Application of (Motor Protection) Circuit Breakers in Combination with Variable Frequency Drives

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***Abstract* - Motor Protection Circuit Breakers (MPCB) are used in multi motor applications with Variable Frequency Drives (VFD). Devices positioned load side of a drive failed after only several months through thermal degradation. Investigations showed that MPCBs rated lower than 10 A suffer most. Similar designs of different brands were compared and showed in principle the same behaviour. Steep slopes of the DC voltage pulses in combination with the surge impedance of the motor and MPCB are responsible for excessive heat generation in the switchgear destroying the short circuit protection function. Similar effects are known in motors directly connected to drives with cables when exceeding a critical length above which reflected voltage waves occur. It is shown that chopping frequencies should not exceed 4 kHz and critical wire lengths of about 20 m should be respected to avoid damage.**

Keywords - Variable frequency drive, circuit breaker, surge impedance, reflected waves, partial discharges, critical length

I. Introduction

VFDs also named Variable or Adjustable Speed Drives (VSD or ASD) are increasingly used in applications requiring frequent ramp ups and downs and/or smooth starts and stops e.g. in conveyor systems. Although Drives include electronic motor overload and current limiting functions in multi motor installations (Fig. 1), where a group of motors is fed by one large drive, the Drive consequently cannot provide protection of individual branches or disconnect one or more motors from the installation for maintenance purpose.

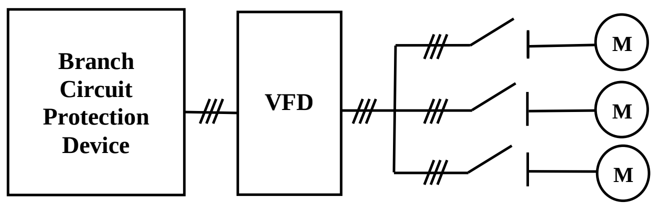

Fig. 1. Multiple motors fed by one common Variable Frequency Drive

Circuit Breakers with motor protection characteristics (MPCB, "Manual Motor Controllers" according to UL 508) are multifunctional devices providing motor overload protection, disconnector / isolator properties and short circuit protection. Therefore they are selected for the type of installations described above, however, some boundary conditions have to be known and followed to avoid damage of the switchgear, the occurrence of dangerous situations and to provide the required durability of the installation. Classical MPCBs use bimetal heater elements for overload function and magnetic trip actuators for short circuit protection. Both are basically inductances designed for operational frequencies of 50 and 60 Hz resp. Therefore considerably higher frequencies will have undesired effects as described in the following.

Existing literature on Drive application refers mainly to the effect of current harmonics which could be mended with various types of filters and to classical EMC problems recommending the use of shielded wires between Drive and motor [1-3]. Since the basic set up on first glimpse doesn't require additional electromechanical switchgear there has not been much effort for investigations and only a few manufacturers give instructions. However, there are situations where additional electro-mechanical switchgear is required and used on the load side between Drive and motor.

II. Basics of Variable Frequency Drives

VFDs consist of semiconductor rectifier bridges, an intermediate DC-bus operating at the peak value of the input sine wave voltage and an output PWM circuit. The chopping frequency f_c is in the range of several kHz providing the DC voltage pulses which drive the load current.

Typical wave forms are shown in Fig. 2. [4]. The upper trace is taken at the Drive output, the lower at the motor input. Each single pulse is characterised by some time parameters given in Fig. 3. Chopping frequencies f_c range up to 16 kHz and may be selectable. The so called rise time t_{rise} describes the steepness of the voltage pulse rise (dv/dt) from 10 % to 90 % of the DC-bus voltage [5]. Another well known definition of rise time per IEC 60034-25 [6] in principle leads to approx. double rise times. Results following below show that the NEMA definition is the appropriate one for the problem discussed here [12]. Rise time and steepness depend a. o. on the semiconductor technology used in the Drive (Table 1).

