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NEW DESIGN OF TRACTION TRANSFORMERS FOR FIXED INSTALLATIONS

SUMMARY

In this paper an analysis of different designs of traction transformers is given. The paper describes three-limb transformer design for 7.5 MVA and 10 MVA units and two-limb transformer design for 15 MVA and 16 MVA units.

Paper also represents noise level measurement results and sound intensity frequency spectrum for 16 MVA unit. Based on results of measurements taken during heat run test on transformer loaded with continuous load equivalent to rated power, simulation of oil and winding temperatures is given for two most common overload cycles of traction transformers.

The paper also gives a description of design and technological measures necessary in case of need to prepare the transformer for short-circuit withstand test, including the procedure and results of tests successfully performed at KEMA High Power Laboratory.

Key words: traction transformer, single-phase transformer, noise measurement, load-cycle calculation, short-circuit withstand test.

1. INTRODUCTION

Traction transformers for fixed installations are used for power supply of single phase railway system today most commonly operated at 25 kV, 50 Hz AC. Transformer primary winding is usually connected between two phases of HV grid at voltage 110 kV or higher, while the terminals of secondary windings are connected to the overhead contact line and to the rail. Power supply from the contact line to electric traction vehicles is accomplished through the pantograph. The value of power required by train is dependant on dynamics of vehicle movement, cargo size and the terrain configuration the railway line is passing through.

Continuous development of power electronics devices and components brought to significant increase in power range of railway electric traction vehicles. Result of this was a need to build new and also upgrade existing catenaries feeder substations, where transformers represent the most important and most expensive components. Taking into consideration operating conditions traction transformers are exposed to and the importance of achieving uninterruptable power supply of railway network, it makes clear that requirements set on design and construction of such transformers are much more strict and complex than those for usual power and distribution transformers. Result of these strict requirements was an adoption of standard EN 50329 [1], where specificities of such transformers are elaborated. To meet the conditions set by standards in force and specific demands stated in the contract, transformer manufacturers today use the most sophisticated technologies and materials available in the construction of new transformer units, and also the most up-to-date methods of calculations available in design process and transformer testing.

This paper gives an overview on design of single-phase traction transformer for power ratings of 7.5 MVA, 10 MVA, 15 MVA and 16 MVA for two state railways. Two-leg and three-leg core designs of single-phase transformers are illustrated with the analysis of the advantages and disadvantages of such constructions and reasons for choosing a specific construction.

The main features of railway transformer operation are non-continuous and cyclic load with frequent overloads, which can be up to several times greater than rated load. Standard [1] stipulates the method of calculating temperature rise of winding and oil and also overload diagrams which are to be applied in case there is no specific customer request stated in the order. Using the results of temperature rise data obtained during temperature rise test the calculation of overload capability of a transformer for specified load cycle has been performed.

A traction transformer in service is exposed to frequent inrush currents and short-circuits. Therefore the calculation and dimensioning of mechanical strength of windings and complete active part in respect to forces produced by over-currents is of great importance for reliable operation of traction transformer. It is common to get a request for dynamic testing of transformer. The paper describes the testing procedure and gives an overview on results of short-circuit withstand test successfully carried out on 16 MVA transformer according to IEC 60076-5 [2] in KEMA High Power Laboratory.

2. CONSTRUCTION OF SINGLE-PHASE TRACTION TRANSFORMER

2.1. Design Analysis of Single-phase Transformer

In general, single phase transformers can be designed with two-limb core where both limbs carry windings, or with three-limb core with windings wound only onto the central limb while other two limbs having two times smaller cross section are used only as path for return magnetic field, (Figure 1). Decision on type of core to apply depends on many factors, such as transformer rated power and voltage, surge voltage distribution, ratio and position of regulation winding, overall dimensions etc. Smaller transformer units have smaller voltage per turn value, therefore having a high number of turns at HV winding. This causes the number of turns per disc to be also high. To get the most suitable surge voltage distribution it is necessary to use relatively costly and complicated interleaved winding. These are the main reasons why, taking into consideration cost-effectiveness and reliability, a much more acceptable solution is three-leg core design with one HV winding. For transformer units of higher rated power generally two-leg core design is used. Most commonly used solution is serial connection for one pair of windings and parallel connection for other pair of windings. In such way continuous distribution of load on both limbs is accomplished. Regulation winding is wounded as a separate winding and positioned as the innermost winding right beside the core for transformers designed with regulation on LV side, or as the most outward positioned winding for transformers designed with regulation on HV winding.

