DUAL-ELEMENT HIGH VOLTAGE BACK-UP FUSES FOR POWER DISTRIBUTION TRANSFORMER PROTECTION

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Abstract: The Authors describe how current-limiting dual-element fuse-links can be advantageously used to protect power distribution transformers against the dramatic effects of internal short-circuits. Originally developed for general purpose or full-range applications, dual-element fuse-links exhibit specific features that make them easily adaptable to the most challenging protection tasks, e. g. the protection of small size power distribution transformers having circuit breakers on the low voltage side.

The favourable time-current characteristics of dual-element fuse-links enable greater tolerances of the transformer impedance and may reduce transformer costs significantly. The combination of different fuse-elements for high and low breaking range enables to design tailor-made time-current characteristics for many applications that cannot easily be covered by single-element fuse-links.

Hermetically sealed dual-element fuse-links have been developed to be installed in transformer tanks under oil. These fuse-links are subjected to new stringent quality control procedures that enable closer tolerance limits and allow to trace each individual product from first manufacturing step until installation in the transformer tank.

I INTRODUCTION

Dual-element fuse-links have originally been developed to meet the requirements of full-range or general purpose fuses acc. to IEC 60282-1 [1]. Some specific properties of these fuses have shown very advantageous with respect to other applications, e. g. the back-up protection of small size power distribution transformers. In addition to well known advantages of dual element fuse-links like

- high inrush withstand,
- low power dissipation and
- extended breaking range,

the time-current characteristics of dual-element fuse-links offer some features that make them very adaptable to specific applications and enables to meet the most challenging tasks of transformer protection.

II PROTECTION OF SMALL SIZE DISTRIBUTION TRANSFORMERS

Power distribution systems in Europe are mainly based on a low-voltage (three-phase 400 V) network which is linked to an overlaying medium voltage (e. g. 20 kV) network by means of distribution transformers. L.v. fuses or circuit-breakers are installed on the l.v. side to protect the transformer from potential overloads caused by excess power consumption and to clear high fault currents occurring in the l.v. network. In some cases, when the load is well under control, no overload protection devices but isolators only are installed to enable the disconnection of the transformer from the l.v. network.

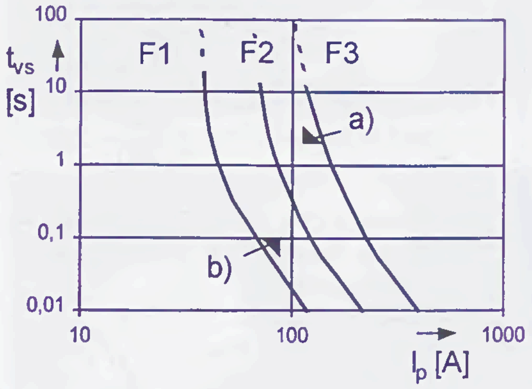


Fig. 1 - Selection of a HV back-up fuse acc. to IEC 60282-1 and IEC 60076-5

High voltage current limiting back-up fuses are installed on the h.v. side of the transformer to prevent catastrophic effects in case of an internal transformer fault. H.v. fuses are therefore selected to be able to safely interrupt the smallest internal transformer fault current, which is three-phase short-circuit current at the l.v. terminals, within two seconds current (see corner a) in fig. 1) and to withstand the maximum transformer inrush current (see corner b) in fig. 1)

[2] [3]. Of the three fuses shown in fig. 1, the time-current characteristic of F2 meets these requirements while F1 and F3 don't.

Depending on the transformer design and protection system, a single-phase earth fault current at the l.v terminals needs to be considered too. If there are fuses or circuit-breakers installed on the l.v. side, the h.v. fuses shall also be discriminating to these devises, e.g. they must not operate in case of any faults in the low voltage network downstream the l.v. protective device.

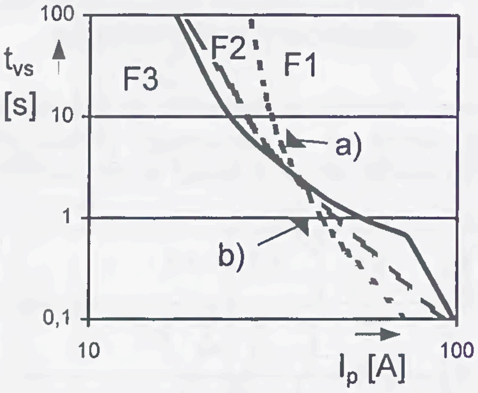


Fig. 2 - Protection of a 100 kVA transformer
with h.v. fuse and l.v. circuit-breaker
F1 back-up fuse
F2 full-range fuse
F3 dual element fuse

