Comparison between a voltage sourced and a current sourced static frequency converter

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Abstract: In accordance with the proceeding technical development in the area of electronic power semiconductors the maximum off-state voltages and on-state currents have rapidly increased in the recent years. As a consequence semiconductor elements are not only used for the known purposes. A new challenge is to replace the standard motor-generator sets with static frequency converters based on power semiconductor elements can be employed to generate test voltages for high voltage testing facilities. This paper deals with two basic solutions for static frequency conversion - voltage sourced and current sourced converters.

Regarding design, realisation and results, a special focus is put on output voltage quality and the background noise for partial discharge (pd-) measurement.

1 INTRODUCTION

Nowadays static frequency converters are commonly used in the drive and powertrain technologies, where they, more or less, displace the frequency converters based on motor-generator sets entirely. The classic motor-generator sets (m.-g. sets) are still in use for the high voltage test engineering all over the world. A special application for some m.-g. sets is to generate sinusoidal voltages with frequencies up to 200 Hz to supply various test circuits. Actual research activities aim to substitute the m.-g. sets with static converters providing variable output frequencies. The main reasons for their displacement are high investment costs and difficulties in acquisition and transportation. Two major problems occur in implementing this technology: The quality of the output voltage and the level of the pd-measurement background noise. The obligatory requirements are noted in the international standards IEC 60060-1 and -3, respectively the German pendant DIN VDE 0432-1 [1] and for testing power transformer IEC 60076-1 respectively DIN EN 60076-1 [2].

The Total Harmonic Distortion (THD) is one of the most important specifications for the voltage form:

$$THD = \sqrt{\sum_{k=2}^{H} {u_k}^2} \leq 5\% . \quad (1)$$

Here $u_k = U_k / U_1$, U_k is the voltage of the kth harmonic and U_1 the voltage of the fundamental component. Frequencies up to the 7th harmonic are considered [2].

During the long duration AC induced voltage test (ACLD) a pd-measurement is obligatory for transformers with maximum voltage Um > 72.5 kV. The maximum background noise level of 100 pC for the accompanying measurement is given in IEC 60076-3 [3]. Special customer requirements can exceed this limit and demand 50 pC or less.

In the following chapters two fundamental principles are presented: A converter with a voltage link and a converter with a current link were designed, inspected and assessed for the problems described above. At the end it is pointed out which system is the more suitable solution for the desired application.

2 STATIC FREQUENCY CONVERTERS

Basically both groups of static frequency converters, devices with a voltage link on one hand and converters employing a current link on the other hand, can be used for testing transformers. As the simple one-level self commutated inverter is the easiest to assemble but also adequate to work out the differences between a voltage link and a current link, the advanced designs, e.g. multi-level inverters and binary converters, are not examined.

As the following paragraphs will show, both systems have a comparable hardware setup but they are operated by an entirely different control unit.

2.1. Voltage Source Converter

The voltage source converter consists of a grid supply connected to a 6-pulse bridge circuit (B6C according IEC 60971 [4]). The rectifier generates a DC voltage. The transmitted energy is stored in the condenser battery with a total capacitance of 40 mF. The DC link voltage is transformed to a pulse-width modulated alternating voltage by the H-bridge converter, and, with the aid of a three stage sinus-filter, the alternating voltage is smoothed to a sinusoidal voltage. Fig. 1 shows the equivalent circuit diagram for the voltage sourced converter.

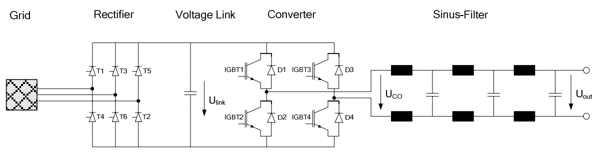

Fig. 1: Simplified equivalent circuit diagram for the voltage sourced converter

To prevent the hole-storage effect of the thyristor rectifier, a surge suppressor circuit is necessary, consisting of a RC-element connected in parallel.

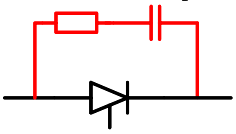

Fig. 2: Surge suppressor for one thyristor

The converter H-bridge is a self commutated three point inverter. To smooth the pulses at the output a three stage sinus-filter with six 120 µH reactances and three capacitors with 11 µF, 22 µF and 47 µF are used. Fig. 3 shows the ideal, theoretical converter output and the smoothed sinusoidal voltage.

