Static converter-fed electrical drives

Safety assessment for use in hazardous areas

by F. Lienesch

The asynchronous machine, in conjunction with the static converter, is being used to an increasing extent in the sector of explosion protection as well for speed control of electrical drives. Speed control allows chemical and petrochemical processes to be controlled with open-loop or closed-loop control. Besides the advantages of static converter-fed asynchronous motors however, there are certain difficulties relating to design and testing in comparison with mains operation and these difficulties also impact on explosion protection.

1. Introduction

Speed control of the drive systems is required for automation of production sequences in the chemical and petrochemical industry in order to pump or transfer liquid or gaseous flammable media as needed. Implementation using static converter drives is a proven technology which does, however, involve additional risks compared with mains supply, and these risks require more detailed consideration, in particular in explosion protection. The purely sinusoidal supply voltages and currents are replaced by pulse-modulated waveforms with higher frequency shares, such as square-wave currents on power converters. Besides power converters with DC link for high power, static converters with voltage link are used for low to moderate power. The configuration options of the closed-loop and open-loop control units for the diverse applications on the market have led to a model diversity, which makes the situation unclear and thus makes a uniform concept for safety assessment more difficult.

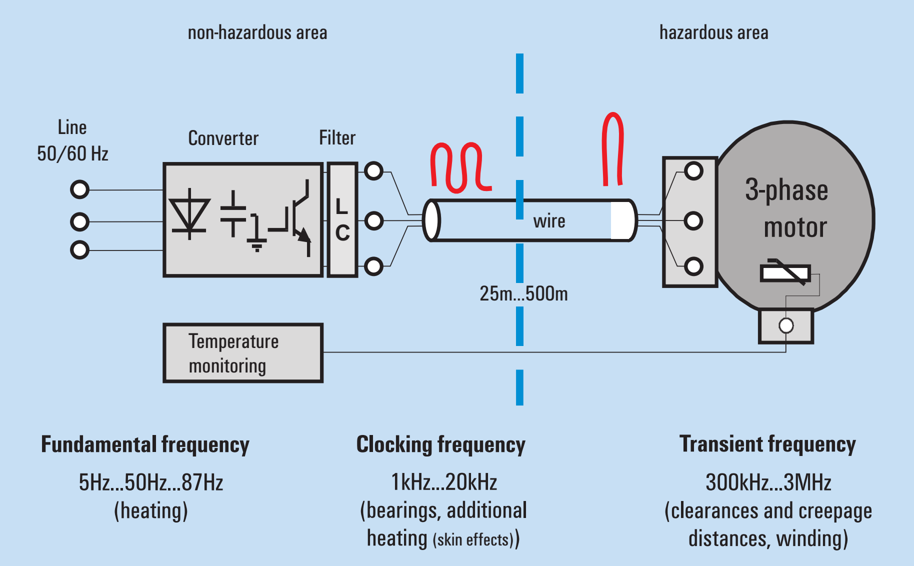

Figure 1: Schematic structure of static converter-fed drives in hazardous areas

2. Static converter-fed motors for hazardous areas

The combination of variable-speed asynchronous machines in hazardous areas comprises three types of apparatus (static converter, motor and monitoring unit, Figure 1), which are installed separately but which must ensure explosion protection when combined.. Frequency converters with voltage link are frequently used to power the motor. This initially involves converting the mains-related 50/60 Hz AC voltage to a DC voltage. The link voltage is smoothed by capacitors. High-speed power transistors (e.g. IBGT) convert the DC voltage to the required AC voltage by correspondingly modulated switchgear assemblies. The static converter is generally installed in the safe area and is therefore not designed with a type of protection for Zone 1. One exception is the static converter integrated in the terminal boxes of type of protection Flameproof enclosure ‚d' or Pressurised apparatus ‚p', and, in particular, the power loss of the static converter limits the drive power to a few kilowatts in this case.

The actual drive is located in the hazardous area and must therefore be explosion protected. The mechanical design may certainly differ from that for conventional mains operation (e.g. with an insulated bearing). In general, the temperature class of the electrical machines is maintained by temperature sensors embedded in the winding overhang in conjunction with a function-tested tripping device. In accordance with Directive 94/9/EC, the tripping devices can be marketed with an EC type examination certificate.

