Comparison of High-Power 2-Level and 3-Level Converters in Terms of Power Density, Costs and Performance

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Keywords

≪Multi-level converters≫, ≪High power density systems≫, ≪Analytical losses computation≫, ≪DC-AC converter≫, ≪AC-DC converter≫

Abstract

This paper compares high-power converters in terms of their power density, costs and performance. 2-level and 3-level NPC phase modules with 1400 A semiconductors are compared. For pulse frequencies higher than 6.75 kHz 3-level NPC converter is twice smaller and 48 % cheaper then 2-level converter, because for 2-level parallel operation of phase modules is necessary. In this case the 3-level NPC has with $0.58\,\mathrm{kVA/dm^3}$ a twice higher power density as the 2-level converter. The performance of 3-level NPC is much higher than of the 2-level, because of the twice higher possible pulse frequency of 16 kHz and therefore higher possible control frequency. Because of the higher pulse frequency and the lower voltage ripple the chokes can be quite smaller for the 3-level NPC and so the maximum current raise is a lot higher than in case of a 2-level converter.

Introduction

The 3-level neutral point clamped converter (3LNPCC) [1] has great advantages over the classical 2-level converter (2LC) in the operation of permanent magnet synchronous machines, which is shown by latest investigations [2], [3]. Depending on the operating point and pulse frequency, the use of the 3LNPCC can significantly reduce losses in the machine (20-30 %) and improve efficiency by 2-3 percentage points [2], [3]. The 3LNPCC also has advantages over the 2LC when used at the grid as an active frond end. For example, due to the lower voltage ripple, smaller AC filter capacitors and chokes can be used [4]. This reduces the volume and cost of the setup [5]. To find out how the use of the 3LNPC affects the overall drive in terms of power density, costs and performance, the losses of the 2LC and 3LNPCC are calculated here. Based on this, the junction temperature of the semiconductors and thus the maximum current carrying capacity of the converter can be determined.

The goal of this paper is to compare grid connected 2LC and 3LNPCC with over 500 kW power. In order to keep the weight of the individual components within limits (less than 40 kg because of occupational safety), the power converters are constructed from individual phase modules. The aim is to use the same semiconductors in order to be able to compare the results better. For the power class, the use of 1400 A PrimePack3 semiconductor modules from Infineon (FF1400R12IP4) [6] is suitable. The Semitrans 10 modules (SKM1400GB12P4) [7] can be used as a one-to-one replacement if the Infineon modules are not available.

The 3LNPCC [1] is the most used 3- or multilevel converter [8, 9]. The mass of 21 kg from the 2-level (2L) phase module increases to 35 kg for the 3LNPC phase module. So a 5-level converter in the targeted power class with two more semiconductor modules and twice as much DC link capacitors as 3LNPCC would be too large and too heavy. In addition, the complexity of controlling so many semiconductors increases significantly.

Besides the classical 3LNPCC, there is the 3-level active NPC converter (3LANPCC) [10]. The 3LANPCC has antiparallel IGBTs to the diodes $D_{5..6}$ of 3LNPCC (compare Fig. 1b). So the connection to the neutral point can be controlled actively. The 3LANPCC is characterized by a slightly better loss distribution to the individual semiconductors. However, the effect is not very large and strongly dependent on the operating point [11]. The 3LANPCC could be constructed from PrimePack3 semiconductors, as planned. However, the 3LANPCC requires two more IGBTs per phase module than the 3LNPCC and is correspondingly more difficult in terms of control and operation. This makes the 3LANPCC much more complex than the 3LNPCC and thus unattractive for the current application.

Another alternative is the 3-level T-type NPC converter (3LTNPCC) [4]. This is built like a 2-level converter, but still has 2 bidirectionally arranged IGBTs with antiparallel diodes from the DC link center to the AC output. For small switching frequencies, the 3LTNPCC has slightly lower losses than the 3LNPCC [4]. However, 3LTNPCC cannot be constructed from PrimePack3 modules only, since bidirectionally arranged semiconductors are required. Accordingly, the 3LTNPCC cannot be considered in the current comparison. Otherwise, the control and the output voltage of 3LNPCC and 3LTNPCC are identical, as our simulations and measurements have shown.

The 3LTNPCC can very easily be configured to operate as a 2LC. To do this, simply deactivate the bidirectionally arranged IGBTs at the middle point. This effect was used in [2] to compare the effects of the 3-level converter on the load with those of the 2LC. At some operating points, it may also be beneficial to switch between the topologies in real operation [12]. However, the impact is relatively small and highly dependent on the operating point.