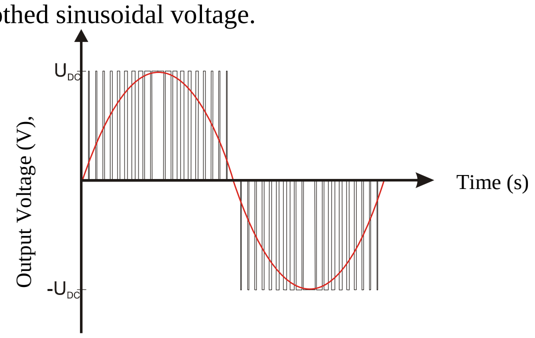

Fig. 3: Ideal pulse width modulated voltage and smoothed output voltage.

2.2. Current Source Converter

The few differences between the voltage sourced and the current sourced converter are shown in the comparison between Fig. 4 and 5.

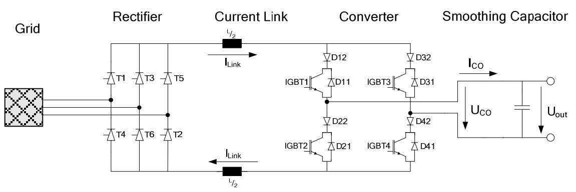

Fig. 4: Simplified equivalent circuit diagram for the current sourced converter

The rectifier hardware module is similar to the one used by the voltage sourced converter but driven by a different control scheme which is attuned to a constant current flow in the DC link. As a consequence the voltage at the rectifier output can be negative thus representing the inverter state of the 6-pulse bridge.

The link energy is stored in DC coils and not in a condenser battery. The inductance of the DC coils for the link is 150 mH and symmetrically balanced (75 mH each).

Apart from additional diodes both inverter modules are designed similar, but again operated by different control principles. The recovery diode, which is necessary for the voltage sourced converter and always integrated in a standard IGBT-module, must be disabled. Due to this the diodes D_{12}, D_{22}, D_{32} and D_{42} are placed in series to the IGBT-modules. Only then a voltage rise over the load is possible.

Special inverter states of the H-bridge transform the DC current into a AC current. Instead of a pulse width modulated voltage a pulse width modulated current is the output of the inverter. The output current switches between 0 and $+I_{Link}$ for the positive half wave and 0 and $-I_{Link}$ for the negative half wave.

With the aid of a capacitor the pulsed output current is smoothed. In difference to the voltage sourced converter it is not necessary to install an expensive and extensive three stage sinus-filter.

Establishing a current link converter it is mandatory to consider the hazard caused by the load-independent direct current. In the case of a switching error in the inverter section or another fault which results in an open loop the current path of the load-independent current is interrupted. The stored energy in the current link is not self-defeating. Dependent on the energy stored in the link heavy hardware damage can occur. It is inevitable to prevent this problem by providing a clamping circuit as shown in Fig. 5.

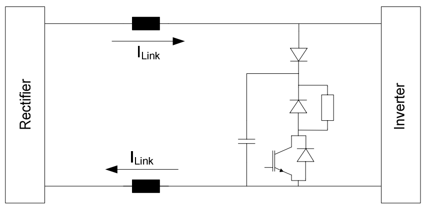

Fig. 5: Simplified equivalent circuit diagram for the clamping circuit

The clamping circuit is designed to work even when there is a blackout in the system or another heavy fault. In a failure case the current commutates from the inverter to the clamping circuit, the capacitor takes on the energy of the link and the voltage over the capacitor rises dependent on the level of the load-independent current. This can be up to 1600 V, if a DC capacitor of 350 µF is in use. If required, the capacitor can be discharged with a parallel IGBT and resistor circuit.

3 CONTROL AND SIMULATION

The standard proceeding for both converter types is to generate a sinusoidal output with a static pulse width modulated signal. Fig. 6 shows the principle.

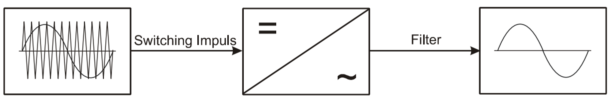

Fig. 6: Basic PWM system

After the adaptation of the PWM principle to both converters the first simulation results can be obtained. As the pulse pattern is predefined and not adaptable for different loads, the required THD < 5 % can not be observed for all loads. Fig. 7 shows a result for the current link converter with a pure ohmic load, which normally is the easiest to handle. Even in this case the THD factor can not be decreased to less than 6%.

