Static converter-fed drives

Basic approach for an innovative protection concept for drives in hazardous areas

by Christian Lehrmann, Harald Pape, Uwe Dreger, Frank Lienesch

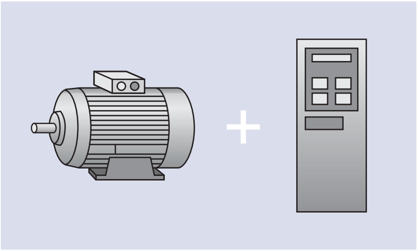
Figure 1: Explosion protected electrical drives in a chemical plant

Static converter-fed drive systems are required in the chemical and petrochemical industry for flexible process technology. This article introduces a new concept for protecting static converter-fed drives in hazardous areas. In order to draw a comparison, we will start by depicting the conventional approval procedures (joint testing of the converter and motor in types of protection ›e‹ and ›n‹). The operating states of the drive system that are critical for explosion protection and the available options to avoid these states will be analysed below. The physical causes for the increased losses and temperature rise during converter operation will be displayed and the available options to mathematically assess the converter-related temperature rise and losses will be introduced. Examples of how the protection concept can be implemented for a size 132 machine will be introduced based on this knowledge.

Testing and approval of static converter-fed drives

The previous protection concept for static converter-fed drives is primarily based on monitoring the stator temperature using a thermistor as well as coupling the converter on the machine for machinery with the type of protection increased safety ›e‹ ([1], [2]). During testing, the critical operating parameters are determined and are a constituent part of the approval certification. The converter type is listed together with the adjustable parameters for the adjustment ranges specified in the certification.

Linking converter and motor in one certification e.g. ›e‹



Advantages:
- Fully tested and certified assembly
- Easy-to-use for the user

Disadvantages:
- Adjusting the user requirements is strictly limited. Significant change require a new approval
- Motor and converters can only be replaced by components of the same type
- Expensive and time-consuming testing for large-scale drives

Figure 2: Previous test and approval method for static converter-fed drives type of protection increased safety ›e‹

Disadvantages of the previous approval method

The previous protection concept for static convert-fed drives of type of protection increased safety ›e‹ is very inflexible and costly, as the converter must be tested together with the machine that it is intended to operate with. This is very time-consuming and expensive for large-scale machines, in particular (see Figure 2). The different product cycles of the motor and converter are considered to be the decisive disadvantage. While configuring a motor frequently takes more than 10 years, the converters are subjected to a continuous technological process of change. This means that the approval must be frequently updated, without influencing a single technical safety aspect. The same applies to subsequent repair or converter replacement or non-critical changes made to the operating parameters. The standardisation of static converter-fed drives in type of protection increased safety ›e‹ does not provide specific requirements for testing, which, depending on the experience of the notified body, can result in different requirements implemented during the procedures involved in the approval methods.

There are no requirements specified in the standard EN 60079-1 (Electrical apparatus for explosive gas atmospheres; Part 1: Flameproof enclosures ›d‹) for static converter-fed drives in flameproof enclosures. The EN 60079-14 (Electrical apparatus for explosive gas atmospheres Part 14: Electrical installations in hazardous areas (other than mines)), for example, specifies the use of thermistors embedded in the winding, without mentioning any other requirements. Since the EN 60079-14 is not primarily aimed at the manufacturer, but rather the erector and user, the situation is not clear. Rotor temperature critical operating states (e.g. undervoltage) may not be detected by using only a thermistors in the stator-winding.

Objectives for improving the protection concept

Essentially, the objectives of the new protection concept involve the following:

- discontinuing the rigid coupling between the motor and converter for type of protection increased safety ›e‹
- incorporating the easy interchangeability of the converter during repair work
- ability to retrofit existing drives with a converter
- providing secure protection for all drive system operating states.

Implementing this concept would both simplify the approval method as well as reduce the related approval costs (Figure 3). Figure 4 displays a possible scenario for machine protection while implementing the future protection concept.

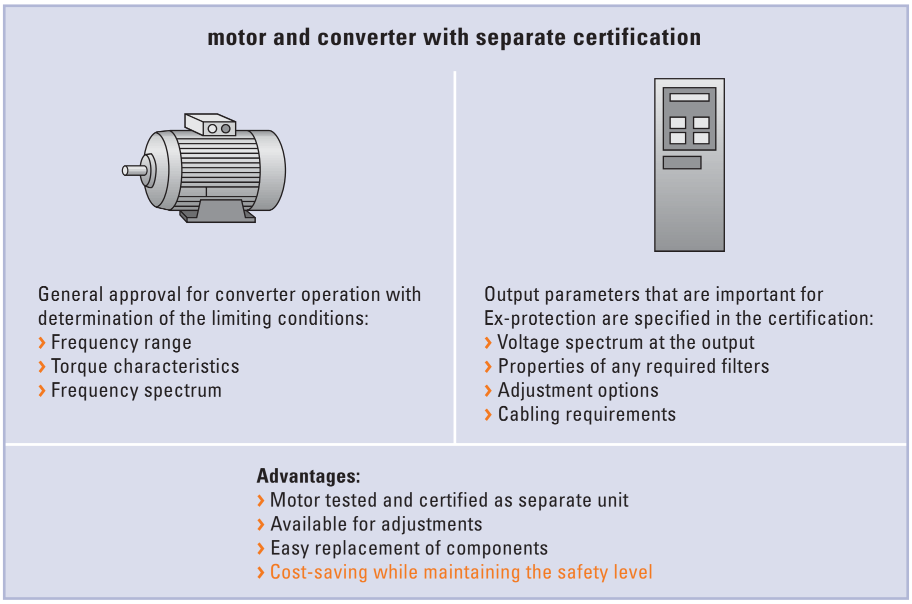
➔

In principle, the same physical dependency applies to the testing and approval of static converter-fed drives of the type of protection flameproof enclosures ›d‹, thus the approach of the protection concept should be implemented. Only the enclosure temperatures must be used for this purpose.

Required fundamentals for the machine protection

To begin with, heat development within the machine must be known during all operation times to ensure the thermal protection of the drive system. Furthermore, particular attention must be paid to the distribution of power loss, since the technical measurement monitoring of the rotor while in operation is extremely complicated and is only worthwhile for large-scale machines (telemetric systems). The rotational speed-dependent heat-transfer resistance between the machine and the environment is a critical point that is considered a measure for the critical lower drive speed.