Small size distribution transformers are especially difficult to protect if they are equipped with circuit-breakers on the l.v. side and a single-phase earth fault at the l.v. terminals shall be cleared by the h.v. fuse. In many cases, the tripping current of the l.v. circuit breaker divided by the transformation ratio is equal or greater than the minimum single-phase terminal fault current of the transformer. Fig. 2 shows an example of a 100 kVA, 20 kV/400 V transformer having a short-circuit impedance of 4 %. The l.v. side is equipped with a circuit-breaker, adjusted to operate at 2.200 A after 1 s (which corresponds to 44 A on the h.v. side, see corner b) of fig. 2). The smallest expected single-phase fault current of 35 A at the l.v. terminals of the transformer shall be cleared by the h.v. fuse within 5 s (see corner a) of fig. 2), while a short-circuit downstream the l.v. network shall be cleared by the circuit-breaker only without operation or whatsoever deterioration of the h.v. fuse.

As can be easily seen from fig. 2, the unusual configuration of the gate, formed by the l.v. current to be tolerated and the h.v. current to be cleared, requires a time-current characteristic having a gradient as low as possible in the area of the gate. The time-current characteristic of a standard back-up fuse-link is hardly able to pass within this gate if reasonable tolerances in the direction of current shall be permitted. General purpose or full-range fuse-links, having single fuse-elements and significantly less gradient in their time-current characteristics than back-up fuses, would possibly fit but still require very tight tolerance limits, i. e. the fuse-links and transformers must be selected during manufacturing process and matched according to their time-current characteristics and their short-circuit impedance respectively. This makes the manufacturing process very complicated and expensive.

The dual-element fuse-link however seems to be best suited to fulfil the requirements of this specific application. It exhibits a very low gradient in the range of 1 s up to 10 s melting time which corresponds to usual transformer short-circuit withstand ratings.

III FUSE-LINK DESIGN

III.1 Selection of fuse-elements

The dual element fuse-link consists of two fuse-elements electrically connected in series and enclosed in one common fuse body (fig. 3). One fuse-element is made of Ag strips having longitudinally arranged restrictions like conventional back-up fuse-links. This fuse-element interrupts high level currents up to the rated breaking capacity of the fuse-link.

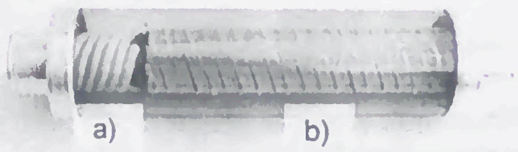


Fig. 3 -Dual-element fuse-link
a) Sn fuse-element
b) Ag fuse-element

The second fuse-element is composed of one or more partial fuse-elements which consist of Sn wires arranged in an armoured silicone hose. This fuse-element is designed to interrupt lower level currents from its melting current up to the take-over current which is greater than the minimum breaking current of the Ag fuse-element.

Each one of the fuse-elements is able to safely interrupt a fault current in its specific breaking range. Different sizes of both fuse-elements may be combined to a variety of characteristics as needed for individual protection tasks (see fig. 4).

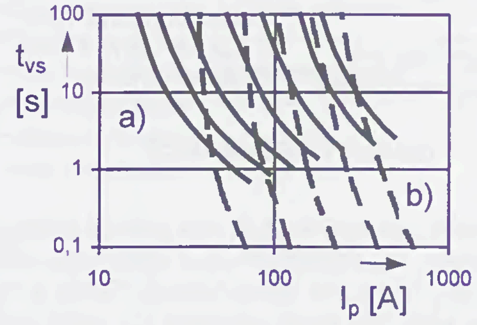


Fig. 4 - Selection of partial fuse-elements
a) Sn fuse-elements
b) Ag fuse-elements

The adiabatic temperature rise of the Sn fuse-element extends to a melting time of about one second, its time-current characteristic does therefore exhibit a very low gradient in the range of the gate to be matched. (Note: the minimum gradient in the logarithmic scales acc. to [1] is at a 45° angle.) The Sn fuse-element is chosen to have the time-current characteristic passing through the centre of the gate in order to allow for the maximum possible tolerances for both the transformer impedance and circuit-breaker adjustment. Fig. 5 shows that the acceptable tolerance limits of the dual-element fuse are greater than ± 20 % in the direction of the current axis. Correspondingly a full range fuse or a back-up fuse would allow for a maximum of ± 10 % and ± 5 % respectively.