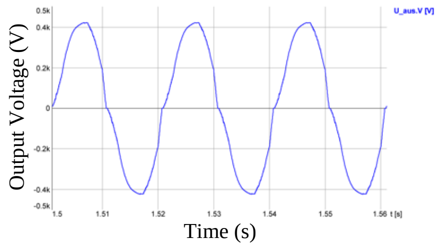

Fig. 7: Simulation result for a load of 20 Ω

Supplying non-linear loads, it is not possible to obtain a THD < 20 %. The voltage sourced converter is similarly loaded with a 20 Ω resistor, producing less THD than before; feeding again a non-linear load the permitted limits are exceeded by far.

Due to these problems it is necessary to establish a closed loop control. The easiest possibility is a two-step control with a nominal/actual value comparison. Fig. 8 shows the principle.

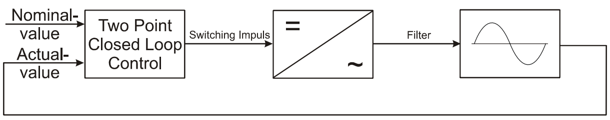

Fig. 8: Fundamental two step nominal/actual value comparison

A complete and more detailed servo loop is shown in Fig. 9.

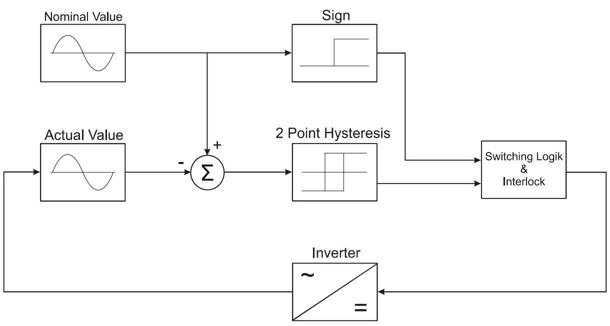

Fig. 9: Advanced control principle

After the implementation of this two-point control, the voltage and current output of the inverter follows its nominal value independently from the kind of load. Thus it is possible to achieve a THD < 5 % in the simulation. Even with non-linear loads like a lightly saturated transformer. Fig. 10 and Fig. 11 show the simulation results for a non-linear load; the output frequency is 50 Hz. The voltage form is exactly sinusoidal which is proven with the THD dynamically simulated over the time in Fig. 11. The non-sinusoidal waveform of the current confirms the non-linearity of the applied load.

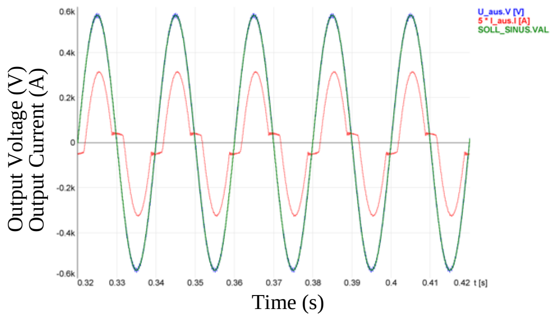

Fig. 10: Output of the current sourced inverter for a non-linear load. The horizontal axis shows the time; the voltage in volts and the current in amperes are plotted on the vertical axis.

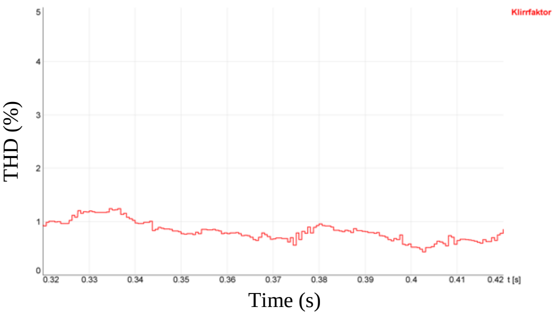

Fig. 11: THD calculation of the voltage in Fig. 10 (in percent)

3.1. Specifics of the Current Sourced Converter

Dependent on the output frequency some adjustments of the current link converter have to be made. At 50 Hz a smoothing capacitor of 150 µF is connected in parallel to the output to have an adequate voltage quality. Due to the resulting time constant of the capacitor and the load the value of the capacitor has to be adapted to the maximum output frequency:

$$\frac{dU}{dt} = \frac{1}{C} \cdot I_0 \cdot e^{\frac{-t}{R \cdot C}} \tag{2}$$

The voltage change is dependent on I_0, the link current and the multiplication of R · C, the load R and the output capacitor C. With a more or less fixed link current and a specified load it's only possible to scale down the capacitor at the output to get a large dU/dt. With this adjustment it is possible to achieve the required output quality for all tested loads, voltages and frequencies.