The heat-transfer resistance was determined using the test set up illustrated in Figure 5. In order to measure the heat-transfer resistance, the machine fan was powered by a DC motor at variable speeds and were heated using a stator winding. Instead of the rotor, the machine only contains the rotor shaft to avoid causing any additional eddy current losses in the rotor. The results for two machine sizes are displayed in Figure 6. If there is an adequate precision torque measuring system available, the entire rotor can be used with a thermally-insulated coupling, as the mechanical output power can precisely be measured. In doing so, a measurement should be made, even for the non-energised machine, to determine



motor and converter with separate certification

General approval for converter operation with determination of the limiting conditions:
- Frequency range
- Torque characteristics
- Frequency spectrum

Output parameters that are important for Ex-protection are specified in the certification:
- Voltage spectrum at the output
- Properties of any required filters
- Adjustment options
- Cabling requirements

Advantages:
- Motor tested and certified as separate unit
- Available for adjustments
- Easy replacement of components
- Cost-saving while maintaining the safety level

Figure 3: Objective for the approval and test method of static converter-fed drives

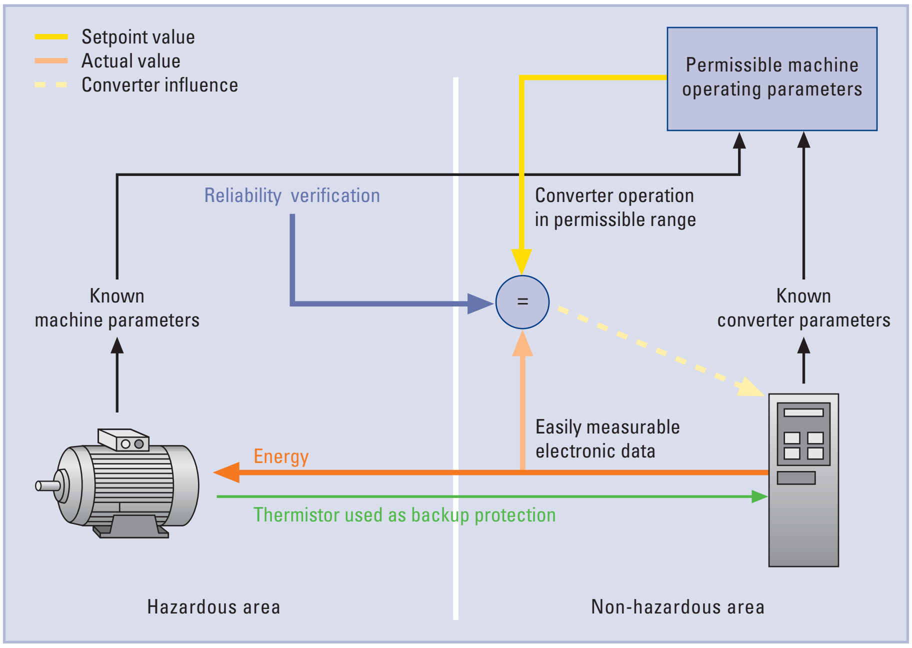


Figure 4: Applying the new protection concept

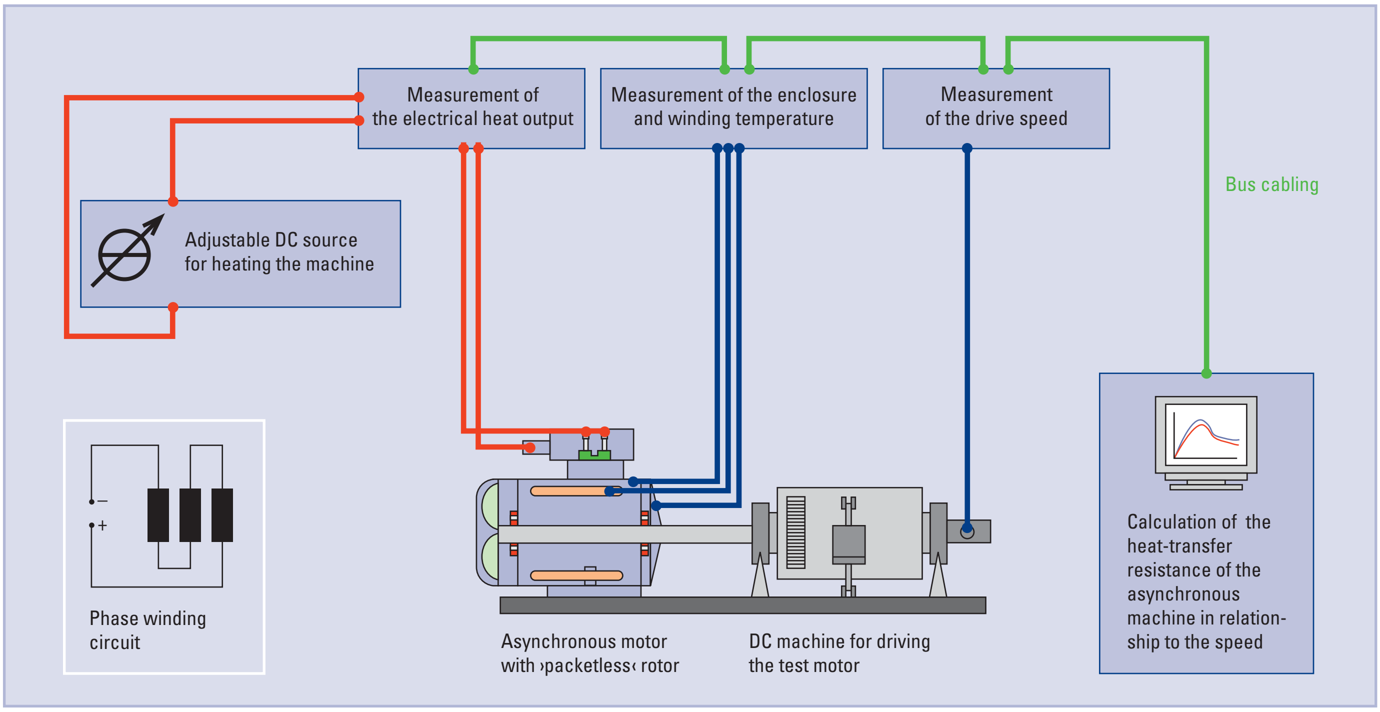


Figure 5: Test set-up for measuring the thermal resistance

the mechanical power absorbed by the machine fans.