With regard to limit the switching power loss of the Drive rather short rise times are aimed at [7]. High chopping frequencies are used to reduce audible noise of Motors fed by Drives. On the other hand the voltage pulses propagate on the cables. Above a certain length, in literature called the critical length l_{crit} , they behave like transmission lines in this case for

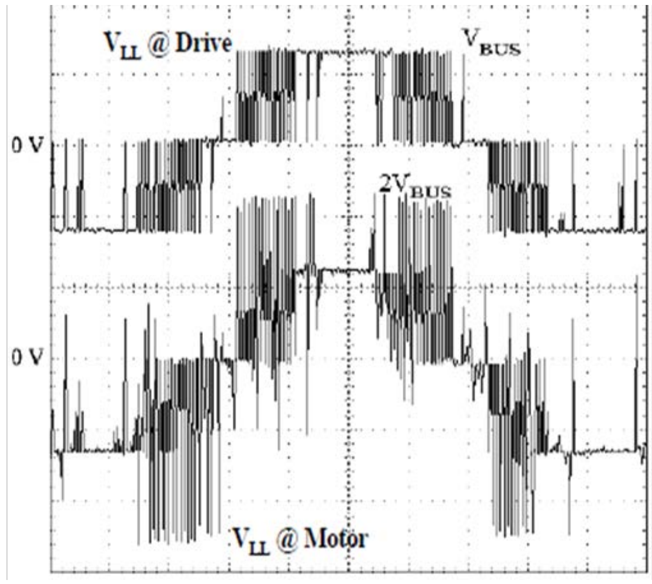

Fig.2. PWM voltage at drive and motor terminals [4]

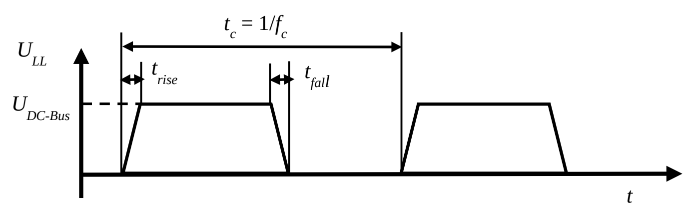

Fig. 3. Time characteristics of sequential DC voltage pulses generated by Variable Frequency Drives

f_c - chopping frequency
t_{rise} - rise time (10 % to 90 % level)
t_{fall} - fall time (90 % to 10 % level)
$U_{DC\text{-}Bus}$ - peak value of AC voltage U_{LL}

TABLE 1
VOLTAGE PULSE RISE TIME T_{RISE} AND CRITICAL CABLE LENGTH L_{CRIT} DEPENDING ON THE SEMICONDUCTOR TECHNOLOGY USED IN THE VFD

Semiconductor Technology	t_{rise} [µs]		l_{crit} [m]	
	t_{min}	t_{max}	t_{min}	t_{max}
BJT	0.2	2	15	150
GTO	2	4	150	300
IGBT	0.05	0.4	3.75	30

digital pulses of rel. high voltage. This also means that reflection and rarefaction effects occur when the surge impedance Z_{Surge} in the system changes. That finally leads to even higher voltage stress, in literature called reflected wave phenomena [7, 8]. Z_{Surge} of an impedance with inductance L and capacitance C generally is defined as

$$Z_{Surge} = \sqrt{L/C} \tag{1}$$

Reflections in principle can be calculated according to (2) [8].

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad (2)$$

r - reflection coefficient
Z_1 - surge impedance range 1
Z_2 - surge impedance range 2.

The relation between rise time t_{rise} and critical length l_{crit} is

$$l_{crit} \approx \frac{v_{cable} \bullet t_{rise}}{2} \qquad (3)$$

where v_{cable} is the propagation speed of pulses. For most cables with plastic insulation material (dielectric constant ε_r H4) v_{cable} is about 150 m/µs i.e. half the speed of light. With the parameters given in Table I critical cable lengths may range from only about 4 m up to 300 m or in other words there is no general dimensioning rule, each application has to be analysed individually.

The situation is even more difficult to analyse in applications with multiple Drives feeding a common bus bar. In this case complex interaction of the travelling pulses and in addition energy feedback through the multiple motors in parallel appears. Even higher voltage peaks occur which cannot be explained with travelling wave phenomena only. A statistical approach of voltage stress evaluation has to be applied to estimate the reliability of coil insulations [9].

A. Equipment used in Motor Feeder Branches

1) Cables, Wires and Motors

In the late 1990s it became obvious that cables and motors suffered from the steep voltage pulses and reflected wave phenomena. A root cause is the fact that the surge impedances of Drives, cables and motors can differ significantly, esp. the step from the cable to the motor causes reflected voltage waves with amplitudes up to 3 times AC peak voltage [7, 12]. This defines the electrical stress level for all components.