3.2. Specifics of the Voltage Sourced Converter

The problem of adapting frequency and the time constant of the smoothing element can as well be transferred to the current sourced inverter: Dependent on the load R and the inductance L included in the sinus-filter the derivative of the output current in time is calculated to

$$\frac{dI}{dt} = \frac{1}{L} \cdot U_0 \cdot e^{\frac{-t \cdot R}{L}} \quad (3)$$

Keeping U_0 and R constant L has to be chosen carefully to get the desired rise time of the current. Simulation for different loads, output power and inductances results in a reactor of 120 mH per stage of the three stage sinus-filter.

4 REALISATION

For both converters it is necessary to develop an appropriate control scheme. With small hardware changes and manifold software adjustments in the control unit it is possible to use the developed unit for both converters. Fig. 12 shows the hardware elements concerned.

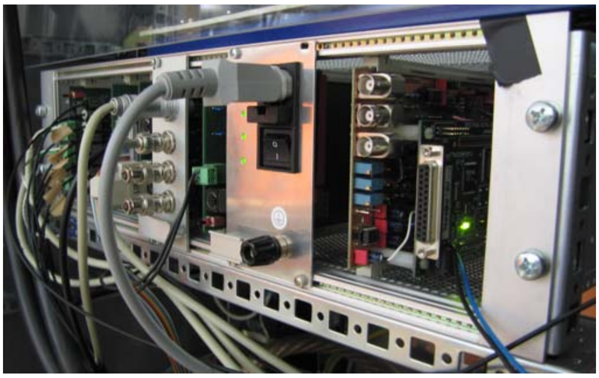

Fig. 12: Central control, feedback-control and measurement unit for both converters

The power components and measuring devices are placed into two different EMC shielded enclosure to minimize the background noise for the comparative partial discharge measurement between both converters. The used hardware components e.g. capacitors, reactors semiconductor devices and safety features are customary components.

4.1. Voltage Sourced Converter

Fig. 13 shows the power stack of the voltage converter with the DC capacitor link upside the fully controlled thyristor rectifier and the IGBT inverter. Apart from the power section some additional auxiliary components are installed e.g. the top hat rail with fuses, the voltage source for the control unit and an additional 50 Hz tuned grid-supplied LC-oscillator for the zero crossing detection, which is necessary for the rectifier control.

Fig. 13: Power stack of the voltage sourced converter

4.2. Current Sourced Converter

The power stack of the current link converter is less highly integrated and more clearly arranged. Thus more details are visible in Fig. 14. The blue capacitor is part of the clamping circuit described above, providing safety for the system. The silver capacitors are the cascadeable smoothing capacitors at the output of the inverter. The IGBT inverter is placed underneath the driver circuit board and hardly visible. The lower third of the picture shows the driver circuit of the thyristor rectifier and the current transformer for the link current. All this parts are mounted on the black heat sink in the background.

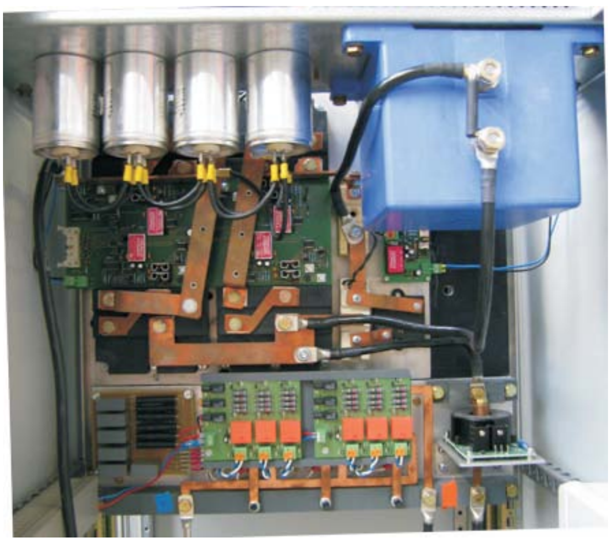

Fig. 14: Power stack of the current sourced converter

5 RESULTS

The results and assessments presented in this chapter are based on real measurements recorded the laboratory.