Besides the used converter topology, many other points have influence on the losses of the converter. For example the gate driver [6], [7], the modulation method [11] and the DC link balancing [13]. Compared to the converter topology, however, their influence is small and is therefore not considered further here.

An important aspect for comparing different converter topologies is their lifetime expectation. Felgemacher [14] clearly shows that this is very complex and it is not the subject of this paper. Just capturing and categorizing load cycles is a complex issue [15].

In recent years, many silicon carbide (SiC) semiconductors have been introduced. Also 3LNPCC with SiC semiconductors have been examined [16]. However, there are still only SiC modules with a few hundred amps available on the market. So SiC semiconductors cannot be considered in this paper.

There are already some papers comparing different power converter topologies [4, 8, 9, 10]. TEICHMANN [5] compares 2LC and 3LNPCC and shows that above 5 kHz pulse frequency the 3LNPCC achieves better efficiency than the 2LC. The paper also discusses costs of many individual components such as terminal filters, DC link capacitance, IGBT modules, gate drivers and cooling.

This paper is the first to compare the complete costs required to build the different converter topologies. This includes costs for mechanics, DC link, busbars, IGBT modules, cooling, chokes and the time of the assembly itself. In addition, the integration into a control cabinet and thus into an overall system is considered. Taking all the components is the only way to determine a realistic power density.

The introduction is followed by a general overview of the differences between 2LC and 3LNPCC. After that, the calculation of losses and junction temperatures is discussed. The paper ends with the evaluation of costs and power density, as well as a conclusion.

Differences Between 2LC and 3LNPCC

A phase module of a 2LC consists of the DC link capacitance C_1, the two transistors ($T_{1..2}$) and the two diodes ($D_{1..2}$), as shown in Fig. 1a. Via the power semiconductors it is possible to connect the positive DC link potential $DC+$ or the negative $DC-$ to the output. So there are two possible voltage levels. The 3-level NPC (3LNPC phase module [1] has two DC link halves ($C_{1/2}$), four transistors ($T_{1..4}$) and six diodes ($D_{1..6}$), as seen in Fig. 1b. With diodes D_5 and D_6 it is possible to connect the output (AC) to the DC link center N. So it is possible to connect three voltage levels to the output ($DC+$, N or $DC-$). The second investigated phase module LT1000-ML (3LNPC) consists of three IGBT modules. Which semiconductors belong to which IGBT modules is shown by the gray circles $M_{1..3}$ in Fig. 1b. In case of M_1 and M_3 one IGBT is deactivated.

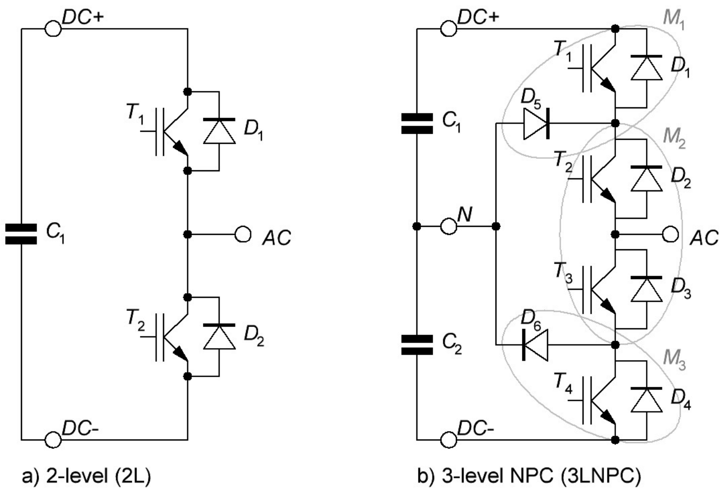
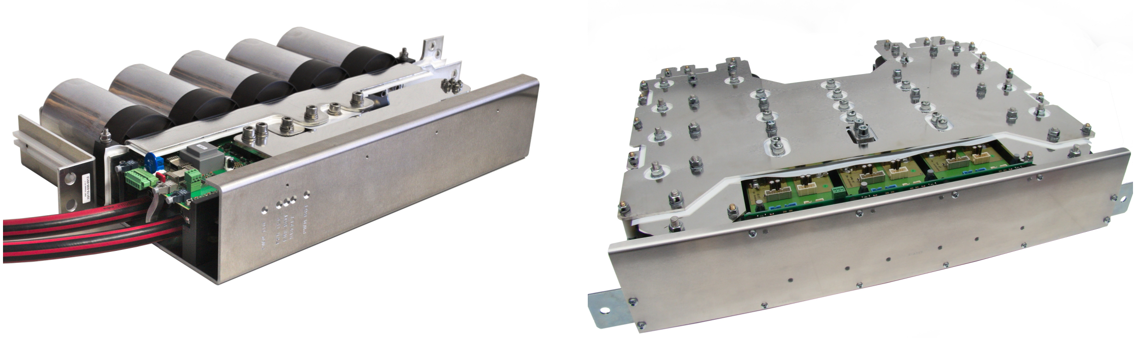


