power cards can be exchanged within a few minutes without special tools in case of a failure [27].

One phase leg of a 4L-FLC VSC is realized by three IGBT cell modules and three floating capacitor modules [Fig. 19(a)] [28]. The IGBT cell modules consist of two IGBT modules with separate heat sinks, gate drivers, and bus bars. To enable
redundancy as an option.

In this case, one additional power of the SCHB VSC can be substantially increased if a redundant VSC and 4L-FLC VSC, respectively. However, the availability replacement of a failed power cell is comparable to the 3L-NPC in this case, the modular design of the IGBT cell and capacitor modules allows a simple replacement of failed power components.

In an SCHB VSC, each converter phase consists of a series connection of isolated low-voltage power cells consisting of one standardized H-bridge of 1700-V IGBT modules, one dc-link capacitor, and a six-pulse diode rectifier [Fig. 19(b)] [30]. Also, in this case, the modular design of the IGBT cell and capacitor modules allows a simple replacement of failed power components.

Table IX summarizes the component count and the expense of active and passive components of the different voltage source converter topologies for an (2.3 kV, 2.39 MVA) industrial MVD. To also include the NPC diodes of the 3L-NPC VSC in the comparison, the total installed switch power \( S_{Stot} \) of a certain converter topology is defined to be

\[
S_{Stot} = V_{CE,n} \times I_{C,n} \times n + 0.5 \times V_{RRM} \times I_{F,n} \times k \quad (14)
\]

where \( V_{CE,n} \) is the rated collector-emitter voltage of IGBTs, \( I_{C,n} \) is the ideal rated collector current, \( n \) is the number of IGBTs in the converter, \( V_{RRM} \) is the rated repetitive peak reverse voltage of diodes, \( I_{F,n} \) is the ideal rated diode forward current, and \( k \) is the number of diodes in the converter.

Considering that the diode silicon area is typically about 50% of that of the IGBTs in IGBT modules, the diodes are weighted with 50% compared to the IGBTs.

The relative total installed switch power is calculated by normalizing the total installed switch power of a certain converter topology to the total installed switch power of the 3L-NPC VSC, i.e.,

\[
S_{Stot,R} = \frac{S_{Stot}}{S_{Stot,3L-NPC VSC}} \times 100. \quad (15)
\]

The 2L-VSC on the basis of the 6.5-kV IGBT modules cannot be applied in applications where a high converter efficiency (e.g., \( \eta = 99\% \)) and a low THD of the output voltage (e.g., \( \text{THD} \leq 5\% \)) are required since an LC sine filter cannot be realized at low carrier frequencies (e.g., \( f_{C} = 450 \text{ Hz} \)). Furthermore, the 2L-VSC is not attractive for high switching frequency medium-voltage applications since the high switching losses of the 6.5-kV IGBT modules strongly limit the switch utilization and the maximum switching frequency.

The unsymmetrical loss distribution within the 3L-NPC VSC and the additional neutral-point-clamp diodes are the reasons why the 3L-NPC VSC (\( \eta \approx 99\%, f_{1cb} = 1000 \text{ Hz} \)) requires the highest installed switch power. On the other hand, the expense of the LC sine filter is moderate. Assuming an installed switch power of \( S_{S} = 38.6 \text{ MVA} \), a maximum first carrier band frequency of \( f_{1cb} = 1900 \text{ Hz} \) can be achieved. The shared load of switching losses causes a reduction of the installed switch power at low switching frequency. A simple grid transformer, a small dc link capacitor, and the possible modular realization of common dc bus configurations are attractive additional features

1The SCHB VSC is the only commercially available converter that offers redundancy as an option.

<table>
<thead>
<tr>
<th>TABLE VII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CARRIER FREQUENCY AND CAPACITY OF FLYING CAPACITORS FOR MAXIMUM SWITCHING FREQUENCY</strong></td>
</tr>
</tbody>
</table>

\( (V_{ll,1,rms} = 2.3 \text{ kV}; I_{ph,1,rms} = 600 \text{ A}; S_{C} = 2.39 \text{ MVA}, T_{j,max} = 125 \text{ °C}) \)