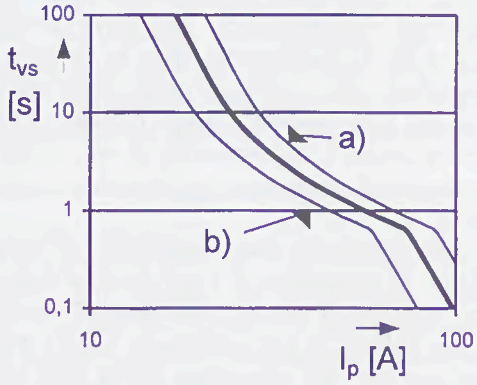


Fig. 5 – Dual-element fuse-link
Time-current zone ± 20 % of mean
corners a) and b) as in fig. 2

The Ag fuse-element is chosen for high in-rush withstand and low power dissipation. The limitations are given by the take-over current only.

III.2 Underoil fuse-links

Current-limiting fuse-links that are supposed to operate under oil, have to meet very stringent requirements concerning vacuum and oil tightness as well as reliability in service. The fuse body needs to be hermetically sealed on order to avoid any leakage of air and/or ingress of oil during the vacuum impregnation process of the transformer or caused by cyclic temperatures and pressure during an extended service life.

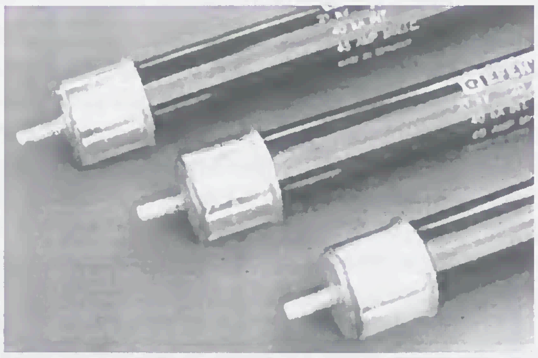


Fig. 6a – Solder sealed underoil fuse-links

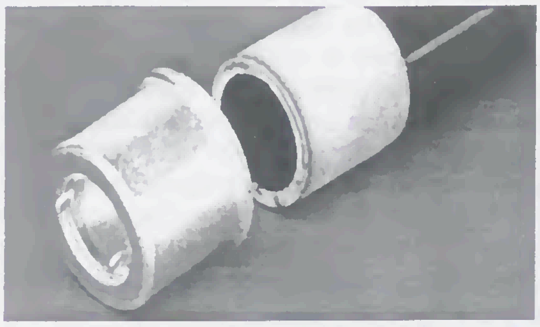


Fig. 6b – Metalized porcelain and contact cap

The underoil fuse-link shown in fig. 6a has got soldered seals at the endplates as well as at the end caps. The outer surface of the porcelain

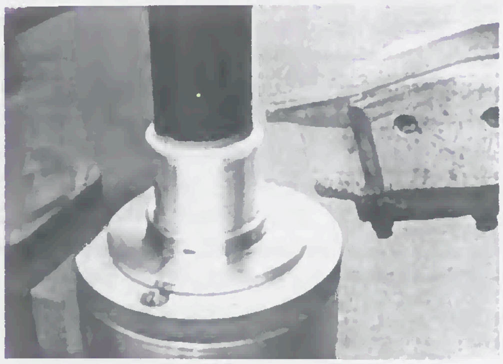


Fig. 6c – Solder casting process

insulator is metalized in the area overlapping to the end caps (see fig. 6b) and the slot in between is cast with solder (see fig. 6c). This method has proven to provide a very reliable seal for a long service life under even extraordinary service conditions. Several hundred thousands of solder sealed oil-tight fuse-links have been installed since 1970 and accumulate in the meantime a total of about 4 million fuse service years of positive results.

H.v. underoil fuse-links have to be selected and designed as to operate in case of transformer faults only. As they cannot easily be replaced, they must not operate unless an internal transformer fault occurs, i. e. the fuse-links have to be insensitive to transformer inrush and lightning pulses in order to avoid nuisance operation caused by partially damaged fuse-elements.

Mechanical damage of partial fuse-element may also cause nuisance operation of the fuse-links. It is therefore necessary to have adequate physical dimensions of the fuse-elements.

The dual-element fuse-link enables the use of relatively large cross sections of the partial fuse-elements even for the protection of small size transformers. The Sn fuse-element, which is supposed to melt at relatively low currents, because of its low conductivity and melting temperature, requires larger cross sections than a corresponding fuse-element made of higher conductivity and melting temperature material. The Ag fuse-element too may have a larger cross section, as it covers the higher current range only. The dual-element fuse-link does therefore by the nature of its electrical design exhibit superior mechanical strength.