Fig. 1: 2L and 3LNPC phase modules with DC link capacitors and all there semiconductors

Three phase modules (2L or 3LNPC) can be used to assemble rectifiers for operation on three-phase mains or inverters for operation of three-phase electrical machines. If the usage of one phase module per converter phase results in too high losses and thus too high junction temperatures, two or three phase modules can also be connected in parallel. Both investigated phase modules use Infineon PrimePack3 (FF1400R12IP4) modules and are shown in Fig. 2.

The power semiconductors in the 2LC must be able to switch and block the entire DC link voltage. In the 3LNPCC, on the other hand, it is only half the DC link voltage. Accordingly, 3LNPCCs with 1200 V



a) 2-level (LT1000)

b) 3-level (LT1000-ML)

Fig. 2: Investigated M&P phase modules LT1000 [17] and LT1000-ML [18]

semiconductors can drive twice as high voltages as 2LCs. In 2LCs usually, the switching frequency of the semiconductors is equal to the pulse frequency at the output. With 3LNPCCs, the effective switching frequency is only half the pulse frequency, since all semiconductors are never switched simultaneously. Depending on the phase angle of current and voltage, as well as the modulation level, only switches T_1 and T_3 or T_2 and T_4 are switched. Further differences between the converter topologies and the used phase modules are shown in Table I.

Table I: Comparison of 2L and 3LNPC Phase Modules Using the Example of LT1000 [17] and LT1000-ML [18]

	2-level (2L)	**3-level NPC (3LNPC)**
Semiconductors per phase module	2 IGBTs, 2 Diodes	4 IGBTs, 6 Diodes
DC link voltage with 1200 V IGBTs	750 V (typ.)	1400 V (typ.)
Price per phase module	100 %	156 %
Max. pulse frequency $f_{\mathrm{p\,max}}$	8 kHz	16 kHz
Max. switching frequency $f_{\mathrm{sw\,max}}$	8 kHz	8 kHz
Volume per phase module	23 dm^3	42 dm^3
Mass per phase module	21 kg	35 kg
Phase modules per control cabinet	3 (typ.)	3 (typ.)
Cooling type and cooling capacity	Water, 4 kW	Water, 6 kW

How the phase modules look like integrated in the cabinet can be seen schematically in Fig. 3. The AC filter inductance can be realized like shown as one 3-phase inductance, but also three single inductances are possible.

Loss and Junction Temperatures Calculation of High Power Converters

In general, there are three main types of losses in power converters: switching, conduction and driver losses. The driver losses can be neglected for high-power IGBT converters, since they are less than 1 % of the total losses. Losses are influenced by many factors. Some of them, such as DC link voltage, power factor, modulation depth and output current, can be well described with analytical formulas. The determination of other factors, such as driver design (gate dropping resistor) and junction temperature,