Unlike the situation in the case of operation in the conventional constant-voltage, constant-frequency mains at a frequency of

50 Hz or 60 Hz, broader frequency ranges must be anticipated when designing static converter-fed drives. Adjustability of the required speed range is defined with the fundamental frequency.

Heating of the electrical machine in the speed range in particular must be determined and must be limited by temperature monitoring.

The clocking frequency of conventional static converters lies between 1 kHz and 20 kHz. High clocking frequencies reduce the ripple of the current characteristic, reduce noise emission and also offer dynamic advantages.

In some cases, it is necessary to span long distances for connection of the asynchronous machine in the hazardous area to the static converter. Travelling wave phenomena which lead to voltage overshoots at the end of the line and which also place an additional strain on the insulation system of the electrical machine occur on the long cables in conjunction with high-speed power transistors. The transient phenomena resulting from travelling waves lie in a frequency range 300 kHz... 3 MHz. The frequency is dependent on the cable length and on the characteristic impedance of the cable. A wide variety of filter types, such as sinusoidal filters or dU/dt filters, are used in order to attenuate the disadvantageous effects of the higher frequencies.

3. Types of protection of static converter-fed drives

The requirements for static converter-fed drives differ substantially in some cases between the relevant types of protection (Figure 2). The temperatures must be measured specifically to the type of protection at the various positions of the motor within the stipulated mains voltage range.

For types of protection ‚e' and ‚n', the combination of motor and static converter is defined in the test so that the static converter type must be specified in the certificate. Changes to the parameters of the static converter or exchange of the static converter by a more recent type are therefore not possible without renewed verification. A procedure differing from this may be agreed between manufacturer and user for Zone 2.

Different static converter types can be combined with the motor for types of protection ‚d' and ‚p'. The static converter type is not necessarily defined in the certificate by the testing authority.

Compliance with the temperature class is guaranteed by the manufacturer or user. Changes to the static converter parameters or exchange of the static converter by a different static converter are possible. Flameproof enclosure necessitates the use of PTC resistors embedded in the winding in conjunction with a function-tested tripping device (EN 60079, Part 14).

4. Testing static converter-fed drives

4.1 Frequency of the fundamental wave

The temperature class of electrical apparatus for explosion protection refers to the rated data listed in the certificate within the defined voltage and frequency fluctuations of the power supply. The electrical machine which is operated connected directly to the mains is also specified in the certificate as a function of the power output at the shaft at a corresponding speed of rotation. The defined supply system conditions change decisively for the electrical machine if using the static converter. The static converter controls the motor by setting the voltage amplitude and the fundamental frequency within specified limits. The torque characteristic as a function of speed is responsible in particular for the heating behaviour of the drive. The starting and overload conditions are also defined by the static converter and must be taken into account in testing. The temperature class of the drive is defined by endurance tests within the rated operating range, and the temperatures are determined at the relevant points. In particular, the maximum temperatures may reach critical values at the cable entry and at the branching point of a wire (EN 50014, Sec. 16.8) on static converter drives.

Variation of the speed causes a variation in cooling of the machine, if the machine is not cooled by forced-air cooling. In such cases, a temperature-rise test is required at the drive's lowest speed [1].

Many models of static converter which may have differing effects on the heating behaviour are offered with various setups. Sinusoidal filters, e.g. at the output of the static converter, reduce voltage at the terminals of the machine. The motor current must

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IEC 60079-0, Para. 24.4.6.1: This test is performed with the advers conditions and at the most unfavourable supply voltage between 90 % to 110 % of the rated voltage,...

Exception: flameproof enclosure ± 5%

	Pressurised apparatus ‚p' IEC 60079-2	Flameproof enclosure ‚d' IEC 60079-1	Increased safety ‚e' IEC 60079-7	Non-sparking ‚n' IEC 60079 - 15
Combination static converter and motor	none	separate if there are PTC resistors in the winding overhang (IEC 60079-14)	Unit	Unit *
Endurance running (temperature)	Enclosure Stator Rotor	Enclosure	Enclosure Stator Rotor	Enclosure Stator Rotor
Protection	Inertisation	No Flame Propagation	Non-sparking	Non-sparking

* Exception see para 9.9.2.2

IEC 60034, Part 17: Rotating electrical machines
Static converter-fed induction motors with squirrel-cage rotors-application guide

Figure 2: Requirements of converter fed drives according to the relevant type of protection

be increased in order to be able to output the required power, and this leads to a higher temperature rise. All parameters of the static converter which impact on the heating behaviour must be taken into account during assessment (Figure 3).