IV TYPE TESTS

Extensive type tests have been carried out in order to verify the performance of the dual-element fuses for this specific application. The type tests include all tests applicable to general-purpose under oil fuses acc. to IEC 60282-1 [1]. In addition to the standard tests, mechanical tests as well as thermal tests were carried out. Time-current characteristics were taken at +125 °C and -25 °C. The transformer impregnation process was simulated by means of an autoclave in the laboratory and in real transformer production. Short-circuit tests were carried out on transformers with the fuses installed in order to verify the selectivity as specified. A summary of special tests that were carried out on the fuse-links is given in table I.

Table I - Special tests

Test	Conditions
Oil-tightness test	1000 hPa, thermal cycles 110/25 °C;
Vibration test	70 Hz; 1,2 mm
Mechanical shock test	Free fall over 100 mm
Temperature shock	3 h at +125/-25 °C, transition time 10 s
Impregnation test	140 °C, 48 h, 1 hPa
Time-current curves	-25 °C; 105 °C

V QUALITY ASSURANCE

Quality assurance is a very crucial issue on h.v. fuses for installation in transformer tanks under oil. Firstly, the fuses have to match a very narrow gate that does not allow for usual tolerances as defined by [1], i.e., ± 20 %. Secondly the tolerances of the initial material (metal wire or strip) must not be limited too much in order to ensure availability in the market and reasonable prices. Thirdly the transformer manufacturer who installs the fuses in the transformer tank should be able to easily and reliably check the fuses for any potential damage that may have occurred during shipping and handling.

Measurement of the electrical resistance of fuse-elements has proven very useful and convenient to discover many irregularities in the assembly process of single element fuse-links. It is, however, not sufficient to assure consistency of time-current characteristics. The physical dimensions of the fuse-elements need to be carefully controlled, too. Dual-element fuse-links consist of two fuse-elements (each consisting of one or more partial fuse-elements) of very much different electrical resistance, connected in series (see fig. 3).

The total resistance does therefore not vary in proportion to resistance of the individual fuse-elements. In order to detect unacceptable variations of the individual fuse-elements during the assembly process, the tolerances of the total resistance must be set very tight. This is in contradiction to the requirement of reasonable tolerance limits and acceptable prices for the initial material, i.e. Sn wires and Ag strips. The quality

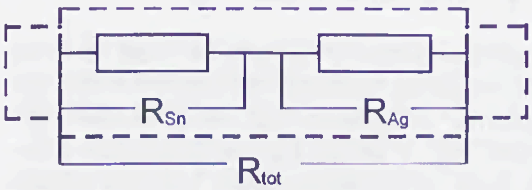


Fig. 7 Resistance measurement

assurance system during final assembly process has therefore been based on resistance tracing during three consecutive electrical tests as follows (fig. 7):

1. Core winding
    - Resistance of the Sn fuse-element
    - Resistance of the Ag fuse-element
    - Total resistance
2. Core installed inside the fuse-body
    - Total resistance
3. Finished product
    - Total resistance

Resistance tracing means that each resistance value taken after consecutive manufacturing steps is related to the individual product and recorded in a PC. The individual values are then compared step by step during the assembly process. Thus the tolerances of the initial material do not need to be considered and can be excluded from the tolerance limits. The tolerance limits can therefore be set very tight and even minor manufacturing influences, e.g. poor welding or damaged fuse-elements can be detected by means of resistance tracing.

In order to be able to assign the resistance value to the individual product, the first test station (after core winding) is equipped with a barcode printer and the products are marked with a serial number on a barcode label attached to them after the first electrical test. The subsequent test stations are equipped with barcode readers and automatically assign each product the corresponding resistance values which are correlated to the previously obtained values.

Based on the serial number, the products can be traced backwards in case of any irregularities being observed later on. They can also be traced forward and enable the transformer manufacturer to check the product for any potential damage before installation inside the transformer. A second label carrying identical information may be supplied with the fuse-link and attached to the transformer for easy identification of the fuse-links installed which are not accessible any more when put into service.

VI CONCLUSIONS

Further progress in the development of fuses may be either related to new fuse technologies or new applications showing up in the market. Both directions are needed and helpful to strengthen competitiveness of fuses over other protective devises. The authors describe a new application demanding non-standard considerations in the selection of h.v. fuses. Dual-element fuses were found to exhibit the most suitable design for back-up protection of small size power distribution transformers. This is especially true, when the fuses are installed under oil inside the transformer tank and not supposed to be replaced during service life of the transformer. Dual-element fuses are extremely adaptable to transformer protection requirements, e.g. Sn and Ag fuse-elements can be selected separately and combined to a wide selection of time-current characteristics. The greater cross-sections of the individual fuse-elements of dual-element fuses compared with single-element fuses make them less sensitive to electrical and mechanical damage. This makes dual-element fuses especially suited for installation under oil in transformers tanks.