On an example of single phase transformer of rated power of 7.5 MVA, given is the comparison of two-leg and three-leg core design. Defined task was to design transformers of approximately the same rated losses and short-circuit impedance levels, at the same taking into consideration technical constraints regarding maximum specific material loads allowed. Results are shown in Table I. It is clear that three-leg solution requires higher quality of core magnetic steel, as a consequence of inherently larger core. Increase in mass of core steel material is compensated by decrease in mass of windings, oil and transformer tank, giving at the end a solution with three-leg core design which weighs less and is more cost-effective compared to transformer of two-leg core design.

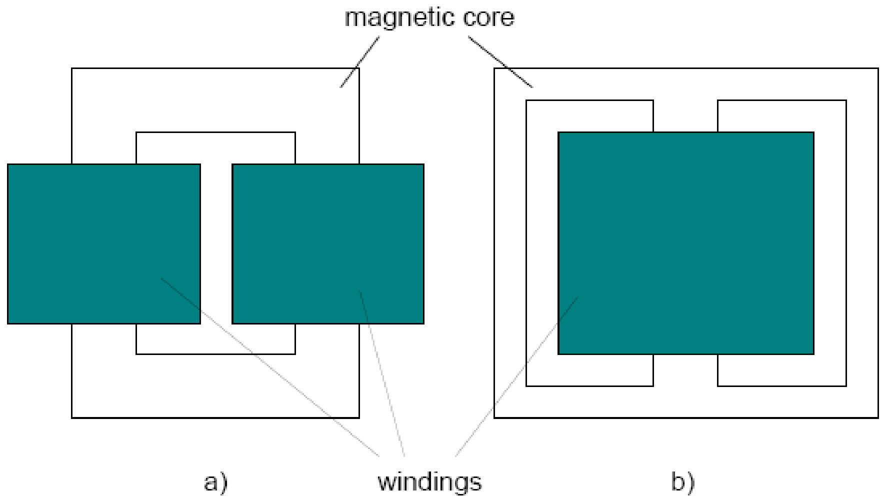


Figure 1 – Two-leg a) and three-leg core b) design of single-phase transformer

Table I – Design data comparison of two-leg and three-leg core of single-phase traction transformer

	two-leg core	three-leg core
Rated power (MVA)	7.5	
Rated voltage (kV)	110/27.5±10x1.5%	
Core steel grade	CRGO/0.27 mm	CDGO/0.27 mm
Impedance voltage (%)	10.24	9.97
No-load losses (kW)	8.4	7.4
Load losses (kW)	32.2	31.8
M_{Fe} (kg)	6200	7400
M_{Cu} (kg)	3400	2600
M_{total} (kg)	22300	21700

2.2. Traction Transformer Construction

2.2.1. 7.5 MVA and 10 MVA Units

Transformers are of three-leg core design with one wound core leg. Magnetic core is built of high quality silicon steel laminations, stacked in a step-lap pattern which is highly effective in reducing transformer noise. The winding conductors are made of electrolytic copper with a specific work of hardening to increase the stiffness of the material. Conductors are insulated by cellulose paper insulation of adequate thickness to get the required dielectric strength and to insure the most efficient cooling of transformer winding. Winding dispositions on the core limb is shown in Figure 2, while technical data of 7.5 MVA and 10 MVA transformers are shown in Table II.