<table>
<thead>
<tr>
<th></th>
<th>2L-VSC</th>
<th>3L-NPC VSC</th>
<th>3L-FLC VSC</th>
<th>4L-FLC VSC</th>
<th>5L-SCHB VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed switch power ( S_{S} )</td>
<td>38.61 MVA</td>
<td>38.61 MVA</td>
<td>38.61 MVA</td>
<td>38.61 MVA</td>
<td>38.61 MVA</td>
</tr>
<tr>
<td>Nominal IGBT / diode voltage</td>
<td>6.5 kV</td>
<td>3.3 kV</td>
<td>3.3 kV</td>
<td>2.5 kV</td>
<td>1.7 kV</td>
</tr>
<tr>
<td>Rated IGBT / diode current ( I_{c,n}/I_{d,n} )</td>
<td>990 A</td>
<td>975 A</td>
<td>975 A</td>
<td>858 A</td>
<td>947 A</td>
</tr>
<tr>
<td>Converter efficiency ( \eta )</td>
<td>98.67%</td>
<td>98.75%</td>
<td>98.03%</td>
<td>98.25%</td>
<td>98.1%</td>
</tr>
<tr>
<td>Carrier frequency ( f_{C} )</td>
<td>750 Hz</td>
<td>1900 Hz</td>
<td>1800 Hz</td>
<td>1500 Hz</td>
<td>1800 Hz</td>
</tr>
<tr>
<td>First carrier band ( f_{1cb} )</td>
<td>750 Hz</td>
<td>1900 Hz</td>
<td>1800 Hz</td>
<td>1500 Hz</td>
<td>1800 Hz</td>
</tr>
<tr>
<td>Capacity of flying capacitor</td>
<td>-</td>
<td>-</td>
<td>929 ( \mu )F</td>
<td>966 ( \mu )F</td>
<td>-</td>
</tr>
</tbody>
</table>

![Fig. 14. Loss distribution and converter efficiency \( (I_{ph,1,rms} = 600 \text{ A}; f_{C,2L-VSC} = 450 \text{ Hz}; f_{C,3L-NPC VSC} = 1900 \text{ Hz}; f_{C,3L-FLC VSC} = 1800 \text{ Hz}; f_{C,4L-FLC VSC} = 1500 \text{ Hz}; f_{C,5L-SCHB VSC} = 1500 \text{ Hz}; f_{o} = 50 \text{ Hz}; m = 1.11; \cos \varphi = 0.9) \).](image)

VI. CONCLUSION

The relative total installed switch power is calculated by normalizing the total installed switch power of a certain converter topology to the total installed switch power of the 3L-NPC VSC, i.e.,

\[
S_{Stot,R} = \frac{S_{Stot}}{S_{Stot,3L-NPC VSC}} \times 100. \quad (15)
\]
TABLE VIII
COMPONENT VALUES AND STORED ENERGY OF 2.3-kV 2.39-MVA VSCs AT MAXIMUM SWITCHING FREQUENCY

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2L-VSC</td>
<td>750</td>
<td>750</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3L-NPC VSC</td>
<td>1900</td>
<td>1900</td>
<td>3 x 450</td>
<td>3 x 110</td>
<td>9.8</td>
<td>4.8</td>
<td>534</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3L-FLC VSC</td>
<td>1800</td>
<td>3600</td>
<td>3 x 230</td>
<td>3 x 50</td>
<td>9.4</td>
<td>4.4</td>
<td>256</td>
<td>929</td>
<td>3987</td>
<td>4243</td>
</tr>
<tr>
<td>4L-FLC VSC</td>
<td>1500</td>
<td>4500</td>
<td>3 x 150</td>
<td>3 x 33</td>
<td>8</td>
<td>4.2</td>
<td>168</td>
<td>966</td>
<td>9213</td>
<td>9381</td>
</tr>
<tr>
<td>5L-SCHB VSC</td>
<td>4580</td>
<td>18320</td>
<td>3 x 50</td>
<td>3 x 9</td>
<td>7.1</td>
<td>3.4</td>
<td>45</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Assumption: converter without dc-link capacitors

Fig. 15. Simulation results of 3L-NPC VSC ($f_{C,3L-NPC\ VSC} = 1900$ Hz).
(a) Phase voltage $v_I$ (inverter side). (b) Inverter current $i_I$.
(c) Phase voltage $v_M$ (machine side). (d) Machine current $i_M$.

Fig. 16. Simulation results of 4L-FLC VSC ($f_{C,4L-FLC\ VSC} = 1500$ Hz).
(a) Phase voltage $v_I$ (inverter side). (b) Inverter current $i_I$.
(c) Phase voltage $v_M$ (machine side). (d) Machine current $i_M$. 
of this topology [1]. Therefore, the 3L-NPC VSC is a competitive topology for a large variety of low and medium switching frequency applications (e.g., $f_C \leq 1000$ Hz).