For types of protection ‚e' and ‚n', the static converter type with its parameters is included in the certificate so that the operator can ensure correct parameterisation of the drive. If the Standard does not define mandatory combined testing of static converter and motor, the manufacturer must make binding stipulations (e.g. in the Operating Instructions) for operation in conjunction with the static converter so that the maximum temperature of the temperature class is complied with.

While the power system conditions can be considered constant and the conventional manual motor starter covers possible faults, a variety of operating states may occur, in principle, in the event of a fault as the result of the static converter. Conceivable states include phase shift or the possibility of differing voltage amplitudes. The static converter's measurement and control equipment may be subject to hardware faults and software errors, which have not been taken into account to date in the safety consideration of the drive. For this reason and for reasons of easy handling, function-tested temperature monitoring, in some cases independent of the static converter, is used.

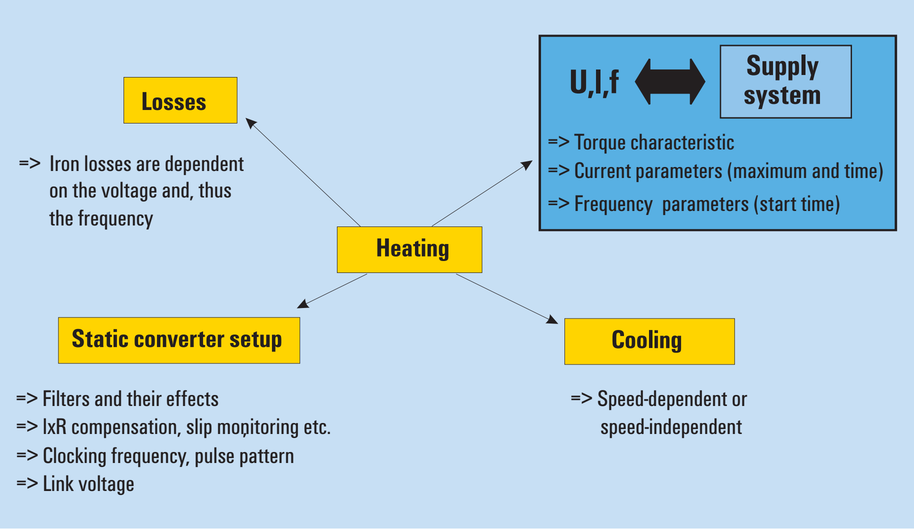

Figure 3: Parameters of the thermal behaviour of drives

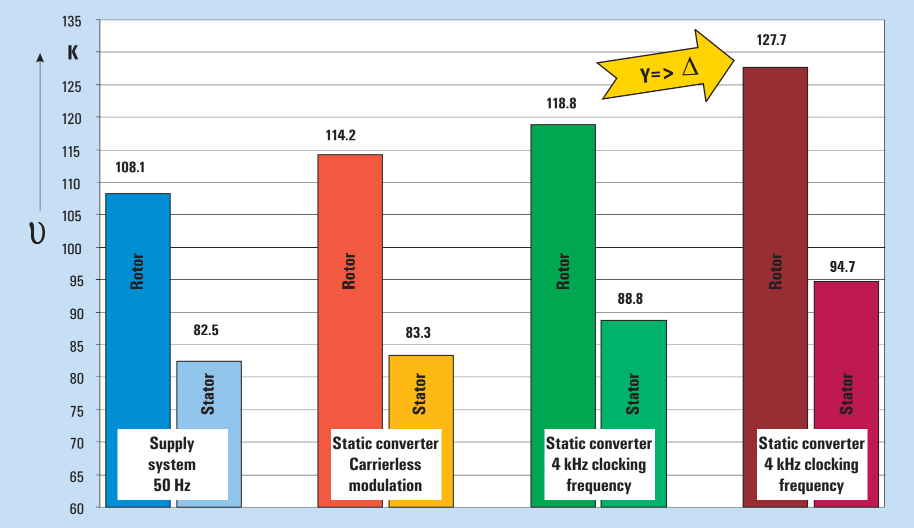

Figure 4: Influence of high-frequency components of voltage and current on heating (temperatur rise in K)

4.2 Clocking frequency

The sinusoidal voltage profile in the case of mains operation is replaced on the static converter with link voltage by square-wave voltage pulses of a specific pulse length. The clocking frequency is normally 1 kHz...20 kHz. The lower limit is determined by the current ripple, which is tolerable for the application and the upper limit is determined by the switching losses of the power transistors. The high-frequency amplitudes of the square-wave voltage lead to a higher current ripple and, therefore, an additional temperature rise of the machine. The harmonics do not make a contribution to generating torques on one hand and the distribution of the current density in the conductor changes on the other.