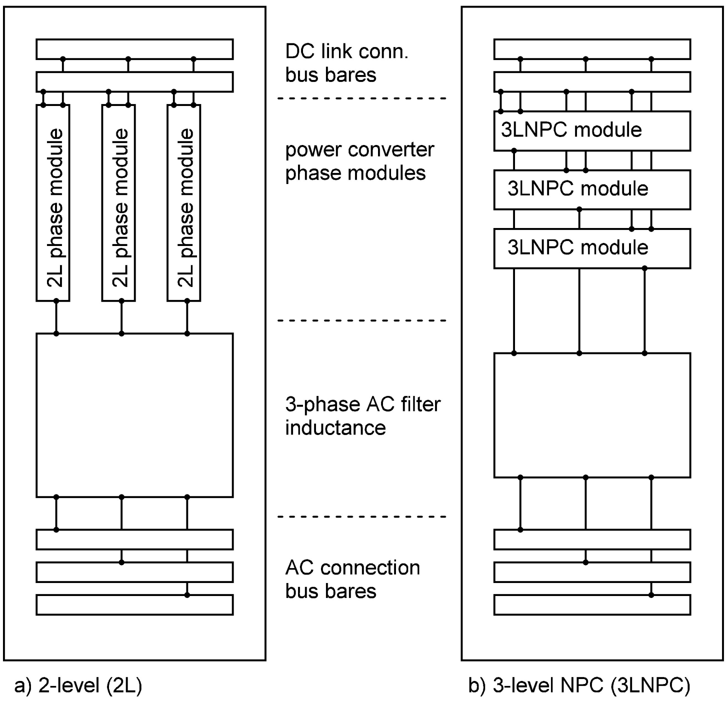


Fig. 3: 2L and 3LNPC phase modules (LT1000 [17] and LT1000-ML [18]) schematically integrated in cabinet with cables, AC filter inductance and connection bus bars

is more difficult. To investigate the influence of the drivers, measurements of turn-on and turn-off loss energy from the LT1000 were made in [19]. These measurements show that the results are comparable to those from the data sheet. The measured values are taken here accordingly. For the junction temperature, 120 °C is assumed. In this paper, 120 °C is also the maximum permissible value for all investigations.

The total losses of the phase module P_{pm} and the junction temperatures $T_{\mathrm{jD/T}}$ of the semiconductors are calculated for a fixed operating point, various pulse frequencies f_{p} and different numbers of phase modules connected in parallel.

The modulation index $M = \hat{V}_{\mathrm{out\,1}}/(V_{\mathrm{DC}}/2)$ is defined using the amplitude of the fundamental harmonic of the phase voltage against the neutral point $\hat{V}_{\mathrm{out\,1}}$ and the DC link voltage V_{DC}. All values that are needed for the calculations of the semiconductors are found in the datasheet [6] and are shown in Table II.

Table II: Values Needed for Calculations from the PrimePack3 (FF1400R12IP4) datasheet

Name	**Value**	**Unit**
Reference voltage V_{ref}	600	V
Collector-emitter supply voltage V_{CC} - 2-Level: $V_{\mathrm{CC}} = V_{\mathrm{DC}}$	750	V
Collector-emitter supply voltage V_{CC} - 3-Level: $V_{\mathrm{CC}} = V_{\mathrm{DC}}/2$	375	V
Reference current I_{ref}	1400	A
Thermal resistance heat sink to ambient per PrimePack3 $R_{\mathrm{th\,s-a}}$	10	K/kW
Collector-emitter threshold voltage (IGBT) V_{CE0}	0.85	V
On-state slope resistance (IGBT) r_{CE}	0.944	mΩ
Energy dissipation during turn-on and off (IGBT) $E_{\mathrm{on+off}}$ [19]	420	mJ
Thermal resistance junction to case to heat sink (IGBT) $R_{\mathrm{th\,j-c-s\,T}}$	28.8	K/kW
Forward threshold voltage (diode) V_{F0}	1.85	V
Forward slope resistance (diode) r_{F}	0.5	mΩ
Energy dissipation during reverse recovery (diode) E_{rr} [19]	110	mJ
Thermal resistance junction to case to heat sink (diode) $R_{\mathrm{th\,j-c-s\,D}}$	53	K/kW

The later used formulas to calculate the losses are only valid for PWM schemes with constant carrier frequency (= pulse frequency), pure sinusoidal reference and $0 \leq \phi \leq \pi$ [10]. In case of Third Harmonic Injection Sinusoidal PWM there are a bit different formulas, but the results are nearly the same as with the given formulas [10].

The switching losses do not increase ideally linearly with the phase current and the DC link voltage. Thus, for the terms $I_{\mathrm{out}}/I_{\mathrm{ref}}$ and $V_{\mathrm{CC}}/V_{\mathrm{ref}}$ in the later shown formulas the additional exponents K_{I} and K_{V} are introduced [20] - [22], resulting in $(I_{\mathrm{out}}/I_{\mathrm{ref}})^{K_{\mathrm{I}}}$ and $(V_{\mathrm{CC}}/V_{\mathrm{ref}})^{K_{\mathrm{V}}}$. For the 3LNPCC, the switching losses for the diodes are further multiplied by an additional factor $G_{\mathrm{I}} = 1.15$. For Semicron modules, $K_{\mathrm{I}} = K_{\mathrm{V}} = 0.6$ for the diodes and $K_{\mathrm{I}} = 1$ and $K_{\mathrm{V}} = 1.4$ for the IGBTs. Each of the factors results in differences of 10 ..15 %. However, the errors in current and voltage dependent switching losses respectively for IGBTs and diodes largely cancel each other out. Thus, the error related to the total losses is significantly smaller than 10 % and can therefore be left out.