Simply formulated: at all times, it must be ensured that the highest permissible temperature is divided by the heat-transfer resistance to the environment and is less than the constantly maintained power loss. Higher power losses are permissible for a short period of time; however, this state may only exist until the highest permissible temperatures have been reached. Afterwards, there must also always be an adequately long cooling phase. An example of the temperature sequence during overload is displayed in Figure 7. To avoid triggering the thermistor, the overload must not last longer than 66 seconds. In practice, the converter is preset with a maximum permissible overload time of 60 seconds. The temperature curves illustrated in Figure 7 are based on a calculation using the thermal equivalent circuit diagram (Figure 8) of the machine, and the temperatures reached were verified by a measurement. The required internal heat-transfer resistance was determined by measuring the temperatures with a known power loss distribution.

Converter-related additional losses

The converter-related additional losses can be divided into two groups:

- Increase in iron losses caused by the harmonic components in the supply voltage, predominantly in the machine stator.
- Increase in electrical heating losses in the stator winding and in the rotor cage. The voltage harmonics drive currents into the stator and the rotor of the machine that cause electrical heating losses in the frequency-dependent ohmic resistances.

The increase in losses caused by the static converter supply can be explain in hat a static converter-fed machine can also be theoretically viewed as a machine that is powered by basic sinusoidal oscillation and is connected in parallel for every harmonic. The speed of this ›harmonic machine‹ is determined by the speed of the ›basic oscillation‹ machine so that in a sense, it is in short-circuit for each harmonic. Each harmonic now causes losses in their

➔

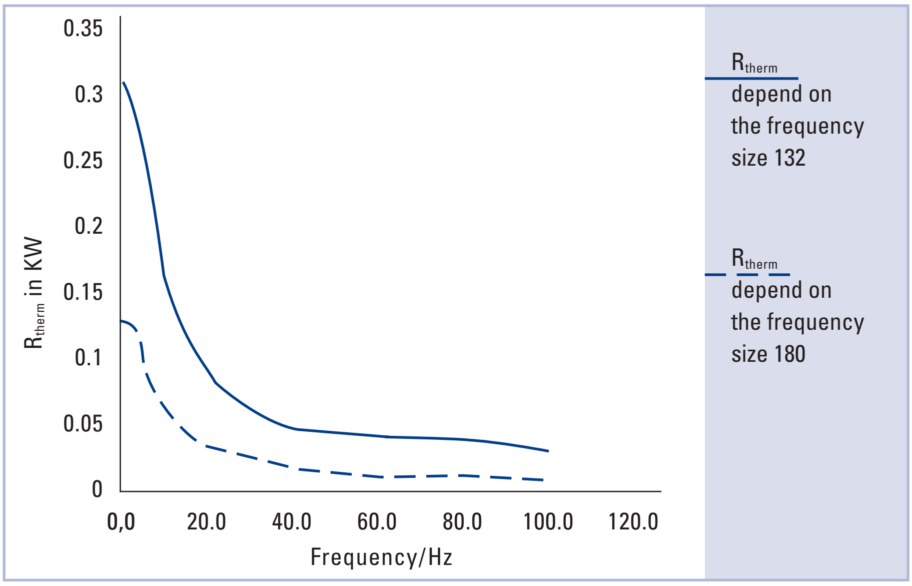


Figure 6: Characteristics of the thermal resistance of the enclosure and envirement R_{therm} in K/W for 180 und 132 size machines, in relationship to the frequency

assigned ›harmonic machine‹ that adds up on all ›harmonic machines‹, which in turn equals the total harmonic loss. According to this, it follows that both the total harmonic loss can be calculated by adding the individual losses and that the harmonic currents are predominantly dependent on the leakage inductances of the machine ($s \approx 1$). The harmonic losses depend both on the voltage of the respective harmonic as well as its frequency [3], [4]. The power loss generated by an individual harmonic can be determined for a strand using the interrelationship $P = U \cdot I \cdot \cos\varphi$. The current I is linked with the impedance Z by the equation I=U/Z so that for the power loss, you can also write:

$$P = U^2 / Z \cdot \cos\varphi$$

The impedance Z and the phase displacement angle are frequency-dependent and must be determined in a separate test.

The current displacement effects primarily occur in the rotor of the machine. This increased ohmic resistance is transformed to the stator winding (for the harmonic, the machine is nothing more than a transformer with a very small resistance in the secondary circuit).

The increase in the ohmic part increases the $\cos\varphi$ and is thus included in the loss calculation.

In contrast, the machine temperature increase favourably effects the converter, as the usual high start-up loss associated with mains operation does not occur (in broad terms, the entire rotational energy to be stored in the drive system is transformed into heat in the rotor during the start-up procedure). Starting from the speed 0, the machine is always operated at the rated point with the usual operational slip values.

The fact that the power supply network is not loaded with high start-up currents when switching on the machine provides another advantage.

In addition, the ›short-circuit operation mode‹ of the machine (blocking the machine with machine currents at rated voltage up to 10 times the rated value) cannot occur, as the converter limits the machine currents to a significantly lower value (generally, no more than 120 % of the rated current). The degree of the converter-related additional losses depends on the operational mode of the converter and its design. However, the dependence can be ascribed to the output spectrum of the converter. The output spectrum is explained in detail in citations [5] and [6].