The influence of the additional temperature rise is shown in Figure 4. Comparing the measurement results in the case of mains operation, the temperatures in the stator and the rotor increase in static converter operation. The static converter with carrier-less modulation shows the lowest temperature rise. In comparison, the stator temperature in particular increases, if fixed carrier frequencies are used. An essential temperature rise results, if the system is switched over from star to delta connection with constant load.

The increased iron losses are essentially responsible for this in the stator.

Sinusoidal filters are used in order to avoid voltage in the range of the clocking frequency. The disadvantages in this case include, in particular, the high cost of the sinusoidal filter, the loss of dynamic response and the voltage losses which occur at the sinusoidal filter.

4.3 Transient frequency

High-speed power transistors in conjunction with ‚long cables (in some cases > 10 m) may result in travelling wave phenomena on the cable. A positive reflection at the terminals of the machines occurs owing to the differing characteristic impedances of cable and stator winding.

The subsequent compensation process is performed with a frequency between 300 kHz and 3 MHz and is dependent on the cable parameters.

The maximum voltage value is determined by the nature of the compensation processes. The travelling wave of a making operation of the transistor leads to twice the link voltage at the end of the cable at maximum.

Unfavourable superimposition of breaking and making operations results in voltage peaks up to three times the link voltage. In order to avoid such phenomena, every switching operation must be concluded before the next switching state is possible. Depending on attenuation, the travelling wave phenomenon generally decreases within 20 propagation cycles on the cable. In the case of ‚very long' cables, this leads to long switching pauses, and this can be implemented only at low clocking frequencies. The maximum anticipated voltage value can hardly be foreseen at the planning phase [3, 4].

The winding of an electrical machine acts like a capacitor chain at high frequencies so that a square-wave voltage pulse with high-frequency components leads to an increased voltage drop at the first windings of the machine. If two windings within a coil contact each other with an adequate voltage difference, partial discharge phenomena in the interpolar gap destroy the insulation. Interturn faults lead to total failure of the machine. The insulation is subjected to additional strain, if dipoles within the insulation layer at high frequencies lead to a further field forcing (Figure 5) [5]. The dimensioning of the air and creepage distances for explosion protection defined for Increased safety ‚e' in accordance with EN 50019 applies to power system-related voltages 50/60 Hz. Transient overvoltages do not need to be taken into account. Since permanent overvoltages, such as those occurring in the case of power converter drives in conjunction with long cables, are not considered, interpretation of the standard requirements is not clear and frequently leads to discussions.

Investigations into the disruptive strength in relation to frequency indicate a clear reduction as of a critical frequency [3]. The magnitude of the reduction is determined by the homogeneity of the field and may lead to halving the breakdown voltage in highly inhomogeneous fields (Figure 6). Investigations into the comparative tracking index of static converter-related overvoltages have shown that only the rms value is the decisive aspect.

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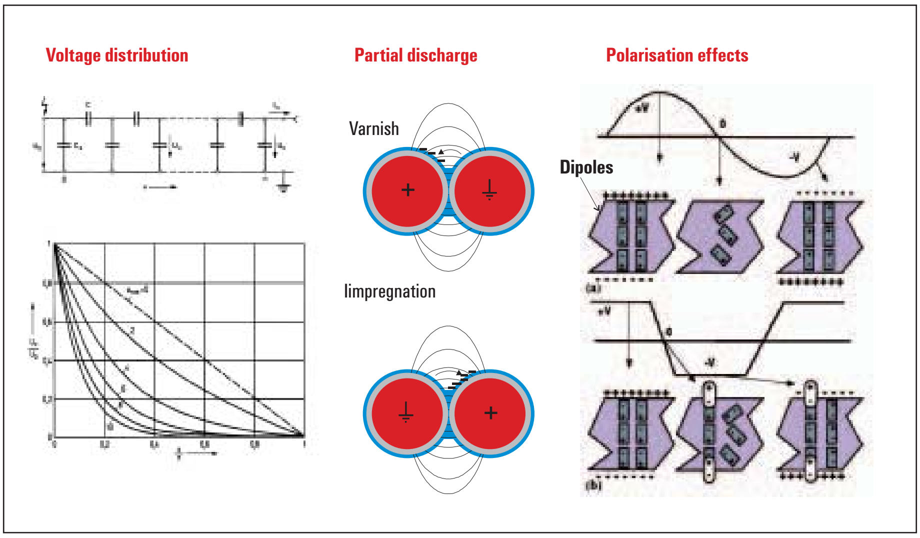