Analytical Loss Calculation for the 2-level Converter

In case of a symmetrical three phase load all six IGBTs and diodes of a 2LC have the same losses. To calculate the losses modulation index M, the values from Table II and the amplitude of the fundamental harmonic $\hat{I}_{\mathrm{out\,1}}$ of the phase current I_{out} are used. The conduction and switching losses of the IGBTs ($P_{\mathrm{cond\,T}}$ and $P_{\mathrm{sw\,T}}$) and diodes ($P_{\mathrm{cond\,D}}$ and $P_{\mathrm{sw\,D}}$) are determined with the help of the following formulas [20, 21]:

$$P_{\mathrm{cond\,T}} = \left(\frac{1}{2\pi} + \frac{M\cos\varphi}{8}\right) V_{\mathrm{CE0}}\,\hat{I}_{\mathrm{out\,1}} + \left(\frac{1}{8} + \frac{M\cos\varphi}{3\pi}\right) r_{\mathrm{CE}}\,\hat{I}^2_{\mathrm{out\,1}} \tag{1}$$

$$P_{\mathrm{sw\,T}} = f_{\mathrm{sw}}\,E_{\mathrm{on+off}}\,\frac{\sqrt{2}}{\pi}\,\frac{I_{\mathrm{out}}}{I_{\mathrm{ref}}}\,\frac{V_{\mathrm{CC}}}{V_{\mathrm{ref}}} \tag{2}$$

$$P_{\mathrm{cond\,D}} = \left(\frac{1}{2\pi} - \frac{M\cos\varphi}{8}\right) V_{\mathrm{F0}}\,\hat{I}_{\mathrm{out\,1}} + \left(\frac{1}{8} - \frac{M\cos\varphi}{3\pi}\right) r_{\mathrm{F}}\,\hat{I}^{2}_{\mathrm{out\,1}} \tag{3}$$

$$P_{\mathrm{sw\,D}} = f_{\mathrm{sw}}\,E_{\mathrm{rr}}\,\frac{\sqrt{2}}{\pi}\,\frac{I_{\mathrm{out}}}{I_{\mathrm{ref}}}\,\frac{V_{\mathrm{CC}}}{V_{\mathrm{ref}}} \tag{4}$$

To obtain the losses of the whole phase module $P_{\mathrm{pm\,2}}$, the individual losses must be added together

$$P_{\mathrm{pm\,2}} = 2\,(P_{\mathrm{cond\,T}} + P_{\mathrm{sw\,T}} + P_{\mathrm{cond\,D}} + P_{\mathrm{sw\,D}}). \tag{5}$$

Analytical Loss Calculation for 3-level NPC Converter

For the loss calculation of the 3LNPCC the same input values are used as for the 2LC. In the case of the 3LNPCC the equations differ for the outer IGBTs $T_{1/4}$ and the inner IGBTs $T_{2/3}$ and also for the diodes $D_{1/4}$, $D_{2/3}$ and $D_{5/6}$ [11]. So the following ten equations are needed to get all the conduction and switching losses [11, 22]:

$$P_{\mathrm{cond\,T\,1/4}} = \frac{M\,\hat{I}_{\mathrm{out\,1}}}{12\pi}\left(3\,V_{\mathrm{CE0}}\,[(\pi-\varphi)\cos(\varphi)+\sin(\varphi)] + 2\,r_{\mathrm{CE}}\,\hat{I}_{\mathrm{out\,1}}\,\left[1+\cos(\varphi)\right]^2\right) \tag{6}$$

$$P_{\mathrm{sw\,T\,1/4}} = f_{\mathrm{sw}}\,E_{\mathrm{on+off}}\,\frac{1}{2\pi}(1+\cos(\varphi))\,\frac{I_{\mathrm{out}}}{I_{\mathrm{ref}}}\,\frac{V_{\mathrm{CC}}}{V_{\mathrm{ref}}} \tag{7}$$