Interrelationship between the losses and the machine temperature raise

Heating during continuous operation

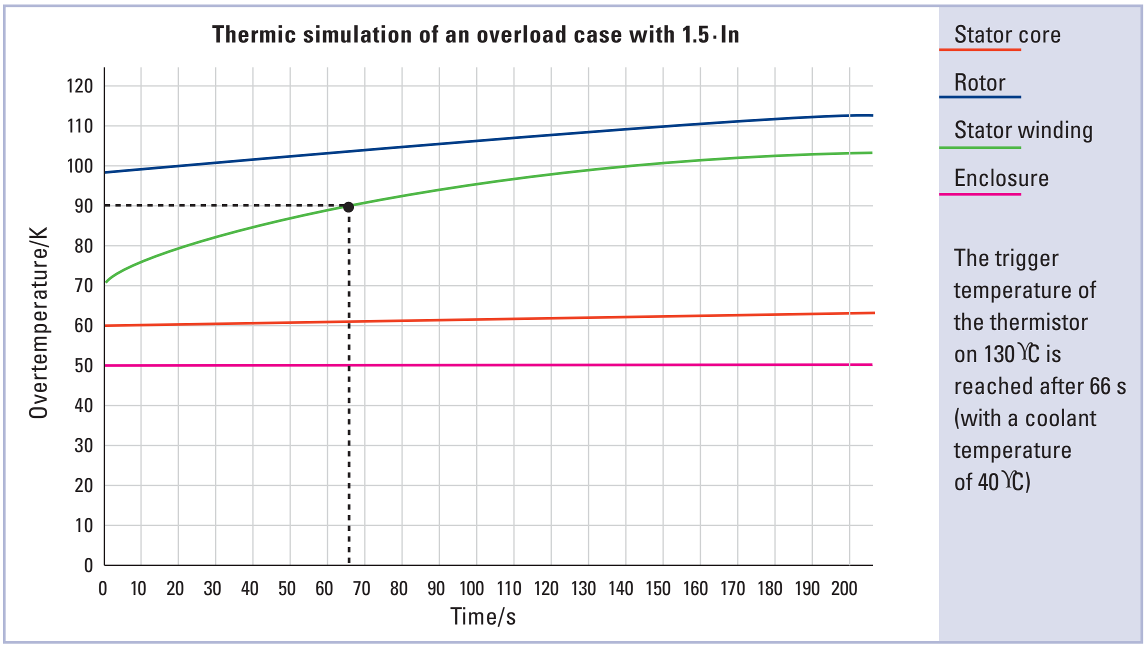
To reach a stationary state, the heat volume generated in the machine for each unit of time must correspond to the heat volume released into the environment. Analogous to the electrical circuit, a thermal resistance can be defined between the environment and the machine and can be calculated using the equation.

$$R_{therm} = \frac{T_{motor} - T_{enviroment}}{P_{Vtotal,\ motor}}$$

In this simplified view, the machine is treated as a separate entity with one temperature (one-body model) and it is assumed that there is thermal equilibrium.

Transient Phenomenon

A transient phenomenon is described as the transient response of the temperature



The trigger temperature of the thermistor on 130 °C is reached after 66 s (with a coolant temperature of 40 °C)

Figure 7: Calculated temperature course during overload. The winding temperature in °C is derived from the sum of the overtemperature in K and the room temperature

during a step change in power loss, e.g. during a brief change in the machine load. As the equilibrium between the generation of heat and the dissipation of heat is disturbed here, the energy difference causes the machine components to heat up or cool down until equilibrium sets in again. As an e-function, the temperature approaches your stationary final value.

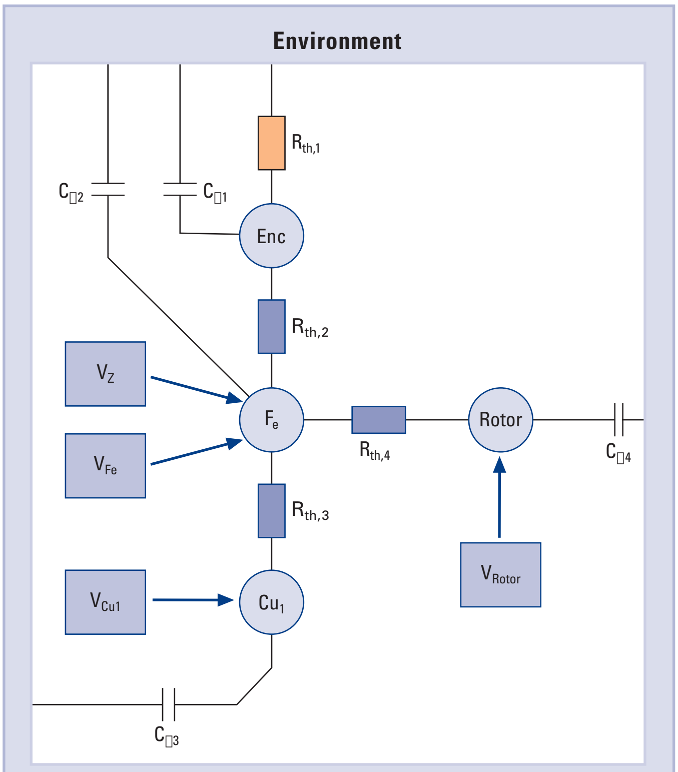
The course of the machine temperature change ΔT can be mathematically described in relation to the time t:

$$\Delta T = (\Delta P_V \cdot R_{therm}) \cdot (1 - e^{(-t/\tau)})$$

$$\text{with } \tau = C_{therm} \cdot R_{therm}$$

To determine the continuous operation temperature at a known power loss, the thermal transfer resistance to the environment plus the thermal capacities of the machine components (Figure 8) are required to calculate transient procedures. The thermal capacity can also be mathematically determined from the temperature time characteristic at a known power loss and the temperature reached during continuous operation by using the thermal time constant. The thermal capacity can also be calculated by using the mass of the materials used for the individual machine components. If the construction data is known, the second method generally provides exacter values.