Figure 5: Stressing of the winding insulation as the result of high-frequency voltages

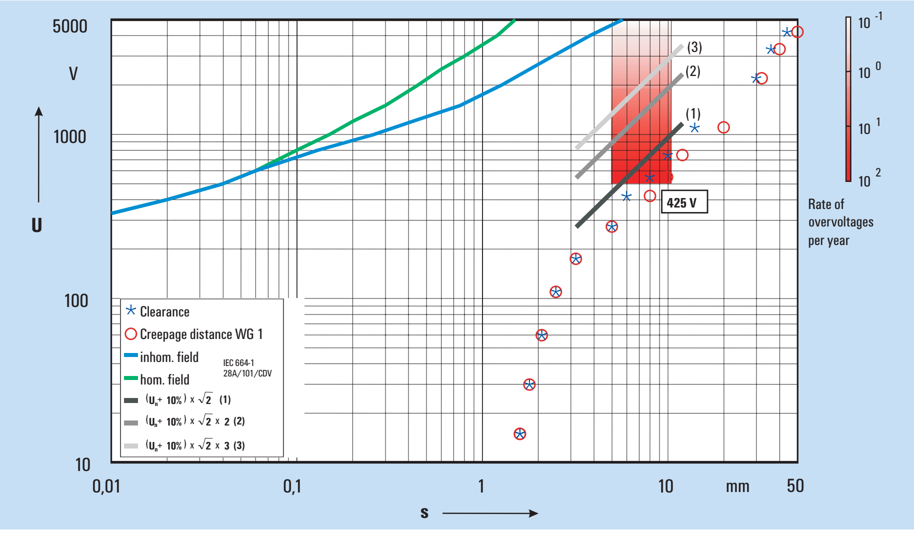

Figure 6: Dimensioning of clearances and creepage distances in the case of static vonverter-related overvoltages

➔ If interpretation of the standard requirement is restricted to low-voltage machines (< 1000 V) however, an adequate safety distance is provided, if the rated value customary for mains operation is used in the case of twice the link voltage at the terminals. Higher overvoltages up to three times the link voltage can be covered by the next rated value from Table 1 EN 50019 [6, 7]. The above interpretation cannot be applied to static converter-fed, high-voltage machines.

The maximum permissible rate of rise at the terminals of the machine is defined in IEC 60034, Part 17, by corresponding limiting curves. The limiting characteristic of the permissible pulse voltage dU/dt, taking into account reflection and attenuation, is stated as a function of the rise time.

The cable filters off the high-frequency components of the voltage with increasing length so that dU/dt is also dependent on the cable length. Due to the fact that the cable length is not known prior to the installation and owing to the difficulty of measuring the voltage profile on site, it is a very complex procedure to comply with the standard requirement in practice.

Since the latest power transistors allow rates of rise of 50 V/ns, the limiting characteristic is easily overshot, in particular in the case of direct connection of motor and static converter, while a ‚long' cable complies with the limiting characteristic despite reflections and high peak value of the voltage.

Travelling wave phenomena can be avoided by so-called dU/dt filters. These filters must, however, be adapted to the cable parameters so as not to produce overvoltages at resonant frequency.

In practice, a maximum cable length can be prescribed.

5. Additional stresses

5.1 Other thermal limits

Other thermal limits must be considered when approving electrical drives. Assuming a motor with type of protection Increased safety ‚e' and a required temperature class T3, we have a maximum temperature of 195 °C of all the surfaces, which may come into contact with the potentially explosive atmosphere. However, this does not mean to say that all components may also be subjected to this temperature (Figure 7).