The innermost winding beside the core is regulating single-loop layer winding. A layer has the same number of turns as the number of turns in a regulating winding. All steps are wound in parallel and the outlets are placed at the top and bottom of the winding. As each step occupies full winding length, a balance between primary and secondary winding is maintained for every tap position. The interconnection between steps is arranged so that the maximum voltage between adjacent conductors is the voltage of two tap steps. Voltage regulation is on-load with reverse-tapping winding arrangement (plus/minus connection).

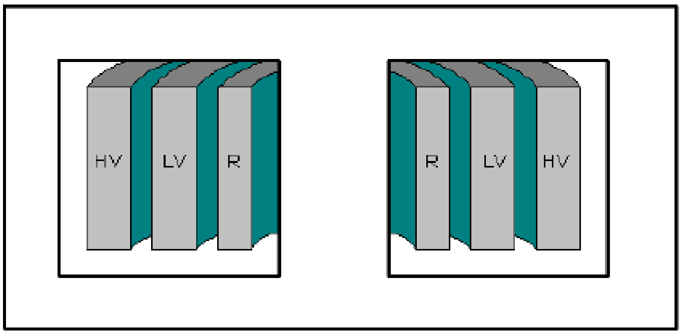


Figure 2 - Windings disposition on the central limb of three-leg 7.5 MVA and 10 MVA transformers

LV winding is next one of continuous disk type. The advantage of this type of winding is its natural strength of the form what makes it a very good design under short-circuits fault conditions. The external winding is HV, made as interleaved disk winding. Its turns are interleaved by special disk connections. Results of this are considerably increased series capacitance and improved initial surge voltage distribution through the winding. That is achieved at the expense of a much higher voltage between adjacent turns in normal service. Interleaved windings require much more skill and labour than simple continuous disk winding. Therefore they are more expensive, but inevitable solution when a transformer is exposed to heavy duty service as it is in the case of railway applications. Figure 3 shows two views of the active part of 7.5 MVA transformer before tanking.

Table II – Main technical data of single-phase 7.5 MVA and 10 MVA traction transformers

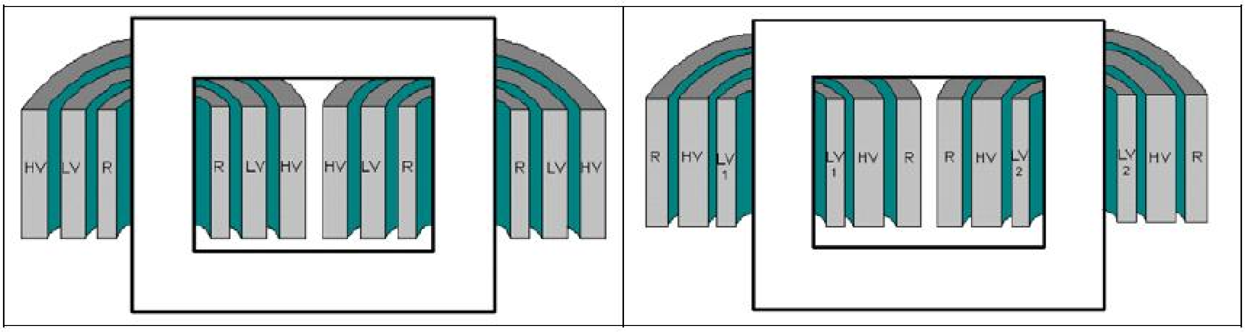
Rated power (MVA)	7.5	10
Rated voltage (kV)	110/27.5±10x1.5%	
Impedance voltage (%)	10.4	10.4
No-load losses (kW)	8.2	10.5
Load losses (kW)	39.8	46.6
No-load current (%)	0.55	0.49
$M_{active\ part}$ (kg)	11000	13000
M_{oil} (kg)	6200	7000
M_{total} (kg)	22500	26000
Type of cooling	ONAN	
Overall dimens. LxWxH (m)	4.02x3.1x3.51	4.28x3.1x3.57

a) b)