Between the wires of both, cable conductors and motor win-dings, corona effects (partial discharges, PD) were detected [10, 11] which destroy the wire insulation either directly through heat generation or in addition through chemical reactions caused by Ozone generated through the discharges [12, 13]. The intensity of these effects is directly related to the conductor diameter, the insulation thickness and grade resp. of the wires. In general larger wire diameter and thicker insulation help to reduce the problem. As a consequence many efforts were made to strengthen the resistance of the insulation of cables and motors against steep voltage pulses and corona resp. Insulation materials like XLPE (cross linked Polyethylene) or mica reinforced materials were developed and used. In 1999 the motor standard IEC TS60034-17 [14] was modified. It now includes two categories of motors (A and B) which are able to withstand different levels of voltage peaks (in addition depending on the voltage rise time) (Fig. 4).

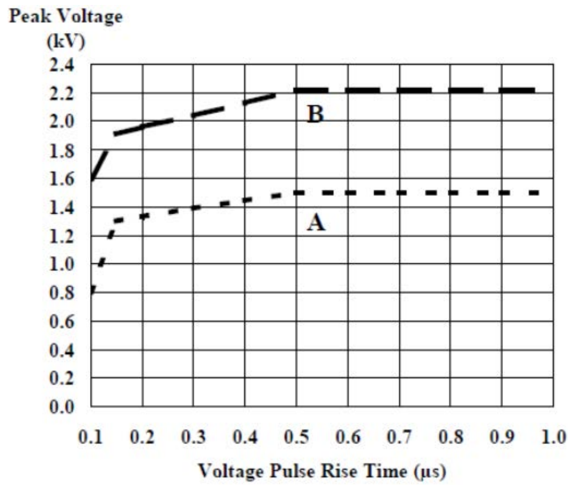

Fig. 4. Limit curves of admissible terminal peak voltages for AC motors up to 500 V AC (curve A) and from 500 V to 690 V AC (curve B), IEC TS60034-17 [14]

The standard NEMA MG1 (1998) [15] covers the so called 1488 V (inverter duty rated) motors which are able to withstand 3.1 times the rated voltage of 480V. Suitable devices are marketed as so called VFD-proof or "Inverter Spike Resistant"® products [16, 17].

As a general dependency Fig. (5) shows the ageing of wire insulation as function of cable length and chopping frequency [2]. Each single pulse acts as eroding event on the material. Literature describing ageing effects of insulations often refers to the number of pulses until a failure occurs. On first sight those are large numbers (e.g. 10^9) but re-calculated to the chopping frequency this can in fact result in only hours!

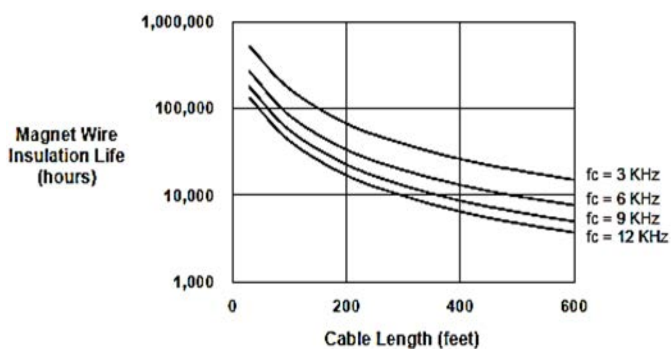

Fig. 5. Insulation life versus cable length and chopping frequency (f_c) [2]

2) Electromechanical Switchgear

Some manufacturers do not permit the use of electromechanical switchgear on the load side of a Drive at all since the switching arc voltage might be able to destroy the semiconductors. Others recommend to not switch under load. Also correction tables for the thermal trip setting of MPCBs are published to avoid nuisance tripping but without referring to cable lengths, rise times or limitation of chopping frequency.

It is also known that the capacities of long cables might cause contacts of load switches and contactors to weld when switched under load if they are not sized appropriately [18]. MPCBs are not susceptible to that since they are designed to handle rel. high short circuit in-rush currents at make anyway.