➔



$R_{th,1}$ = Enclosure environment
$R_{th,2}$ = Stator core-enclosure
$R_{th,3}$ = Stator winding-stator core
$R_{th,4}$ = Rotor-stator core
$C_{\square 1}$ = Enclosure heating capacity
$C_{\square 2}$ = Stator core heating capacity
$C_{\square 3}$ = Stator winding heating capacity
$C_{\square 4}$ = Rotor heating capacity

Figure 8: Thermal equivalent circuit diagram of the asynchronous machine
Enc = enclosure

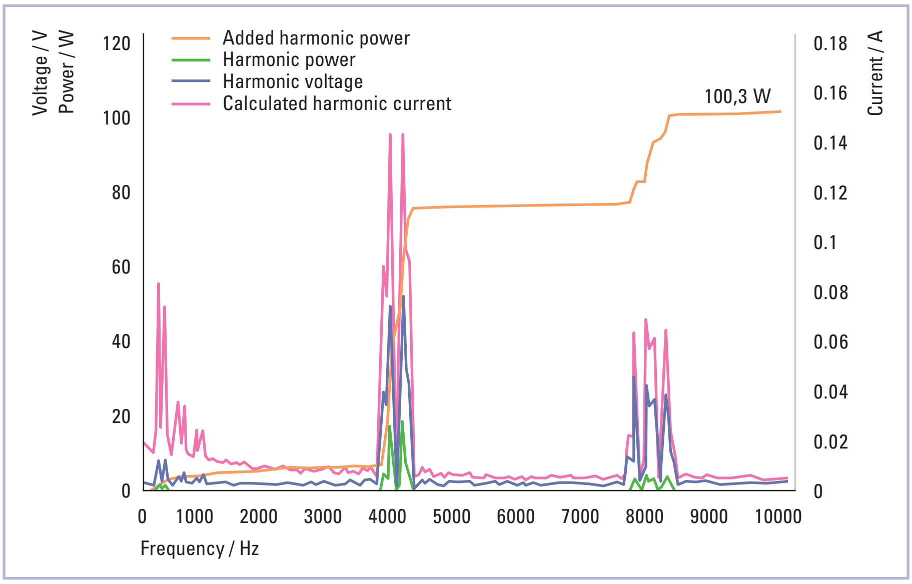


Figure 9: Example of calculated harmonic losses

Projection of converter-related additional loss

Harmonic losses

A possible method for projecting the additional losses and temperature rise caused by harmonics is based on the method of describing the machine using a frequency-dependent impedance (see section Converter-related additional losses). This procedure is displayed as an example for a machine in Figure 9. The figure illustrates that the impedance strongly increases with the frequency (comparison of the voltage and current curve). The converter pulse frequency (4 kHz) has the largest proportion [6] of converter-related additional losses for the machine in question.

The additional temperature rise caused by the harmonic losses can be calculated together with the speed-dependent heat-transfer resistance.

The metrological determination of machine impedance was realised using a function generator with an upstream linear amplifier system. The procedure is examined in detail in [6].

Losses caused by current displacement effects

The impedance measurement takes into account the influence of the current displacement effects. The current displacement effects primarily occur in the rotor bars with the machine sizes in question (up to approx. 200). However, the current displacement effects in the stator cannot necessarily be ignored, as even with the wire cross sections, less than twice the current penetration occurs in the winding due to current displacement effects of the wire bundling [7]. The influence of the current penetration in the rotor depends on the groove shape. With a double bar rotor at the identical frequency, the current density on the upper edge is considerably greater than with a round bar rotor with the same bar cross section surface [8] [9].

Calculating the machine temperatures

In order to assess the machine regarding the explosion protection, the temperature class is determined for which the temperature reached during continuous operation must be ascertained.

To project the temperature rise caused by converter operation, the calculated power loss must be calculated for the considered speed using the equation

$$\Delta T = P_V \cdot R_{therm}$$

The fundamental frequence losses, which occur in the motor, raise the machine temperature the most, however, these losses can be significantly increased during operation with undervoltage (voltage requirement of converter, filter or ›long‹ lines).

Additional influences on the machine temperature

Undervoltage

The conducted measurements show that operation with undervoltage is very a critical event. If the torque is held constant, machine slip increases as the voltage is reduced due to the lower magnetic field strength. As the slip increases so do the rotor currents that then raise the rotor temperature via the ohmic losses. Operation with undervoltage can occur very quickly with a static converter-fed machine, as the converter has a voltage requirement of approx. 10 – 15 V, depending on the load. However, significantly larger values can also be achieved through unfavourable converter configurations.

In worst-case scenarios (long line routes, using a sinusoidal filter), the total voltage drop between the mains and the motor can significantly increase. If the permissible tolerance range (± 5 %), according to range A, of the mains voltage is now utilised, this results in a converter input voltage of 380 V with a 400 V network. While taking into account the converter voltage requirement and any cable or filter losses, the fundamental frequency voltage at the machine terminals can drop to 340 V.

This raises the temperature of the test machine at a rated load of approx. 30 K, see Figure 10.

Converter with a broad input voltage range

To achieve universal applicability, the converters are more and more frequently equipped with a broad input voltage range that allows them to be operated, for example, using a 400 V supply voltage and 500 V industrial networks. If the converter is operated with 500 V instead of 400 V, the intermediate circuit voltage is increased by the same ratio. To generate the identical fundamental frequency output voltage, the modulation ratio must be decreased, which in turn increases the machine losses (mainly iron losses) ([7] [10] [11]). This was proven through measurements conducted at the PTB. This effect is ascribed to an increase of the harmonic proportion that can be seen in a Fourier analysis.

Operation at low speeds

During operation at low speeds, the cooling capacity initially moderately drops with the speed and then begins to drop at a considerably accelerated rate upon reaching a specific speed. The previous

→

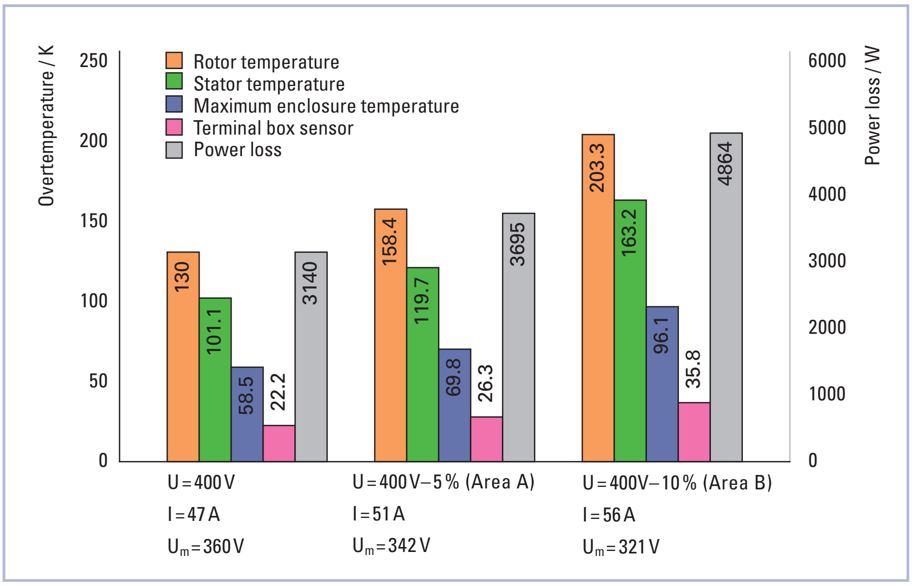


Figure 10: Influence of the converter input voltage on the machine temperature increase and U_m = fundamental frequency voltage at the machine terminals