It means that the insulation class of the winding must be taken into account for every electrical machine, and the continuous operating temperature is the measure of the service life. All plastic components (e.g. auxiliary terminal boxes and plastic fans) of the machine are subjected to further tests in respect of their thermal endurance. Sealing materials are tested in order to establish whether they increase in hardness at a specific temperature.

Importance must be attached in particular to heating at the cable and cable entry in the area of the cable surface and at the branching point of the wire on static converter drives since high-frequency currents lead to additional heating.

5.2 Bearing currents and voltages

Owing to the asymmetrical structure of an electrical machine, an asymmetrical magnetic field is produced besides the actual symmetrical magnetic field. The asymmetrical magnetic field induces a voltage (10...500 mV) along the shaft and, consequently, a current, if the circuit is able to short via the bearings. This results in bearing damage. This fault must be taken into account in particular in the case of large drives.

A three-phase sinusoidal supply system is symmetrical and has zero volt at the neutral point. A PWM converter initially converts the AC voltage to a DC voltage. The high-speed power transistors, in turn, modulate a three-phase AC voltage from the DC voltage,

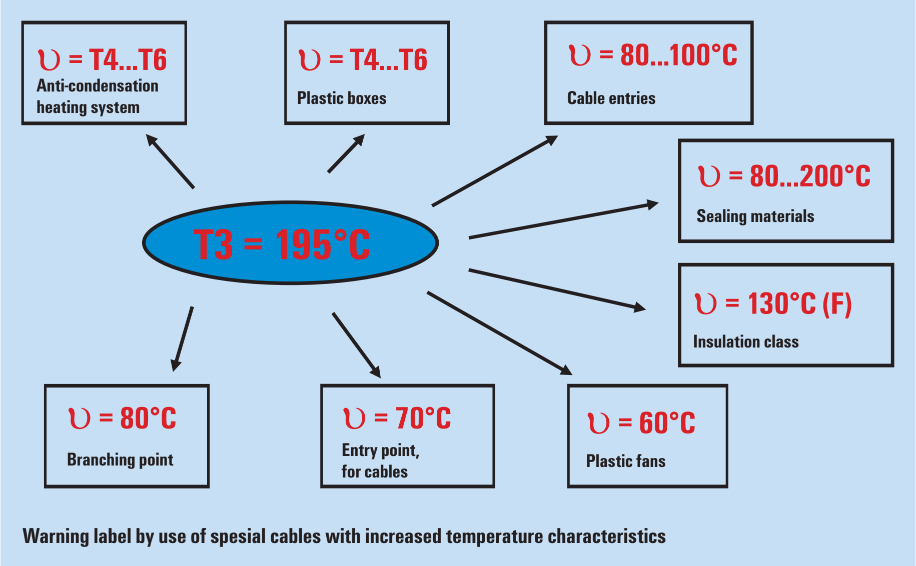

Figure 7: Temperature limits with the type test, temperature class T3

whereby the neutral point simulates the pulse pattern of the three phases. This voltage is referred to as common mode voltage and drives a current through the earth capacitances of all components of the drive. This current flows back through the stray capacitance of the static converter.

The current amplitude is dependent on the motor enclosure, the cable shielding and earthing and possible conductivities of the structure.

The common mode current searches for the path of least impedance. Voltages higher than 100 V may occur in a frequency range 50 kHz...1 MHz [9] between motor enclosure and static converter enclosure. In order to reduce or avoid high-frequency bearing currents, shielded cables should by used in particular. The wires of the three phases should have a symmetrical structure with respect to PE. If this is not the case, it is advisable to connect the PE only in the static converter. The additional earth connection should be laid > 300 mm away from the cable to avoid inductive coupling. In addition, the earthing of the entire system must have a low impedance so that the high-frequency currents are able to flow back.

6. Approval of static converter-fed drives

The relevant standards foresee differing concepts for the various types of protection in relation to approval of static converter-fed drives (Figure 8) (see also Section 3). The combined approval of motor and static converter, as is demanded for types of protection ‚e' and ‚n', also results in serious disadvantages besides affording various advantages. Consequently, the drive is certified for a very specific application.