Figure 3 - Active part of 7.5 MVA traction transformer: a) HV terminal side, b) regulating winding connections to OLTC

2.2.2. 15 MVA and 16 MVA Units

Both transformer units are have a two-limb core and windings positioned on both limbs. Basic design data of these units are shown in Table III, and winding dispositions on core limbs are shown in Figure 4.



a) b)

Figure 4 - Windings disposition on two-leg core of a) 15 MVA and b) 16 MVA transformers

Since 15 MVA unit is designed having a regulation on LV side, regulation winding is positioned as the most inward winding, right beside the core. For 16 MVA transformer unit with regulation on HV side, a normal disposition of windings is chosen: LV, HV and R as the most outward winding. This transformer has two separate secondary windings and its structural design with two wound legs, each one with LV and HV winding, is equivalent to two single transformers. Each single-phase transformer is connected across two HV phases. Hence, the regulating winding is foreseen to withstand directly applied lightning impulse and switching overvoltages. For this reason special care has been devoted to the design of the regulating winding, resulting in simple and reliable construction. The core is fastened by means of a sturdy metal frame, which allows the lifting of the active part and the axial clamping of the windings. Figure 5 shows active part of 16 MVA transformer before tanking and 15 MVA unit at site in operation.

a) b)

Figure 5 – a) Assembled active part of 16 MVA unit in the workshop and b) completed 15 MVA transformer at site during operation.

All transformers have undergone successfully routine and type tests, including lightning impulse test, sound level measurement and heat run test at full rated power. 16 MVA transformer successfully passed short-circuit withstand test in KEMA High Power Laboratory.

Table III – Main technical data of single-phase traction transformers 15 MVA and 16 MVA

Rated power (MVA)	15	16
Rated voltage (kV)	110/27.5±10x1.5%	126±9x1,78%/ 2x27.5
Impedance voltage (%)	9.75	11.8
No-load losses (kW)	11.2	8.7
Load losses (kW)	63	74.3
No-load current (%)	0.16	0.07
$M_{active\ part}$ (kg)	16500	18900
M_{oil} (kg)	8000	8500
M_{total} (kg)	31000	34500
Tape of cooling	ONAN	ONAF
Overall dimens. LxWxH (m)	4.9x3.1x4.0	5x3.47x4.68

3. SPECIFIC REQUIREMENTS FOR TRACTION TRANSFORMER

Due to heavy service conditions of traction transformers, rigorous demands are set on such transformers regarding overload capability, and high dielectric and mechanical withstand capabilities to overvoltages and overcurrents respectively. Besides these common strict demands, nowadays are more than ever emphasized demands related to environment safety. Cause of this is the fact that traction transformers are often mounted in substations situated relatively nearby or within inhabited areas, even in the water protection areas. Low losses, low sound level, increased safety level regarding flammability and also usage of environmentally friendly materials and fluids, are the most common demands set by customers of such transformers.

3.1. Noise Level Requirements and Measurements

Based on how rigorous are demands set by customers regarding low noise level, transformer manufacturers can apply some of the following solutions:

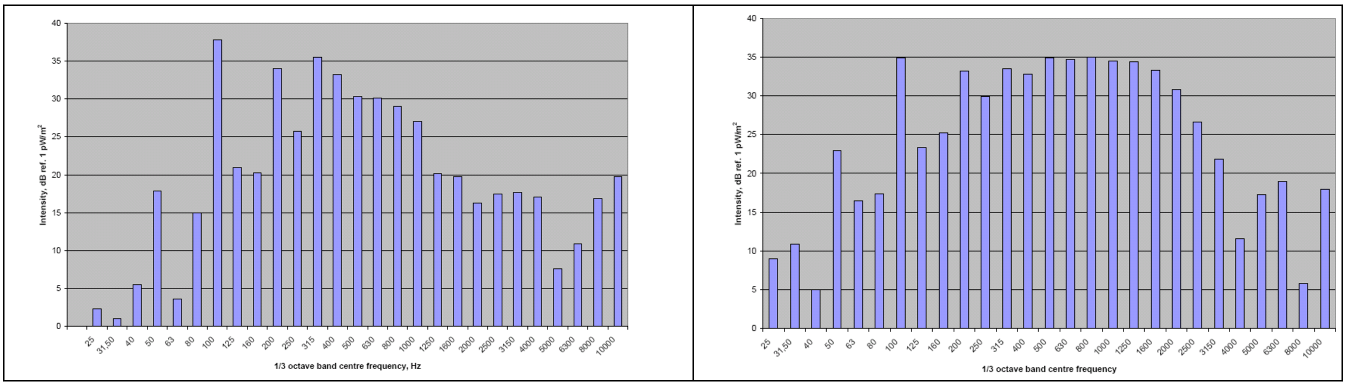
- Employ flat steel of low magnetostriction.
- Reduce the flux density in the core by increasing the core cross section. Consequential effects will be lager dimensions, higher total mass, increased load losses and manufacturing costs. No-load losses, no-load current and inrush current will decrease.
- The mechanical stresses in the core should be limited.
- Core and tank resonances should be avoided.
- No rigid connections between core and tank. A pad of damping material between the active part and tank bottom.

The measurement of sound from transformer may sometimes be disturbed by high background sound or from other strong sound sources in the surroundings. To determine the noise of the transformer in such situations sound intensity measurements are made. Sound intensity is the time-average product of the sound pressure and particle velocity of the medium in which the sound waves are propagating. Therefore, by measuring the noise level using sound intensity method, the influence of background noise and sound wave reflection in testing room are eliminated. Relationship between sound intensity L_I and sound pressure level L_p is, [3]:

$$L_I = L_p - 10 \cdot \log K \tag{1}$$

where K= constant = I0 x $\rho c/P_0^2$ is dependent upon ambient pressure and temperature. The quantity 10 log K will equal zero when K = 1, what is under commonly encountered temperature and atmospheric conditions. Therefore, $L_p \approx L_I$, noise pressure and noise intensity measurement in free space yield the same numerical value. The results of transformer noise measurement are acceptable if the difference between uncorrected average A-weighted sound pressure level L_{pA0} and the average A-weighted sound intensity level L_{IA} is not bigger than 8dB(A) [4].

By applying the above mentioned measures at 16 MVA transformer units, much lower noise levels are achieved compared to guaranteed sound level of L_{pA0}=50 dB(A). The measured values are 42.7 dB(A) at ONAN cooling and 44.7 dB(A) at ONAF cooling. Figure 6 shows 1/3 octave spectrum of sound intensity measured in ONAN and ONAF cooling. The measurements are performed with Brüel & Kjaer 2260 Investigator device.

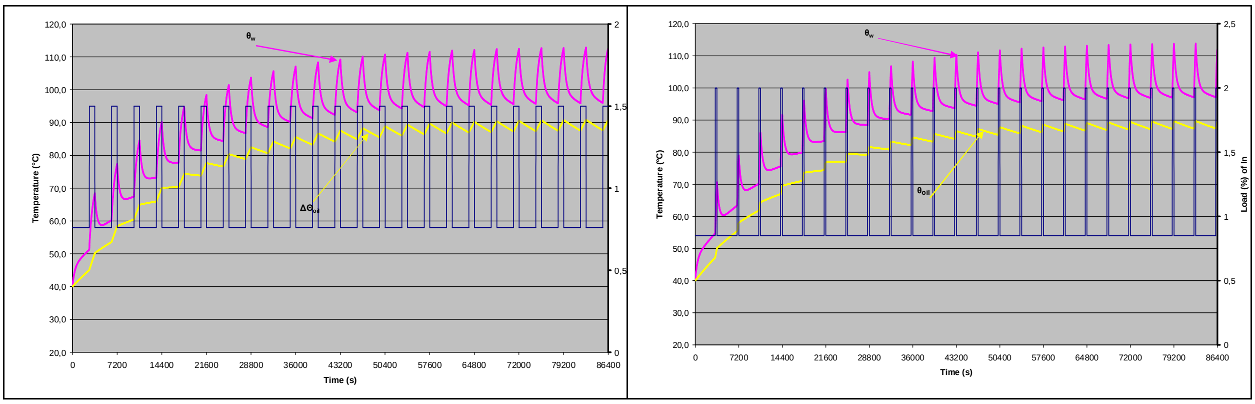


a) b)