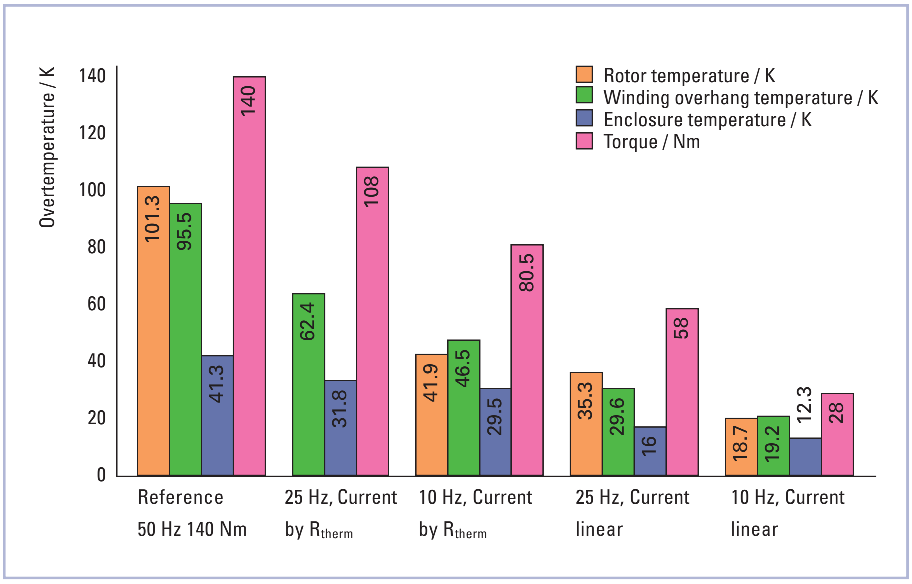


Figure 11: Temperatures for different torque adjustment procedures

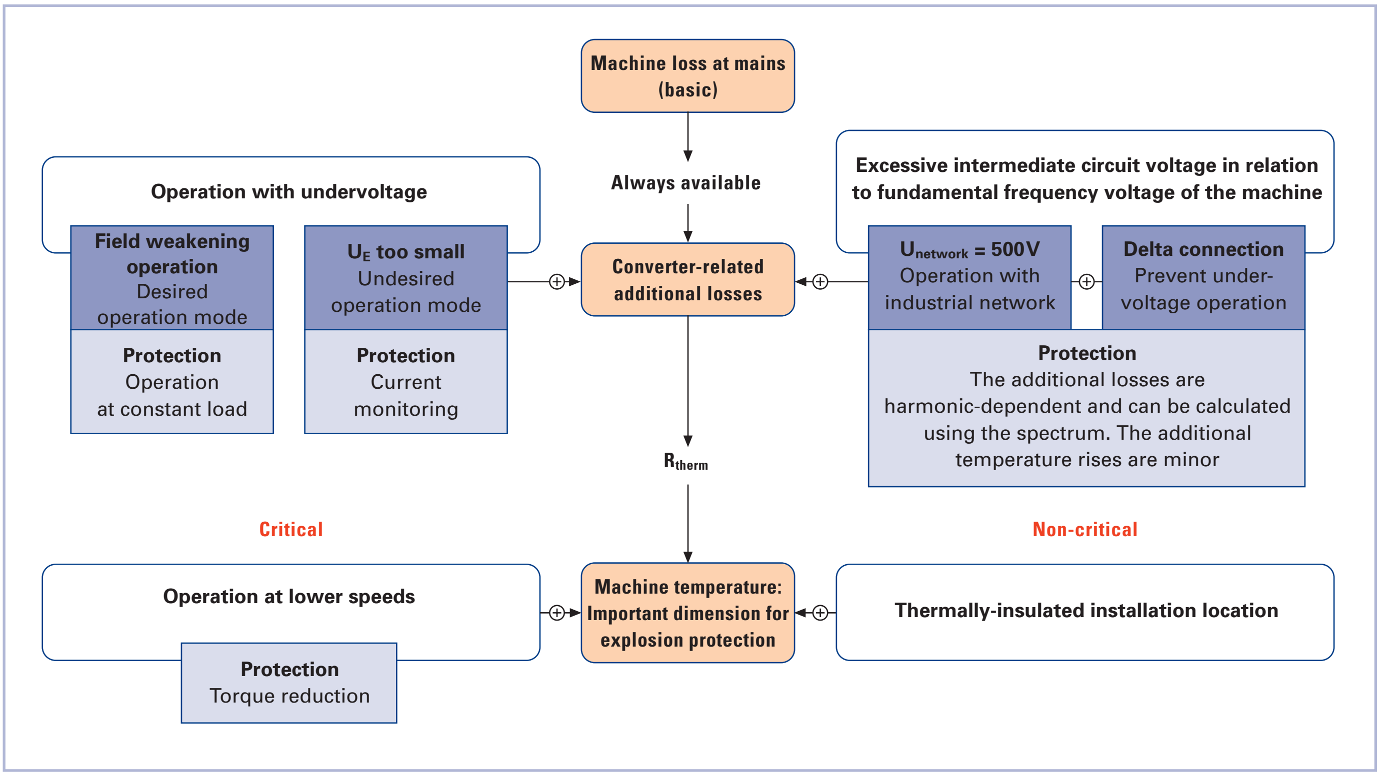


Figure 12: The most important parameters for the rise in machine temperature

approval method accommodated this state by using forced air ventilation or by utilising a temperature-rise test at the lower rated speed. In most cases, the temperature-rise test is not necessary if a working machine is utilised to ensure a quadratic reduction of torque along with the speed.