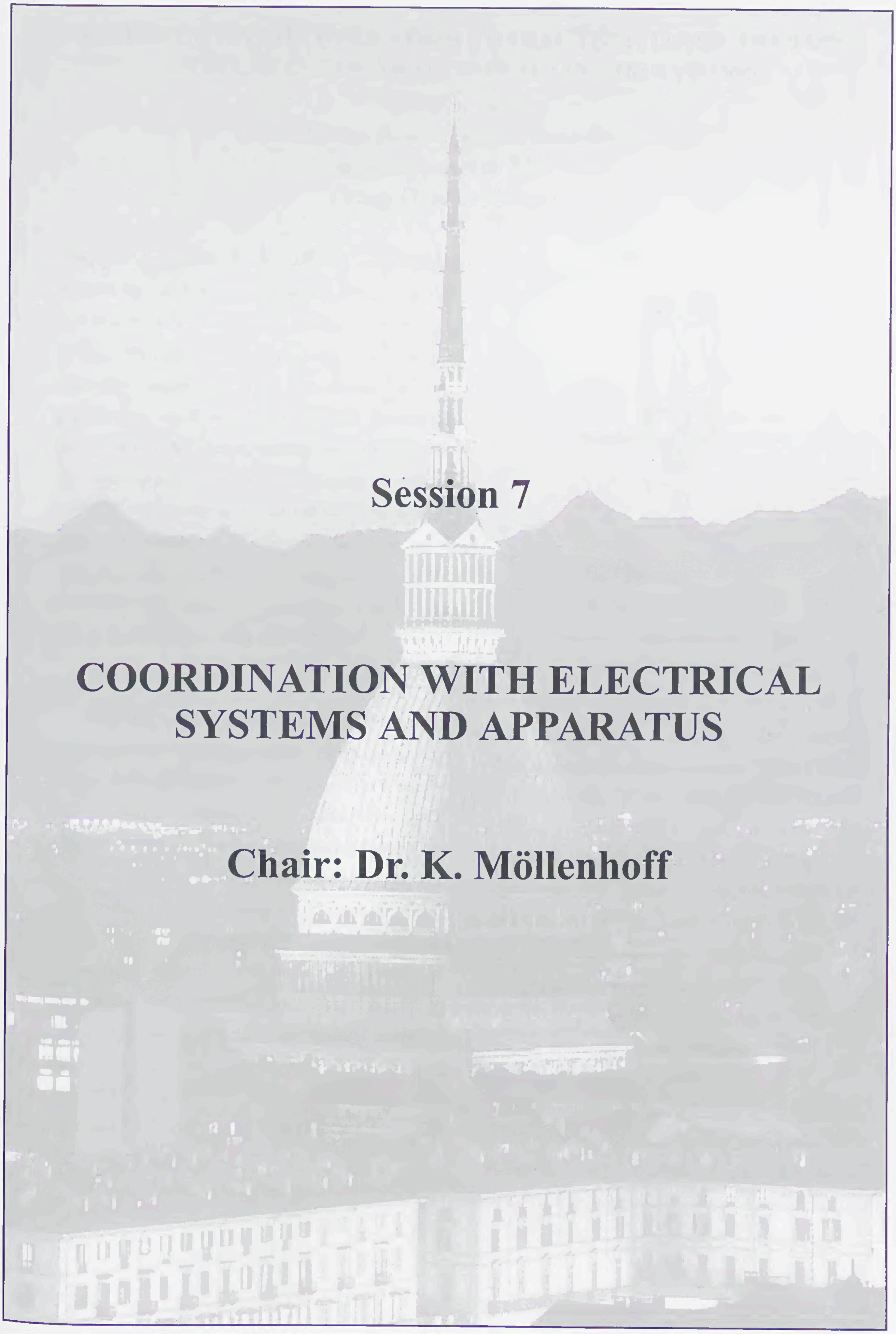
Resistance tracing from the beginning of the manufacturing process to the installation in the transformer ensures a high level of reliability in service

VII REFERENCES

[1] IEC Publication 60282-1 High-voltage fuses – current-limiting fuses

[2] IEC Publication. 60787 Application guide for the selection of fuse-links of high-voltage fuses for transformer circuit applications

[3] IEC Publication. 60076-5 Power transformers – ability to withstand short-circuit



Session 7

COORDINATION WITH ELECTRICAL SYSTEMS AND APPARATUS

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