Figure 6 - Sound intensity level measurements in a) ONAN cooling, b) ONAF cooling

3.2. Demonstration of Transformer Capability to Sustain Overloads and Load Cycles

Transformers for power supply of railway catenary network are subject to frequent overloads, both amplitude- and duration-wise. For this reason, while stating an order purchaser must define a daily load diagram or equivalent overload value, thus making it possible to design a transformer that complies with real service conditions. By experience, customers most commonly order transformer rated for overload of 50 % above rated current value and duration of 15 minutes every hour, or overload of 100 % above rated current value for duration of 5 minutes every hour. According to [1], the winding temperature rise after short time overload conditions are allowed to exceed by 15 K the applicable standard temperature rise, what is 65 K for mineral oil filled ONAN cooled transformers. Using the results given by the heat run test at rated transformer load of 10 MVA ($\Delta\Theta$w-o = 11.5 K and $\Delta\Theta$o= 46.3 K), simulation of oil and winding temperatures is performed in case of above stated overload for duration of 24 hours and maximum ambient temperature of 40°C. Overload and temperature diagrams are shown in Figure 7, while in Table IV an overview of results is given.



a) b)

Figure 7 - 10 MVA transformer, oil and winding temperature simulation for 24 hours cyclic loads: a) 50 % overload of 15´duration, b) 100% overload of 5´duration.

From the steady-state temperature rise an increase of average oil temperature can be seen - from 86.3 °C at continuous load and rated power up to 90.8°C in case of overload a), or up to 89.7°C for overload b). Increase of winding temperature is even higher. In case of 50% overload, average winding temperature reaches 112.7°C, while at 100% overload winding temperature reaches as high as 113.9 °C.

At ambient temperature value of 40°C, average winding temperature rise is 73,9 K, which gives an increase of 8.9 K, less than allowed 15 K.

Table IV – Load cycle data and final oil and winding temperature after 24 hours cyclic loads in overload cases a) and b)

Case	Load	One hour cycle		Final temperature (°C)	
		p.u. of In	Duration (s)	θoil (°C)	θw (°C)
a)	I	0.76	2700	90.8	112.7
	II	1.5	900		
b)	I	0.85	3300	89.7	113.9
	II	2.0	300		

3.3. Ability to Withstand Overcurrents and Short-circuits

As stated in 3.2, service conditions transformers for feeding railway catenary networks are extremely severe, from cyclic overloads twice the value of rated current, to frequent short-circuits. According to [5], number of short-circuits can be even up to 250 per year. This fact is the reason why for railway transformer it is almost a rule to demand a short-circuit withstand test as type test.

Values of short-circuit forces highly depend on chosen transformer design. The most basic relations for evaluation of short-circuit forces in transformer are given in [6]. Total radial force on transformer windings in case of short-circuit is calculated according to:

$$F_{rt} = \frac{510 \cdot S_l}{f \cdot (d + \frac{a_1 + a_2}{3})} \cdot r \qquad \text{(kN)} \qquad (2)$$

Axial force is calculated using a similar expression:

$$F_{at} = \frac{510 \cdot S_l}{f \cdot H_w} \cdot r \qquad \text{(kN)} \qquad (3)$$

in which:

S_l = rated power per limb (kVA),
r = overcurrent factor,
f = frequency (Hz),
d = width of the main duct between windings (mm),
a1, a2 = radial width of winding 1 and 2, respectively (mm),
H_w = axial average height of windings (mm).