However, experiments have demonstrated that considerably higher torque levels can be achieved at lower speeds than those torque levels achieved by inducing a quadratic reduction, without posing a risk of excessive temperatures. The objective here is to determine, where possible, a universally valid limiting curve for the maximum permissible torque for self-ventilated machines during continuous operation.

A testing procedure has been developed in which the constant permissible power loss at a speed value is determined using the ratio of the heat-transfer resistance of the enclosure and the environment. Previously this was determined using technical measurements (see Figure 5). Supposing that the machine losses are primarily electrical heating losses and these quadratically depend on the equation $P_V = R \cdot I^2$, the current must be converted using the root from the ratio of the heat-transfer resistances. The torque levels possible while limiting the calculated current are considerably higher than the values calculated with the quadratic conversion using the speed. During the previously conducted trials, the temperatures while operating with an adjusted current at 25 Hz and 10 Hz in the stator and rotor were significantly lower than the temperature at 50 Hz and the rated load. Plans have been made to record full load curves at low speeds for different machines in order to determine the moment of load in which the machine temperature corresponds to the value at 50 Hz. The objective here is to determine the correction factor for the current adjustment that depends on the heat-transfer resistance and allows the machine current to be calculated for every speed in which the temperature rise corresponds to the value at 50 Hz.

Field weakening operation

Operation within the field weakening range occurs once the converter can no longer track the voltage in proportion to the frequency, as the intermediate circuit voltage is being limited by the line voltage. If the load is not reduced, the machine slip increases and extremely high temperatures may occur in the rotor. To avoid this problem, the output power in the field weakening range must be kept constant. Since the voltage is constant, constant output power also means an approximate constant current. Depending on the supply voltage or due to the voltage drop on the converter, filter or longer line, the field weakening operation mode can start prior to the rated speed, and then the motor can no longer be loaded with the rated output.

Basic approach for a protection concept

The objectives of the future protection concept are primarily concerned with reducing the testing costs for the approval of explosion-protected converter fed machines of the type of protection increase safety ›e‹.

A central point of the new concept is to avoid the strict coupling between the motor and the converter for the type of protection increased safety ›e‹. One method of achieving this lies within defining an interface between the motor and the converter in which the output parameters of the converter that cause the additional losses (harmonic spectrum, voltage requirement of the converter, modulation procedures, adjustable pulse frequency range) are determined.

The ›sensitivity‹ of the converter-related influences must be defined for the machine, e.g. the frequency-dependent impedance, the relationship between the speed and the heat-transfer resistance to the environment as well as the voltage range in which the machine can provide full torque at the rated speed. This value is important for the start of the field weakening operation. When applying the new procedure, this interface definition for explosion protection is synonymous with the rating plate specifications of the machines during mains operation.

Interface parameters

Output parameter of the converter, metrological determination

The converter is operated at its rated output on the upper and lower limits of the rated voltage range. For these operating states, the spectrum is measured and the worst-case scenario is used for further observation. If the converter allows different pulse frequency settings, the spectrum must also be verified for the lowest and highest possible frequency.

For a converter with a broad input voltage range (e.g. 400 V – 500 V), the spectrum, including the highest input voltage, must be taken into account, since the converter input voltage influences the output spectrum.

The measurement at maximum current is required, as the harmonic rates in the lower range of the spectrum increase in some converters operating with increasing current. Such increases appear especially in the harmonic rate at 150 Hz. This must be taken into consideration, especially for converters with a ›narrow intermediate circuit‹. At a higher current load, the lower capacity of the intermediate circuit capacitor causes a considerable ripple to occur that is conveyed into the output. A ripple voltage of approx. 20 % was measured in the intermediate circuit of the utilised testing converter at rated current.

Machine-side interface parameters (for the certification)

The machine-side interface parameters essentially consist of:

- The frequency-dependent impedance and the frequency-dependent phase angle between the current and voltage.
- The speed-dependent heat-transfer resistance between the machine enclosure and the environment.
- The permissible operating voltage range of the machine at rated load and rated frequency. The lower limit of this range is defined at the beginning of the field weakening range during operation.

Metrological determination of the converter-related additional losses and temperature rise for testing the projection

The technical measurement of the converter-related additional losses is determined by comparing the power loss generated in the machine (absorbed electrical input power minus the released mechanical output power) at the identical mechanical load between network and frequency converter operation. To conduct these measurements, even at frequencies other than 50 Hz, a generator was used to supply the energy for the tests conducted. These tests were performed using various converter settings and external limiting conditions (e.g. pulse

➔

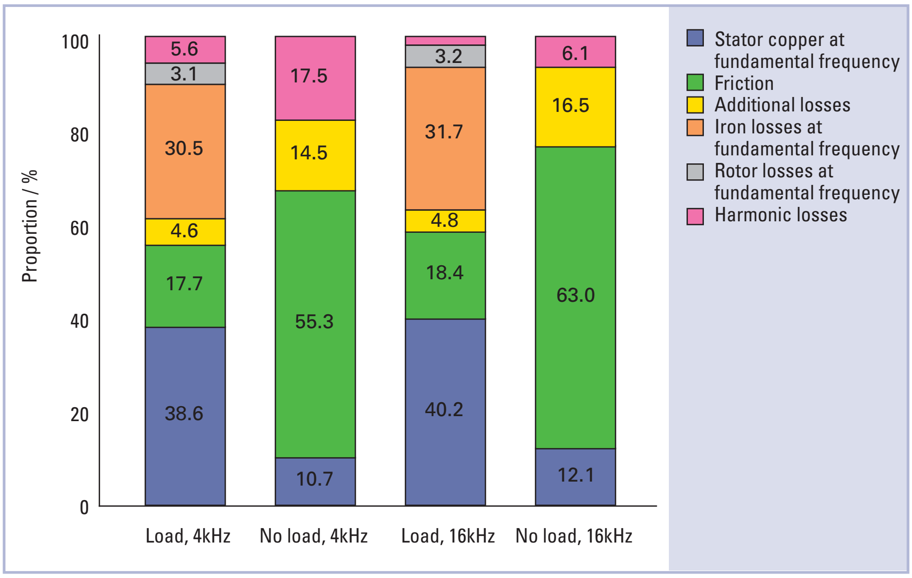
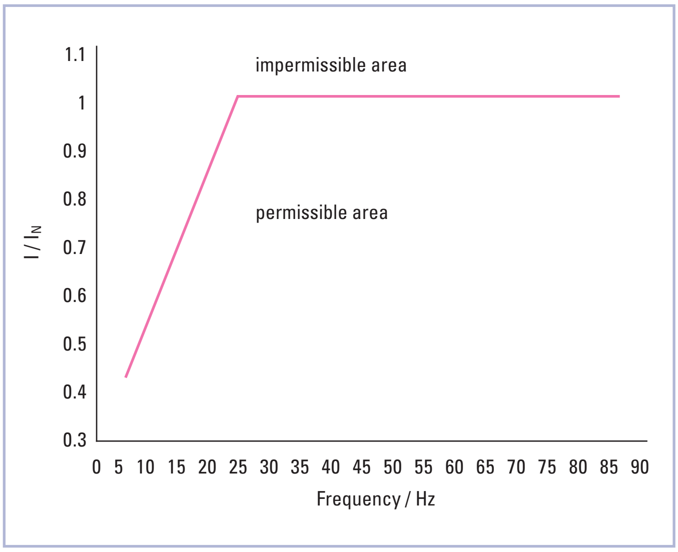