In multi-motor applications the requirement of an individual motor overload protection function appears. In addition the disconnection of branches e.g. for maintenance is useful to enable maintenance on one or more motors while others are not affected. Since some MPCBs are suitable for use as disconnecting means as well they are attractive as multifunctional devices. It has to be considered, however, that the trip unit does not react below e.g. 13 times rated current and the associated Drives might have a max. output current below that.

Also load switches and contactors are used to control individual branches remotely. Both types of switchgear are less critical with regard to voltage wave reflections since they do not contain high impedances and therefore their surge impedance is low. That changes significantly with MPCBs. This kind of device in principle is designed for 50/60 Hz and reacts under DC voltage pulse application in principle like a filter, however, it is not designed for that purpose and to accommodate the additional power loss related to this. In addition the insulation voltage is normally not twice the rated peak opera-tional voltage or more, i.e. pulse reflections shall be avoided.

The impedance of the trip coils in addition varies with the rated current of the circuit breaker. Fig. 6 shows the surge impedance of trip coils of typical MPCBs rated up to 25 A (40 Ω) and down to 0.1 A (13 kΩ). In addition a typical cable surge impedance of 80 Ω is compared.

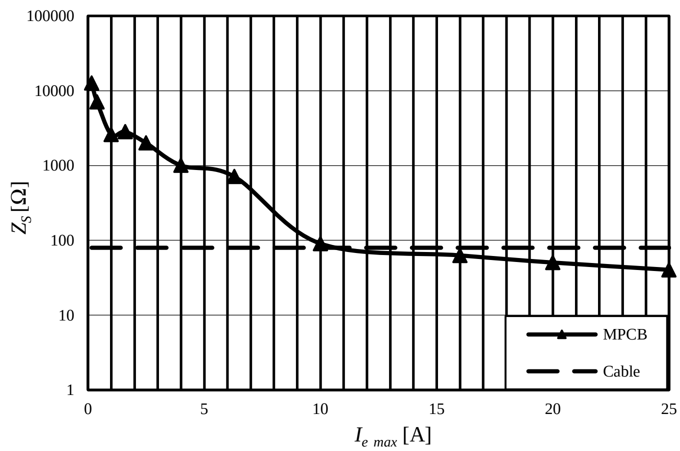

Fig. 6. Surge impedance Z_s of trip coils of a Motor Protection Circuit Breaker (MPCB, different current ratings I_{emax}) in comparison to a cable

It turns out that below rated current of 10 A the surge impedances increase significantly which results in strong voltage reflections. Due to the functional requirements designs of different manufacturers are similar and do not vary principally. Lower current ratings need larger numbers of trip coil turns which lead to higher inductances. Multiple layers of coil windings may be required as well. In combination with thin wires this results in reduced capacitances. Both tendencies lead to higher surge impedance (Equ. (1)).

3) Electronic Controlgear

The surge impedance of a Drive, Z_{SVFD}, can be calculated according to Equ. (4) [19].

$$Z_{SVFD} = \frac{U_{line-line}}{\sqrt{3} * I_{input-rating}} \qquad (4)$$

B. Summary

Fig. 7 shows as summary typical surge impedance values of motors and cables [17]. The values of MPCBs and Drives have been imported from Fig. 6 and Equ. (3) for different hp values. It can be stated that within a motor feeder branch nothing is adjusted with regard to avoid voltage wave reflections a priori. Voltage pulses entering the connection between a MPCB and a motor get quasi trapped due to the surge impedance values involved resulting in multiple reflections tending towards an elevated voltage level at the load terminals of the MPCB and Motor [8].