If major modifications in the application process, which could not be foreseen in the run-up, occur, the approval does not necessarily cover this. On the other hand, a comprehensive test covering a broad application range would excessively reduce the output power. High testing costs are incurred on large to very large drives due to the necessary combined testing of static converter and motor. Only spare parts of the same type may be used if the motor or static converter fails during the period of operation. This may be difficult, particularly on the static converter, since short development cycles mean that such static converters are no longer available in the original form.

By contrast, if we consider the test independent of the static converter, the static converter may load the motor with any voltage and current spectra in broad speed ranges as a ‚black box'. The motor and the motor's protective system must cover all risks in this case, even though they do need to be known before. Neither is it obligatory to mark the motor as ‚suitable for the static converter'. The manufacturer of the motor generally does not assume responsibility for the drive if the user procures the static converter separately. The risk of operation then frequently lies with the user who, in turn, can rarely grasp the range of characteristics of the various static converters.

Fundamental problems of static converter-fed drives must be considered independently of the type of protection (e.g. bearing voltages

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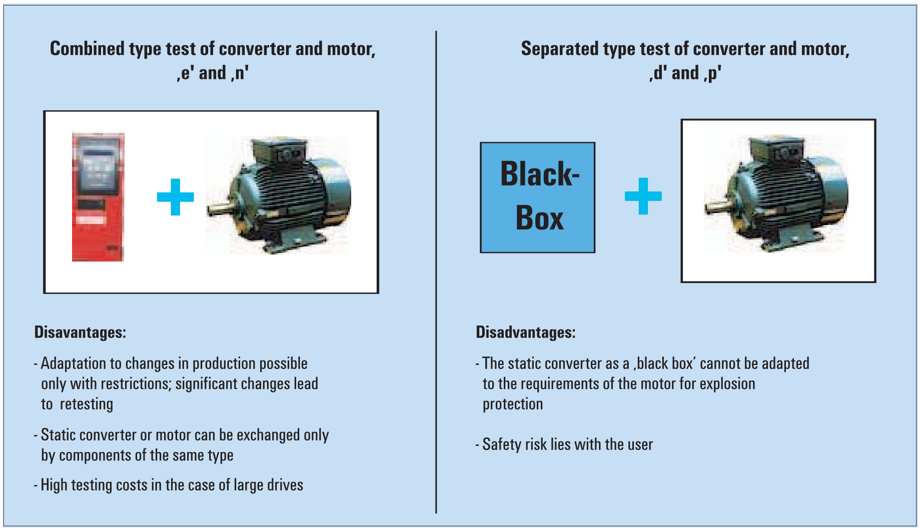

Combined type test of converter and motor, ‚e' and ‚n'

Disavantages:

- Adaptation to changes in production possible only with restrictions; significant changes lead to retesting
- Static converter or motor can be exchanged only by components of the same type
- High testing costs in the case of large drives

Separated type test of converter and motor, ‚d' and ‚p'

Disadvantages:

- The static converter as a ‚black box' cannot be adapted to the requirements of the motor for explosion protection
- Safety risk lies with the user

Figure 8: Type examination in accordance with the type of protection

and overvoltages at the terminal box). Consequently, it should be endeavoured to develop general requirements applicable to static converter drives for explosion protection, which can be derived from the basic standards for motors.

The focus should be on the definition of the interface between motor and static converter to avoid the disadvantages of strict testing as a combination and separation between motor and static converter with undefined interface. Accordingly, the motor could be approved for a defined field of application, taking into account the voltage and current ranges, and this field of application may, in turn, be used for a static converter, which is able to guarantee this.

7. Summary

The share of static converter-fed drives and their importance in future will increase greatly still further for explosion protected apparatus. What has been said indicates that static converter-fed drives will increase explosion protection requirements more than is the case with mains operation.

Corresponding dimensioning aspects must be taken into account for protection against the effects of the additional frequency spectra of voltage and current. The increasing demand in relation to extending existing conventional drives of types of protection ‚e' and ‚n' by static converter supply without necessarily having to conduct a complete acceptance retest, including the heating tests, necessitates a definition of the interface between motor and static converter. If we include other safety factors, a concept is conceivable but does require corresponding fundamental investigations in respect of the possible interface parameters.

To date, the design of static converter-fed drives for explosion protection has not been regulated adequately by standards. On the one hand, there is a need for specific recommendations, which must be followed specifically for the type of protection, and general requirements of explosion protection should be elaborated for static converter-fed drives on the other.

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