Figure 13: Converter-related additional losses of a size 132 machine with no load and at rated load

Figure 14: Permissible continuous machine current in relation to the rated current and depending on the speed



frequency, converter input voltage, load state of the converter).

It must also be taken into consideration that the percentage of the harmonic losses for the entire machine changes with the load, even if the absolute value is not load dependent.

An example of the interrelationship for a size 132 machine is displayed in Figure 13.

Summary of the new protection concept

An essential component of applying this protection concept requires precise knowledge of the machinery (sensitivity with respect to the harmonics caused by the converter) as well as the converters being used (output spectrum, voltage requirement, etc.) in order to correctly assess the individual influencing factors on the rise in machine temperature (see Figure 12). To simplify this protection concept in the future, it would be worth considering defining a reference machine whose parameters allow the converter-related additional losses to be calculated for the considered converters. To simplify the process for selecting the converter for the machine manufacturer, it would also be reasonable to introduce a classification for converters similar to the energy efficiency classes for electrical household equipment. Using the fictive reference machine, the converter would be classified in the corresponding class, depending on the degree of additional losses caused by this converter in comparison to mains operation. If uniformly implemented by all manufactures, this marking could considerably simplify the process of selecting a suitable converter for the user and further reduce the testing costs concerning explosion protection. In order to achieve a simple and practical implementation, it would be suitable to regulate the speed-dependent cooling effect by reducing the machine load in linear fashion to a level below a critical speed. Although this would make the machine more difficult to utilise than by simply reducing the torque via the thermal resistance (Figure 11), it would, however, enable a simple implementation into the control software of the converter. The machine current allows the torque characteristics to be easily monitored. An example displaying the characteristics of the permissible machine current in relation to the speed for a 132 size machine is shown in Figure 14.

Literature

[1] IEC/EN 60079-7:2002
Electrical apparatus for explosive gas atmospheres – Part 7: Increased safety ›e‹

[2] Directive 94/9/EC of the European Parliament and the Council of 23 March 1994 on the approximation of the laws of the Member States concerning equipment and protective systems intended for the use in potentially explosive atmospheres, Official Journal of the European Communities, 1994 No L 100/1-29

[3] Müller, G.; Bunzel, E.: Oberschwingungsverluste in Niederspannungs-Asynchronmaschinen, Die Antriebstechnik, 2000, volume 8, pages 59 – 61

[4] Müller, G.; Bunzel, E.: Oberschwingungsverluste in Niederspannungs-Asynchronmaschinen, Teil II Analytische Untersuchungen, Die Antriebstechnik, 2000, volume 9, pages 71 – 73

[5] Lehrmann, C.; Engel, U.; Lienesch, F.: Oberschwingungsverluste und Erwärmungen umrichtergespeister Induktionsmaschinen, Bulletin des Schweizerischen Elektrotechnischen Vereins, des Verbandes Schweizerischer Elektrizitätsunternehmen, 2002, volume 15, pages 9 – 14

[6] Lehrmann, C.; Engel, U.; Lienesch, F.: Verluste umrichtergespeister Induktionsmaschinen in Funktion der Betriebsparameter, Bulletin des Schweizerischen Elektrotechnischen Vereins, des Verbandes Schweizerischer Elektrizitätsunternehmen, 2003, pages 9 – 15

[7] Heimbrock, A.: Analyse der Oberschwingungsverluste zweipoliger Induktionsmaschinen am Pulsumrichter, Dissertation University Hannover, 2004

[8] Seinsch, H. O.: Grundlagen elektrischer Maschinen und Antriebe, Teubner-Verlag, 1993

[9] Beständig, N.: Ermittlung der Ströme, Verluste und Erwärmungen eines Asynchron-Normmotors bei stationärem Betrieb an einem selbstgeführten Stromrichter mit konstanter Eingangsgleichspannung, Dissertation University Karlsruhe, 1986

[10] Boglietti, A.; Ferraris, P.; Lazzari, M.; Pastorelli, M.: About the Possibility Defining a Standard Method for Iron Loss Measurement in Soft Magnetic Materials with Inverter Supply, IEEE Transactions on Industry Applications, 1997, volume 5, pages 1283 – 1288

[11] Boglietti, A.; Bottauscio, O.; Chiampi, M.; Pastorelli, M.; Repetto, M.: Computation and Measurement of Iron Losses under PWM Supply Conditions, IEEE Transactions on Magnetics, 1996, volume 5, pages 4302 – 4304

[12] Lehrmann, C.: Ex-Geschützt: Antriebe mit Frequenzumrichter, Vorschlag für ein neues Zulassungskonzept, Bulletin des Schweizerischen Elektrotechnischen Vereins, des Verbandes Schweizerischer Elektrizitätsunternehmen, 2004, volume 24/25, pages 17 – 23