5.1. Comparison of the Voltage Quality

The voltage and current diagram in Fig. 15 is characteristic for both types of converters; here the differences between voltage link and current link are negligible.

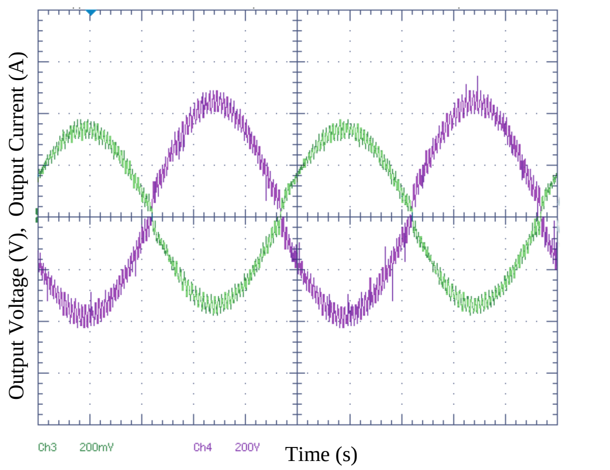

Fig. 15: Output voltage $U_{A,\ RMS}$ = 300 V CH4 and output current CH3 $I_{A,\ RMS}$ = 25 A (inverted) of the current sourced converter.

The voltage form of the converters is sinusoidal but the sinusoidal band in which the wave is controlled is very wide. This is not because of the characteristic hysteresis curve of the two point control, but is caused by the non-ideal voltage measurement. The employed voltage transformer at the converter output needs a Hall sensor to detect a possible DC offset, enabling the control to work against. However, voltage transformers with a Hall sensor always have a response time of approx. 90 µs. This means that the voltage transformer acquires the accurate value but transmits the measuring result with a time shift of 90 µs to the two point control. Consequently the control can detect and compensate the exceeding of the limit with a delay of 90 µs producing the wide voltage band shown above. For an exact output voltage within the limits a voltage transformer with less than 10 µs response time is necessary. Tests with differential probes show a better shape with smaller voltage bands but without the DC component. Further investigations with both types of converters indicate that for some loads, especially the inductive load, voltage quality is not compliant to the international standard concerned. Thus a more complex and better detailed closed loop control has to be developed for the type of converter, which proves to be the more qualified solution regarding the pd-measurement and the economical aspects in reference to the output power.

5.2. Comparison of the Partial Discharge Measurement

Generally it is possible to generate test voltages for the pd-measurement with both types of converters. The quality of the output voltage is sufficient to assess the pd-background noise produced by the converter. In Fig. 16 the simplified circuit diagram for the measurement is shown.

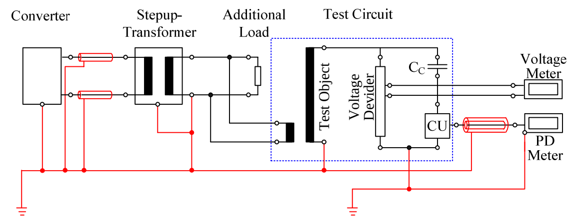

Fig. 16: Simplified circuit diagram for the pd-measurement

For the inspection of the radiated emission the connection to the step-up transformer is disconnected and the following circuit is replaced by an ohmic resistor to load the converter. This test is carried out for both converters alternately. Table 1 shows the result for the current sourced converter.

However, the maximum converter noise should be less than 50 pC for power transformer testing. All attempts to minimize the pd-level for the current link converter are in vain. The assumption, a large di/dt may be less critical for pd-measurement than a large du/dt provoked by the switching impulses of the inverter proves false. The first pd-measurements for the voltage sourced converter are in same range as the results of the current sourced device. Extensive studies to suppress the background noise for the voltage link converter are successful and thus the results in Table 2 could be reached.