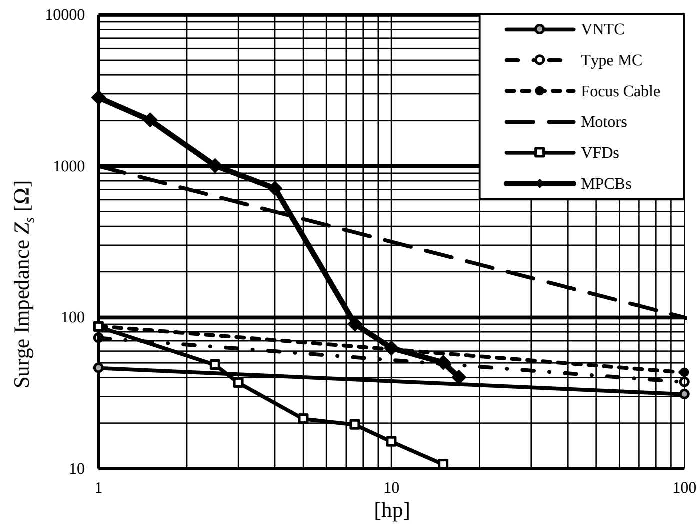

Fig.7. Surge impedance Z_s of AC motors, 3 different cable types, MPCBs and Variable Frequency Drives vs. motor size [hp], [17]

III. Experimental Results

A. Circuit Breaker located close to the Drive

In an industrial application (3 motors fed by one Drive) with 150 m cable between MPCB and each motor operated at chopping frequency of 3 kHz severe degradation of the trip coil has been observed after approx. 9 months of continuous service. This happened although the motor current was below the min. of the MPCB setting range due to partial load of 50% which is common in Drive applications. The MPCB was set at 90% of its maximum so thermally there was no reason to trip. The simulation of this set-up in the lab and recording of temperature up to the stable condition showed similar behaviour also with devices of different manufacturers, different cable lengths and chopping frequencies.

To collect further test results in rel. short time tests were made on MPCBs of six different manufactures (rated current 2.5 A) energized by a Drive at 400 VAC (566 VDC bus) and f_c = 16 kHz. The temperature was measured by a thermographic camera [1a]. Fig. (8) shows the temperature of the short circuit trip coils over time. The breakers were wired with a short cable (1 m) at the output of the Drive, the connection between MPCB and motor was 40 m, i.e. above the critical length. A very quick temperature rise was observed with all designs. The max. permissible temperature (RTI) of a typical coil former material PA 66/6 was exceeded within approx. 5 minutes (circle).

[1] Thermographic camera Optris PI, Optris GmbH, Berlin

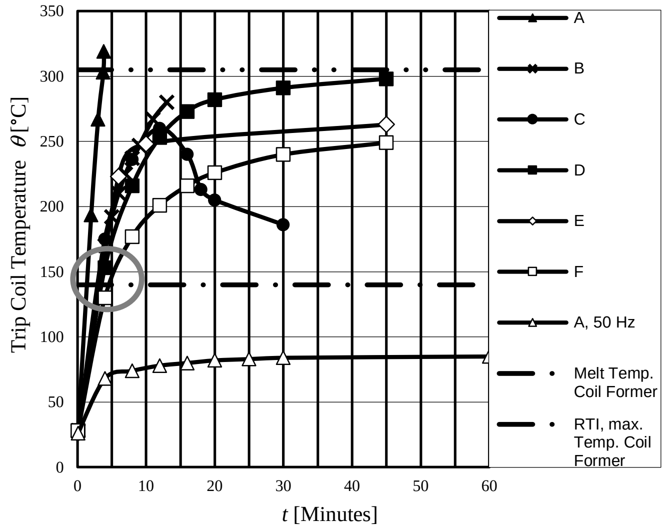

Fig. 8. Temperature θ vs. time of Short circuit trip coils of MPCBs of six different manufacturers, cable length 40 m, f_c = 16 kHz

Some designs exceed or come close to the plastic melt temperature within minutes or in less than one hour. A special case is the behaviour of Product C showing lower temperatures after a maximum value. Examination of the coil showed that due to molten wire insulation some coil turns were short circuited which reduces the impedance and further heat generation. As reference the 50 Hz situation curve of Product A is included as the lowest.

During continuous operation the coil formers melted and the armatures were blocked (Fig. 9a, b; 10; 11). Thereby the short circuit trip units are destroyed and became inoperative. This is a considerable safety risk in such installations where the Drive is capable to supply output currents exceeding the trip current. Sometimes the distortion is not detectable from visual inspection, even operation of the test button does not indicate this defect since it simulates a thermal overload trip function but not a trip through a short circuit event.