$$P_{\mathrm{cond\,T\,2/3}} = \frac{\hat{I}_{\mathrm{out\,1}}}{12\pi}\left(V_{\mathrm{CE0}}\,[12+3M\,(\varphi\cos(\varphi)-\sin(\varphi))] + r_{\mathrm{CE}}\,\hat{I}_{\mathrm{out\,1}}\,\left[3\pi - 2M\,(1-\cos(\varphi))^2\right]\right) \tag{8}$$

$$P_{\mathrm{sw\,T\,2/3}} = f_{\mathrm{sw}}\,E_{\mathrm{on+off}}\,\frac{1}{2\pi}(1-\cos(\varphi))\,\frac{I_{\mathrm{out}}}{I_{\mathrm{ref}}}\,\frac{V_{\mathrm{CC}}}{V_{\mathrm{ref}}} \tag{9}$$

$$P_{\mathrm{cond\,D\,1/4}} = \frac{M\,\hat{I}_{\mathrm{out\,1}}}{12\pi}\left(3\,V_{\mathrm{F0}}\,[-\varphi\cos(\varphi)+\sin(\varphi)] + 2\,r_{\mathrm{F}}\,\hat{I}_{\mathrm{out\,1}}\,\left[1-\cos(\varphi)\right]^2\right) \tag{10}$$

$$P_{\mathrm{sw\,D\,1/4}} = f_{\mathrm{sw}}\,E_{\mathrm{rr}}\,\frac{1}{2\pi}(1-\cos(\varphi))\,\frac{I_{\mathrm{out}}}{I_{\mathrm{ref}}}\,\frac{V_{\mathrm{CC}}}{V_{\mathrm{ref}}} \tag{11}$$

$$P_{\mathrm{cond\,D\,2/3}} = \frac{M\,\hat{I}_{\mathrm{out\,1}}}{12\pi}\left(3\,V_{\mathrm{F0}}\,[-\varphi\cos(\varphi)+\sin(\varphi)] + 2\,r_{\mathrm{F}}\,\hat{I}_{\mathrm{out\,1}}\,\left[1-\cos(\varphi)\right]^2\right) \tag{12}$$

$$P_{\mathrm{sw\,D\,2/3}} = 0 \tag{13}$$

$$\begin{aligned} P_{\mathrm{cond\,D\,5/6}} = &\frac{\hat{I}_{\mathrm{out\,1}}}{12\pi}\Big(V_{\mathrm{F0}}\,[12+3M\,((2\varphi-\pi)\cos(\varphi)-2\sin(\varphi))] + \\ &r_{\mathrm{F}}\,\hat{I}_{\mathrm{out\,1}}\,\left[3\pi - 4M\,(1+\cos^2(\varphi))\right]\Big) \end{aligned} \tag{14}$$

$$P_{\mathrm{sw\,D\,5/6}} = f_{\mathrm{sw}}\,E_{\mathrm{rr}}\,\frac{1}{2\pi}(1+\cos(\varphi))\,\frac{I_{\mathrm{out}}}{I_{\mathrm{ref}}}\,\frac{V_{\mathrm{CC}}}{V_{\mathrm{ref}}} \tag{15}$$

To get the losses $P_{\mathrm{pm\,3}}$ of the whole 3LNPC phase module, the individual losses must be added together:

$$\begin{aligned} P_{\mathrm{pm\,3}} = &2\,(P_{\mathrm{cond\,T\,1/4}} + P_{\mathrm{sw\,T\,1/4}} + P_{\mathrm{cond\,T\,2/3}} + P_{\mathrm{sw\,T\,2/3}} + P_{\mathrm{cond\,D\,1/4}} + P_{\mathrm{sw\,D\,1/4}} + P_{\mathrm{cond\,D\,2/3}} + \\ &P_{\mathrm{sw\,D\,2/3}} + P_{\mathrm{cond\,D\,5/6}} + P_{\mathrm{sw\,D\,5/6}}) \end{aligned} \tag{16}$$

Calculation of Junction Temperatures

The junction temperature can be calculated from the losses of the semiconductor S by $P_{\mathrm{S}} = P_{\mathrm{cond\,S}} + P_{\mathrm{sw\,S}}$ via the sum of thermal resistances and the ambient (water) temperature T_{a}. One PrimePack3 consists of four semiconductors (two diodes and two IGBTs). The thermal resistance $R_{\mathrm{th\,s-a}}$ per semiconductor $R_{\mathrm{th\,s-aS}}$ is $R_{\mathrm{th\,s-aS}} = 4\,R_{\mathrm{th\,s-a}}$. Finally, the junction temperature of the semiconductor S results from the equation $T_{\mathrm{j\,S}} = T_{\mathrm{a}} + P_{\mathrm{S}}\,(R_{\mathrm{th\,s-aS}} + R_{\mathrm{th\,j-c-s\,S}})$ using the thermal resistance $R_{\mathrm{th\,j-c-s}}$ between junction, case and sink.