Tab. 1: Radiated emission caused pd-level for the current link inverter

S_{out} [kVA]	U_{out} [V]	I_{Link} [A]	Remarks	PD–level [pC]
0,0	0,0	0,0	background noise	20
0,0	0,0	0,0	converter no load	200
0,37	65,0	25,0		700
1,49	130,0	25,0		1200
4,48	225,0	35,0		2000
9,63	330,0	45,0		3000

Tab. 2: Radiated emission caused pd-level for the voltage link inverter with noise suppression

S_{out} [kVA]	U_{out} [V]	U_{Link} [V]	Remarks	PD–level [pC]
0,0	0,0	540	background noise	3
0,0	0,0	540	converter no load	5
0,37	65,0	540		14
1,53	130,0	540		15
4,15	225,0	540		15
9,12	330,0	540		18

After the pd-measurement for the radiated emission the measurement setup shown in Fig. 16 is used. The additional resistor is inserted to increase the effective load at the converter output. The results for the converters are shown in Table 3 and 4. They are consistent with the measurements of the radiated emission.

Tab. 3: Pd-level caused by conducted and radiated emission of the current link inverter

S_{out} [kVA]	cos φ	U_{out} [V]	I_{Link} [A]	Remarks	PD–level [pC]
0,0		0,0	0,0	background noise	20
0,0		0,0	0,0	converter no load	130
1,10	0,55	65,0	25,0		1350
2,55	0,6	130,0	25,0		2270
3,74	0,6	150,0	35,0		2870

Tab. 4: Pd-level caused by conducted and radiated emission of the voltage link converter with noise suppression

S_{out} [kVA]	cos φ	U_{out} [V]	I_{Link} [A]	Remarks	PD–level [pC]
0,0		540	0,0	background noise	2
0,0		540	0,0	converter no load	5
0,42	0,71	540	25,0		20
1,78	0,81	540	25,0		24
2,38	0,82	540	35,0		27

5.3. Energy and Costs

The power rating of the test system is essentially dependent on the energy storage capability of the link. As the energy density of reactors and capacitors is not equal, the energy stored in the link with capacitors is higher compared to the deployment of reactors.

For the voltage sourced converter the stored energy is calculated to

$$\begin{aligned} W_{el} &= \frac{1}{2} \cdot C \cdot U^2 \\ &= \frac{1}{2} \cdot 40\ mF \cdot (540\,V)^2 = 5832\ J \end{aligned} \tag{4}$$

and for the current based converter it results in

$$\begin{aligned} W_{el} &= \frac{1}{2} \cdot L \cdot I^2 \\ &= \frac{1}{2} \cdot 150\ mH \cdot (70\ A)^2 = 368\ J \end{aligned} \tag{5}$$

Considering the current values for both types of converters, it is obvious that the current converter is at a disadvantage. Additionally the costs for the voltage link are less than the expenses for the current link. Two DC-coils with 75 mH each and I_{max}=70 A charge roughly 5000 Euro. The capacitors for the voltage link with 40 mF costs approx. 3000 Euro. However, adding the expenses for the smoothing filter at the output of the voltage sourced converter, the costs for both converters are nearly the same - but still with a significant difference in the stored energy.

5.4. Conclusion

The demands on a voltage source for testing power transformers with a semiconductor based frequency converter are highly diverse. To assess different converter types for this purpose a voltage sourced and a current sourced frequency converter are designed, calculated, simulated and built-up.

The voltage form is in compliance with the international standards not for all tested loads. The problems can be determined and with a more detailed closed-loop-control it should be possible to improve the quality of the output voltage in the future.

For safety reasons the voltage sourced converter should be used preferably, as, to avoid serious hazard or damage, the current flow in the current link must not be interrupted in any case. A voltage link can safely store the energy without any danger in the case of failure.

Due to the larger energy storage capability of the capacitor bank, converters with a DC voltage link are smaller and cheaper as converters providing the same power with a current link.

The crucial and most important advantage of the frequency converter with a DC voltage link over the current sourced converter is the reduced background noise for partial discharge measurements.

6 REFERENCES

Standards:

[1] DIN EN 60060-1 “Hochspannungs-Prüftechnik” 06/1994

[2] DIN EN 60076-1 “Leistungstransformatoren” p. 14 chapter 3.6.5, 01/2003

[3] DIN EN 60076-3 “Leistungstransformatoren” p. 19 chapter 12, 03/2001

[4] DIN IEC 60971 “Semiconductor converters - Identification code for converter connections, 08/1989