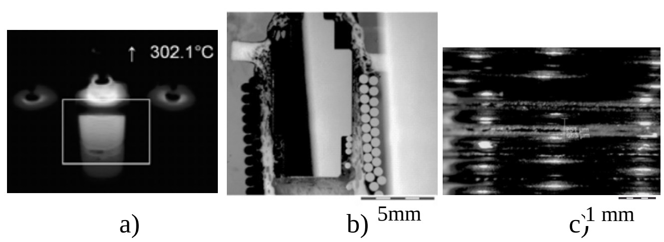

Fig. 9. Thermografic picture [2] a), molten coil former b) and damaged coil wire insulation c) (Prod. A)

[2] Thermographic camera Optris PI, Optris GmbH, Berlin

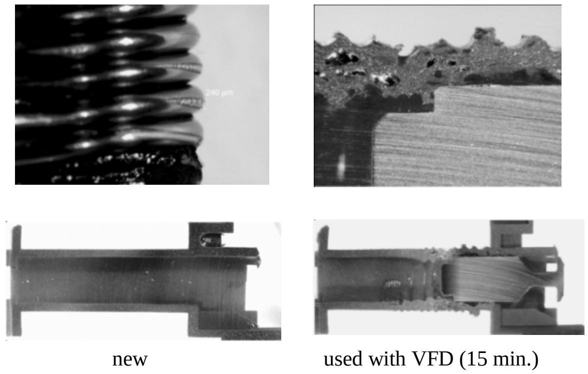

Fig. 10. Damaged coil wire insulation and molten coil former with mechanically blocked Armature (Product C).

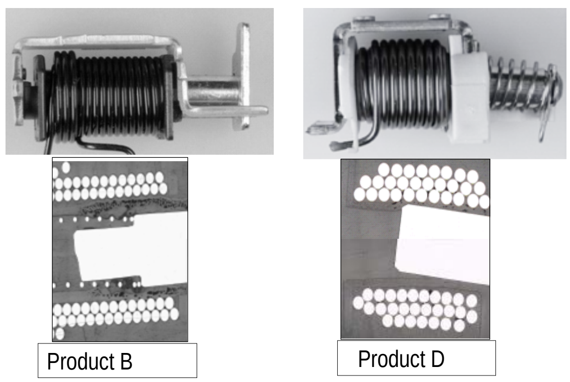

Fig. 11. Molten coil formers (Products B and D)

Fig. 12 tracks only the products with max., intermediate and min. temperature rise. The situation improves with chopping frequency of 4 kHz instead of 16 kHz, an unproblematic situation is reached, however, only when the cable length in addition is limited to 20 m, i.e. < l_{crit}.

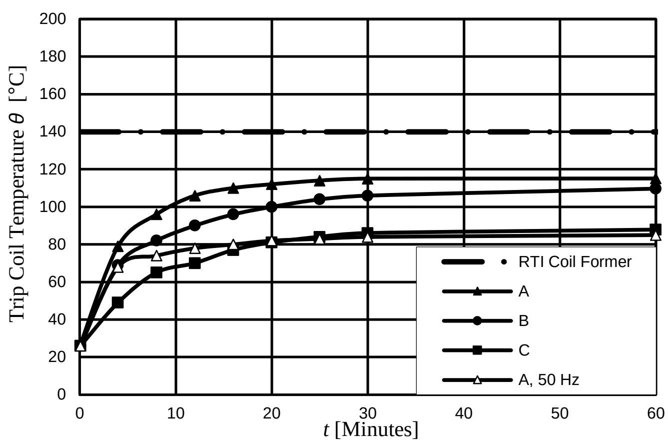

Fig. 12. Temperature θ vs. time of short circuit trip coils of MPCBs, 3 different manufacturers, cable length 20 m, f_c = 4 kHz

The total thermal stress is caused by combination of heating through Skin and Proximity effects in both magnetic plunger and coil wires. In addition the effects described in chapter II,*A* (electrical stress, partial discharges, Ozone generation) occur all acting simultaneously. At l_{cable} = 40 m the estimated contribution of plunger and coil is 85 % (16 kHz, refer to Fig. 8) and 54 % (4 kHz) resp. additional temperature rise compared to the 50 Hz load. The step across l_{crit} to 40 m at f_c= 4 kHz adds 37% (refer to Fig. 15).