From (2) and (3) it can be deduced that an increase in transformer power per limb is accompanied by an increase in short circuit-forces. Other factors being equal, both radial and axial forces are inversely proportional to the winding axial length H_w. This means that when transport limitations or the size of the unit make it necessary to reduce winding height, higher short-circuit forces are to be expected.

To design and produce transformer which will withstand heavy short-circuit operating conditions encountering in network is a special challenge for any transformer producer. The following are preconditions which must be fulfilled to be certain that the customers are supplied with transformers suitable for railway operation:

- Knowledge of expected service conditions in terms of frequency and severity of short-circuits.
- Software for calculation of the worst short-circuits cases and the relevant current values.
- Solid design criteria, suitable for different types of short-circuit forces, stresses and failure modes.
- Computing procedure aimed at optimizing design through correct selection of winding arrangements and proportions, in order to minimize the forces.
- Proper choice of tap-changer, to avoid internal short-circuits.
- Materials suitable for that kind of applications, purchased from qualified suppliers according to agreed specifications.

- Controlled manufacturing processes, including complete manufacture of windings, winding sizing and stabilization, positioning of the windings when assembled on the core, the drying and oil impregnation process, final clamping, etc.
- Systematic methodology for keeping track of and measuring the key factors throughout the engineering, manufacturing and testing process.
- Fully trained, skilled and highly-motivated workshop workers.
- Cleanliness throughout the manufacturing process.

On the client's request short-circuit withstand test was performed on the 16 MVA transformer. During the testing the both LV windings were connected in parallel and pre-set short-circuited. Each regulating position was tested by full short-circuit current, as Z_{supply}/Z_{trafo} = 3.93 % and peak factor according to X/R relation is 2.58. Thanks to taking all measures stated above strictly into consideration, starting right from the point of contract details negotiation and all up to the point of transformer design and construction, all tests required by customer are successfully performed. Result was acquiring a Type test Certificate of short-circuit performance from KEMA High Power Laboratory. Figure 8 shows transformer during testing in KEMA and the obtained type test certificate.

Figure 8 – a) Transformer during short-circuit withstand test in KEMA High Power Laboratory and b) Type test Certificate of short-circuit performance.

4. CONCLUSION

Based on analyzed solutions of single-phase transformers for power supply of railway catenary network, it can be concluded that in case of transformer units of small power and high voltage level, the most convenient design solution is three-leg core with windings mounted onto the middle limb. For larger transformer units, especially in case when transformer has two secondary windings, the best solution, technically and economically, is two-leg core design with windings on both limbs.

Nowadays it is very common to install railway transformers close to inhabited areas or in water protected areas. Demands regarding transformer's environmental acceptability become the 'decision-making' ones when placing a transformer order. Customers are looking for transformers with low noise levels, oil transformers filled with non-flammable and environmental-friendly insulation liquids (natural or synthetic ester liquids, silicone liquids, SF6, etc.) Measurement of transformer noise level performed using new method such as measuring sound intensity level tends to be the most acceptable solution for transformer manufacturers. It is expected that this method, and part considering application of new and ecologically acceptable materials, to be included in the next edition of standard [1].

Based on results of heat run test performed at continuous rated power, the paper shows how to simulate by calculation winding and oil temperature in case of two most common overloading types. Method of calculation of overload according to [1] differs from procedure defined by standard in force for power transformers [7]. Taken into consideration that [7] is the most up-to-date standard where the most recent knowledge regarding the ability of overload of oil-immersed transformer is given, it is expected that [1] and [7] will be synchronized in the near future.

By the majority of customers today, testing of traction transformers by applying peak short-circuit current is considered a type test. Standard [1] defines this as special testing and refers to related standards for power transformers [2]. However, since this is a matter of specific service conditions characterized by frequent short-circuits occurrence, recommendation would be to elaborate this issue for the next edition of [1] and to synchronize it with the practice in use today.

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