Cost Evaluation and Calculation Results

The costs for the individual components depend heavily on how much raw materials (e.g. copper) and components (e.g. semiconductors and capacitors) currently cost. In order to be able to make a comparison that is as generally valid as possible, all costs are therefore given in relation to the costs for three 2L phase modules (LT1000 [17]). This base cost equals 100 % and includes the costs for semiconductors, DC link capacitance, bus bars, housing, control electronics, time for assembly, as well as current and voltage measurement. Based on experience, the cost of construction and materials (water cooling tubes, bus bars, mounting frame) is about 25 % of the base cost. The costs of the chokes (compare 3-phase AC filter inductance in Fig. 3) for the 2LC are about the same as the base cost. From experience, about 40 % of the cost of the chokes is fixed and the rest is variable cost depending on the size of the inductor. To achieve the same filtering effect, it is sufficient for the chokes of the 3LNPCC to have 70 % of the value of the 2LC [5]. Taking into account the fixed cost of 40 %, the costs is then 82 % ($= 70\% \cdot 60\% + 40\%$) of the base cost. When two 2L phase modules are connected in parallel, the current is halved and thus the choke required is also much smaller. The variable cost per choke is assumed to decrease by 50 %. Since the two control cabinets also require two chokes, the total costs for the chokes increases to 140 % ($= 2\,(60\%/2 + 40\%)$). Similarly, with three parallel 2L phase modules, the total costs increases to 180 %. The total costs of the systems is then the sum of the phase modules, the chokes, and the control cabinets. All data are summarized in Table III.

Table III: Costs and power density for the investigated configurations (p. m. - phase module)

Configurations	3LNPC, 1 p. m.	2L, 1 p. m.	2L, 2 p. m.	2L, 3 p. m.
Number of cabinets	1	1	2	3
Rel. costs for phase modules	156 %	100 %	200 %	300 %
Relative costs for cabinets	25 %	25 %	50 %	75 %
Relative costs for chokes	82 %	100 %	140 %	180 %
Relative total system costs	263 %	225 %	390 %	555 %
Costs compared to 2L, 1 p. m.	117 %	100 %	173 %	247 %
Volume of system V_{sys}	960 dm ^{3}	960 dm^3	1920 dm^3	2880 dm^3
Power density p of system	0.58 kVA/dm^3	0.58 kVA/m^3	0.29 kVA/dm^3	0.19 kVA/dm^3

Costs for main switches, main contactors, fuses, and any necessary devices for rapid safety-related fault shutdown were not considered. This would be the same for all systems and would only equalize the system costs. Line voltage measurement, precharging and control play a subordinate role in terms of costs and were not taken into account. If a constant current ripple of e.g. 10 % of the rated current is to be achieved, different values for the chokes result depending on the pulse frequency. However, taking these into account here makes the comparison of the configurations much more difficult. Thus, values for the chokes were calculated independently of the pulse frequency.

A typical operation point for grid-connected converters (active front end) was used for the investigations:

- DC link voltage $V_{DC} = 750\,V$
- grid voltage $V_{AC} = 400\,V$
- output current $I_{out} = 800\,A$
- modulation index $M = 87.2\,\%$
- power factor $\cos(\varphi) = 0.93$
- water (ambient) temperature $T_a = 25\,°C$

To determine the power density $p = S/V_{sys}$ related to the volume, the apparent power $S = 554\,kVA$ and the volume of the system V_{sys} are required. The system volume results from the number of control cabinets and its volume $V_{cab} = 960\,dm^3$ ($= 20\,dm \cdot 8\,dm \cdot 6\,dm$). The different system volumes and the calculated power densities can be found in Table III.