According to [20] direct electrical measurement and detec-tion of partial discharges in Drive applications is extremely difficult because of the high background noise level through the voltage pulses. Since detection of Ozone is an indirect method to prove occurrence of partial discharges an indicator strip [3] was mounted between coil former and 1st layer of the winding. The coil was disassembled and inspected after 8 minutes of operation to not create thermal damage. The strip shows brown coloration esp. at the location of the gaps between the coil turns (Fig.13 a)) which confirms generation of Ozone in this case through partial discharge processes.

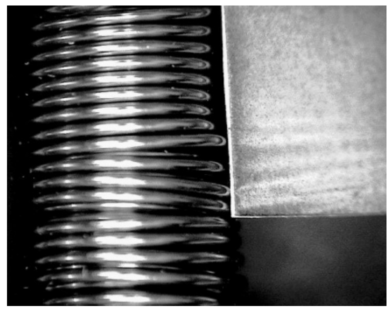

Fig. 13. Trip coil after test (left) and dark coloration of Ozone detection strip (right)

Fig. 14 summarizes results of an MCCB rated 2.5 A for a wire size AWG 14 and lengths up to 150 m (f_c = 4kHz). There is a significant temperature rise at the predicted critical length. The max. permissible temperature of the coil former material would be reached at approx. 28 m only. This corresponds to observations in [21]. In practical applications, however, some head room is required to cover ambient conditions of up to

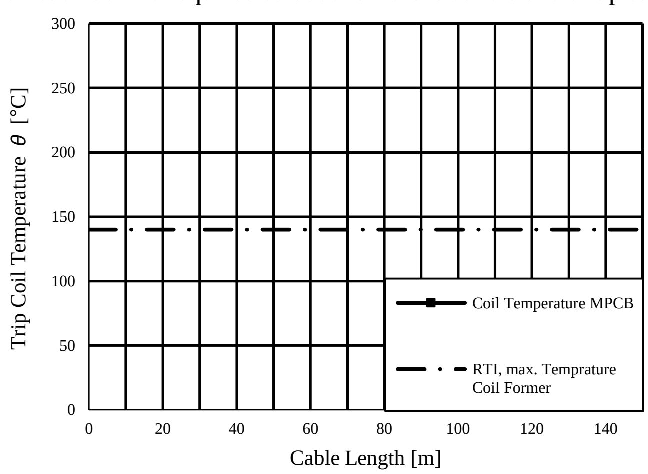

Fig 14. Trip coil temperature θ vs. cable length, f_c = 4 kHz

[3] Ozone Detection Strips, Macherey-Nagel, Düren, Germany

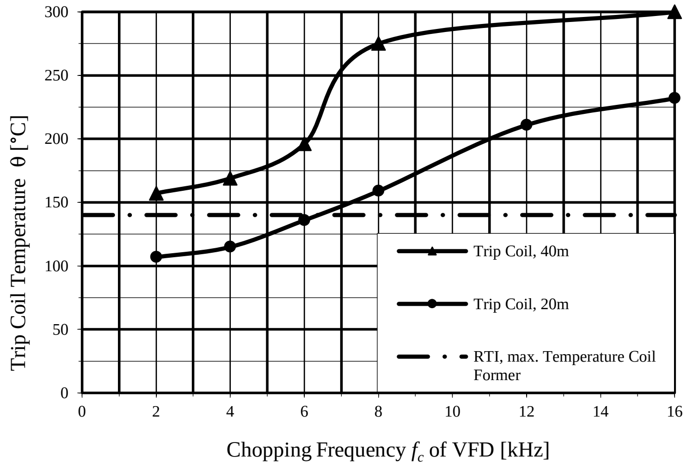

Fig. 15. Trip coil temperature θ (I_e = 2.5 A) vs. chopping frequency f_c depending on the cable length

60 °C in switchboards and Motor Control Centers e.g. if the devices are mounted side by side. Fig. 15 shows the trip coil temperature vs. chopping frequency for two cable lengths (20 m and 40 m). It can be clearly seen that for lengths exceeding the “critical length” even the chopping frequency of 2 kHz causes excessive heat. This is somehow consistent with recommendations given by manufacturers also offering filter solutions. They limit the max. permissible chopping frequency to 4 kHz or even 2 kHz depending on the cable length and level of motor insulation voltage [22].