The high capacitance values and stored energies of the flying capacitors limit the use of the 3L/4L-FLC VSC to high switching frequency applications (e.g., $f_C \geq 1200$ Hz) like high-speed drives and test benches. In these applications, the 3L-FLC VSC is an interesting alternative to the 4L-FLC VSC due to the reduced expense of flying capacitors. At lower carrier frequencies (e.g., $f_C = 250–1000$ Hz) and high converter efficiency (e.g., $\eta = 99\%$), both topologies are not competitive compared to the 3L-NPC VSC and the 5L-SCHB VSC.

The 5L-SCHB VSC requires the lowest installed switch power and stored energy of the $LC$ sine filter. Compared to the 3L-NPC VSC, the installed switch power and the stored energy of the 5L-SCHB VSC ($\eta \approx 99\%$) are reduced by 28% and 84%, respectively.

Furthermore, an extraordinary high maximum first carrier band frequency of the converter voltage can be achieved at a given installed switch power (e.g., $S_S = 38.6$ MVA, $f_{1cb} = 18320$ Hz). However, a complicated grid transformer, increased dc link capacitance values compared to the 3L-NPC VSC, and the absence of a common dc voltage bus are the disadvantages of this topology [1]. Nevertheless, the 5L-SCHB VSC is an attractive topology for manifold MVDs including high-speed drives.

REFERENCES


Fig. 19. Mechanical design structure. (a) One phase leg of a 4L-FLC converter. (b) 5L-SCHB converter.

### TABLE IX

<table>
<thead>
<tr>
<th>Description</th>
<th>2L-VSC</th>
<th>3L-NPC VSC</th>
<th>3L-FLC VSC</th>
<th>4L-FLC VSC</th>
<th>5L-SCHB VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of IGBTs</td>
<td>6 x 6.5 kV</td>
<td>12 x 3.3 kV</td>
<td>12 x 3.3 kV</td>
<td>18 x 5 kV</td>
<td>24 x 1.7 kV</td>
</tr>
<tr>
<td>Number of diodes</td>
<td>6</td>
<td>18 (incl. 6 NPC Diodes)</td>
<td>12</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Number of gate units (GU)</td>
<td>6</td>
<td>12</td>
<td>12</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Number of flying capacitors</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Number of LC filter capacitors / inductors</td>
<td>-</td>
<td>-</td>
<td>3 / 3</td>
<td>3 / 3</td>
<td>3 / 3</td>
</tr>
<tr>
<td>Total component count</td>
<td>12</td>
<td>36</td>
<td>33</td>
<td>48</td>
<td>54</td>
</tr>
</tbody>
</table>

Comparison @ \( n = 99\% \)

- Carrier frequency \( f_c \) [Hz]:
  - 450 Hz
  - 1000 Hz
  - 500 Hz
  - 1000 Hz
  - 1000 Hz
  - 825 Hz
  - 3940 Hz
- First carrier band frequency \( f_{	ext{band}} \) [Hz]:
  - 450 Hz
  - 1000 Hz
- Total Installed switch power \( S_{	ext{inv}} \) [MVA]:
  - 43.87
  - 52.67
  - 35.64
  - 42.53
  - 38.06
- Capacitance of flying capacitors \( C \) [\( \mu \)F]:
  - 3344 [\( \mu \)F]
  - 5269 [\( \mu \)F]
- Inductance of filter \( L_f \) [\( \mu \)H]:
  - 3 x 800
  - 3 x 800
  - 3 x 800
  - 3 x 240
- Capacitance of filter \( C_f \) [\( \mu \)F]:
  - 3 x 375
  - 3 x 375
  - 3 x 370
  - 3 x 47
- Stored energy of filter \( W_f \) [J]:
  - 1424
  - 1424
  - 1411
  - 232
- Stored energy of filter and flying capacitors \( W_{f+c} \) [J]:
  - 15775
  - 51670
  - 232

Maximum carrier frequency \( f_{	ext{max}} \) [Hz]:
- 250 Hz
- 1900 Hz
- 1800 Hz
- 1500 Hz
- 4580 Hz
- 18520 Hz
- 929 [\( \mu \)F]
- 966 [\( \mu \)F]
- 9213 [J]
- 3 x 230
- 3 x 33
- 9 x
- 534
- 256
- 168
- 45
- 4243
- 9381
- 45


[27] A. Mertens, M. Bruckmann, and R. Sommer, “Medium voltage inverters using high-voltage IGBTs,” in Proc. 8th EPE, Lausanne, Switzerland, Sep. 1999, CD-ROM.