Calculated losses per phase and maximum junction temperature can be seen in Fig. 4. For the configurations with parallel phase modules (2 m. and 3 m.) a maximum asymmetry of 10 % is considered, so the current of one module is 5 % higher and the other 5 % lower. In case of two modules the current is not

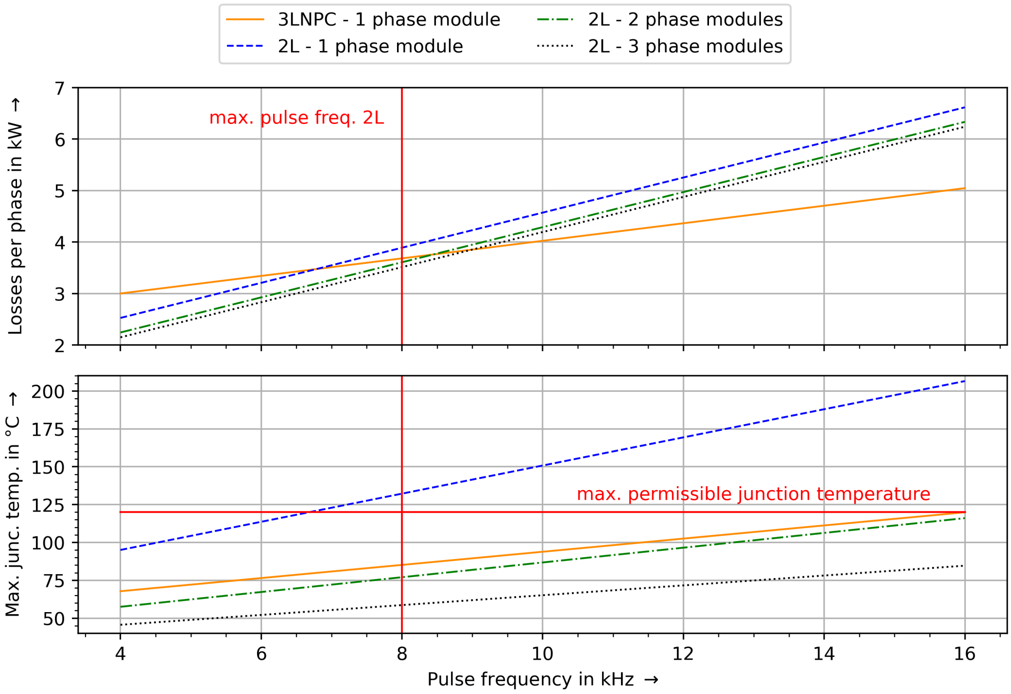


Fig. 4: Calculated results for one 3LNPC phase module and one, two or three of parallel 2L phase modules with different pulse frequencies, DC link voltage of 750 V and output current of 800 A

$I_{\text{out}}/2 = 400\,\text{A}$ but the worst case is 420 A. Up to a pulse frequency of 6.75 kHz, all configurations can be operated at the considered operating point, since the maximum junction temperature is below 120 °C.

The variant with the three parallel 2L phase modules has up to the 9 kHz pulse frequency the lowest total losses, but the costs are 2.47 times higher than the costs for 2L with one phase module and the power density is the lowest as seen in Table III.

To reach a pulse frequency of more than 6.75 kHz it is possible to use the converter with two parallel 2L phase modules. However, this solution is twice as large and 1.73 times more expensive than 2LC with one phase module. But the configurations with 2LC are limited by the gate driver to 8 kHz pulse frequency. The better option for higher switching frequencies is the 3LNPCC. At only 17 % extra cost and the same volume as the 2LC with one phase module, it offers the possibility to work with up to 16 kHz pulse frequency. If the pulse frequency equals the control frequency the 3LNPCC can react two times faster then the 2LC. Because of the smaller AC choke of the 3LNPCC a higher current rise can be achieved with the same driving voltage (DC link voltage). Due to the higher control frequency and the larger possible current rise, the performance of the 3-level is significantly better than that of the 2-level.

Conclusion

The losses and junction temperature calculations for 2-level (2L) and 3-level Neutral-Point-Clamped (3LNPC) converters with the Sinusoidal PWM, 800 A output current in a grid application are investigated. In addition, the costs for phase modules, control cabinets, chokes and their construction for various configurations were determined.

Up to a pulse frequency of 6.75 kHz it is possible to use one 2L phase module (LT1000 [17]) per converter phase for the given operating point. For higher pulse frequencies at least two 2L phase modules in parallel are necessary. But with two phase modules in parallel the system costs are 1.73 times higher. Also two cabinets instead of one cabinet are needed and the system is limited to 8 kHz pulse frequency.

For a slightly higher costs (17 %) compared to one 2L phase module, the configuration with 3LNPC phase modules (LT1000-ML [18]) provides by far the highest performance, cause of the high pulse frequency of up to 16 kHz. Furthermore the 3LNPC converter has the smallest volume and the highest power density of all investigated system configurations.

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