B. Circuit Breaker Located Close to the Motor

This condition is the preferred one. Voltage wave reflections are suppressed since the connection to the motor is far below the critical length and the rel. high impedance of both motor and MPCB is similar so they act as voltage divider.

C. Considerations on Energy Efficiency

The use of filters reducing the rise time could be a technical improvement, however, following facts have to be taken into consideration: Filters operate as energy sinks i.e. instead of the Circuit Breakers they run considerably hot. Fig. 16 shows data taken from a catalogue [22]. The power loss of filters in addition is dependent on the cable length connected. These values compare to the power loss of a Drive of 120 W (I_e = 25 A) and reach from 100…500 % of the power loss of an MPCB. Furthermore installation of filters in front of each MPCB generates additional cost in the order of magnitude of 100 % or higher.

Drives on the other hand should also be used to increase energy efficiency and to fulfil new regulations e.g. in Europe [23, 24]. The regulation [23] says that beginning in 2011 in future all motors not fulfilling the efficiency class 3 have to be fed by Drives. In [24] on one hand it has been shown in an example that Drives are advantageous against an electromechanical starter only if they exceed approx.300 cycles/h. The power loss of a Drive, however, can be 3…25 times that of an electromechanical starter [25].

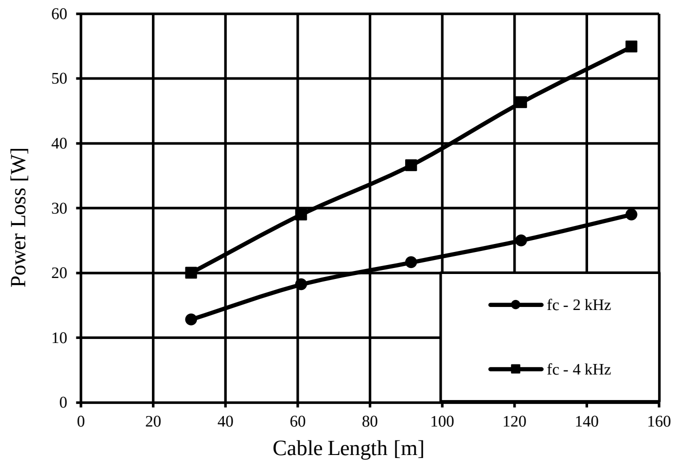

Fig. 16.Power loss of filter solutions depending on the cable length between filter and motor and chopping frequency.

Additional loss created by the filters needed to enable MPCBs to survive are not yet considered in the comparison mentioned above.

To cover the environmental aspects and all relevant technical requirements an installation intending to use Drives and MPCBs in combination have to be carefully engineered.

IV. OUTLOOK

The results presented were collected with 400 V AC set- ups. Tests with higher voltages (480 V…690 V) need to follow. First spot checks at 525 V with 40 m cable and chopping frequency 4 kHz showed 20 K higher coil temperature compared to the 400 V whereas tests with 20 m cable showed approx. unchanged temperature.

Similar investigations to confirm that contactors and load switches are definitively not affected need to be conducted.

V. CONCLUSIONS

According to the description given above some care must be taken to select suitable components for use in a multi motor application fed by a Drive.

General recommendations:

- The MPCB Breaker should be selected so that its current setting is close to the low end of the setting range. This reduces the basic temperature level at the trip coil by approx. 25 K.
- The chopping frequency of the VFD should be as low as possible and not exceed 4 kHz.
- Preferred location of MPCBs is close to the motor.
- Detection of excessive heating by thermographic cameras is not suitable since the user does not know the normal or permissible internal operational temperatures. This leads to misinterpretation.

The rise time of the Drive should be known, the critical cable length should be calculated according to Equ. (3) and not be exceeded in the installation to avoid voltage overshoot.

To recognize the potential degree of damage to MPCBs and to achieve the intended service life period the peak voltage and rise time at the terminals should be measured during initial set-up, corrective actions should be taken if required.

The use of filters reducing the rise time could be a technical improvement for longer cables, however, additional power loss and additional cost will occur.

Standards should be modified to take care of this kind of application and risk of damage also with respect of product substitution. Specific tests, data to be published and probably a suitability or non-suitability marking might be needed.

Switchgear manufacturers might consider to prepare VFD proof products for the future similar to motors and cables.

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BIOGRAPHY

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