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Identification of operating conditions of transformer working in power electronics circuit

Streszczenie. *Transformatory z izolacją suchą są stosowane od ponad 30 lat w energoelektronicznych układach napędowych i pracują poprawnie. Transformatory olejowe z izolacją papierową są stosowane także w układach energoelektronicznych: w małej energetyce, a także w elektrotermii do zasilania pieców indukcyjnych. Izolacja papierowa w tych transformatorach ulega szybkiej degradacji. Powodem jest komutacja zaworów energoelektronicznych. Impulsy prądów komutacyjnych generują napięcia, między uzwojeniem i kadzią transformatora, o pochodnej ponad 100V/µs. (**Identyfikacja warunków pracy transformatora olejowego współpracującego z układem energoelektronicznym**)*

Abstract. *Dry-type transformers have been successfully used for more than 30 years in power electronics ac and dc drives and they operate correctly. Oil-filled transformers with paper insulation are also used in power electronics circuits, for instance in small power plants, in electric heating (for furnace supply). The paper insulation in these transformers degrades quickly. This is due to commutation of power electronics elements, which is accompanied by overvoltages between transformer winding and tank, with voltage change rate greater than 100V/µs.*

Słowa kluczowe: izolacja transformatora, energoelektronika, degradacja izolacji papierowo-olejowej
Keywords: transformer insulation, power electronics, oil-paper insulation wear

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Introduction

Transformers may be classed as dry-type and oil-filled transformers. Dry-type transformers have been successfully used for more than 30 years in power electronics ac and dc drives and they operate correctly. In power engineering, i.e. in power plants and distributing stations, oil-filled transformers are used; their operation does not present any problems and they operate for 30 or more years without failure. They are often exchanged for transformers with smaller power losses for purely economic reasons even though their technical condition is faultless. During last years we have seen dynamic development of small power plants (wind and solar farms, small hydroelectric plants). These energy sources usually use power electronics converters with PWM and oil-filled transformers. Operating conditions of oil-filled transformer working in PWM power electronics circuit widely differ from operating conditions existing in circuits supplied with sinusoidal voltage and loaded with sinusoidal currents. The oil-filled transformers are also used in foundries to supply induction melting furnaces (converters with controlled output frequency are used).

The primary (high voltage) winding wire is insulated with Kraft-type paper, and aluminium or copper foil of secondary (low voltage) winding is insulated with tape or paper foil. Main insulation consists of insulating barriers made of insulating boards (these may be found between core and winding and between the windings). The windings insulation system consists of oil and cellulose. Oil fulfils two functions – it acts as cooling agent and insulation agent at the same time. Cellulose (paper or cotton) impregnated with oil makes good turn-to-turn insulation. Transformer insulation is graded as insulation class A (105°C), but oil temperature should not exceed 90°C. Oil acting as cooling medium makes it easy to solve the issue of transferring away the heat from the core and the windings to the coolers. Transformer tank provides the cooling and protects transformer from mechanical damage. Oil-filled transformers are much cheaper than dry-type transformers, since their cooling conditions are better, insulation system is cheaper and processing costs less. Operational practice shows that life time of oil transformers working in power electronics circuits is short, about 5 years maximum.

Identification of operating conditions of transformer working with PWM converter

Identification of operating conditions of oil-filled transformer supplying induction melting furnace in foundry will be demonstrated with the help of transformer rated at: S_N = 670 kV·A; U_{1N} = 3x6 (1 ± 0,0225) kV; I_{1N} = 64,47 A; U_{2N} = 3x590 V; I_{2N} = 656,6 A; windings arrangement Dy11; $u_{zN\%}$ = 5,85 %; built in 2006.

The melting furnace heats and melts the charge with time-varying magnetic field generated by heating inductor; the magnetic flux is proportional to inductor current, which is controlled by PWM power electronics converter. Tests of oil transformer voltage and current waveforms at the inverter side were conducted in the foundry. They helped to identify reasons of accelerated wear of paper-oil insulation system in the transformer.

The transformer's primary winding was delta-connected, and the secondary winding was star-connected with isolated neutral point (this was enforced by the design of induction furnace, which was water-cooled). Transformer was installed in expressly built and ventillated room. The scheme of induction furnace supply circuit is shown in Fig.1. Inverter's output frequency could be set in the range 70-9600 Hz. After five years of operation, the transformer's insulation system broke up. The cause of the damage could only lie in transformer's operating conditions, i.e. supply voltage and load current.

Transformer's supply voltage was sinusoidal with higher harmonics content not exceeding 2%; therefore explanation must be sought after at the load side. In order to identify loading conditions, the following waveforms were recorded at the secondary winding: load current (Fig.2), phase-to-phase voltage (Fig.3) and voltage between phase and transformer tank (Fig.4).

On the basis of the recorded waveforms the harmonic spectra and total harmonic distortion factors (THD) were calculated for:

- current, THD_i = 26%,
- phase-to-phase voltage, THD_u = 5.5%,
- voltage between phase and transformer tank, THD_{uf} = 113%.

Distortion factor of transformer's load current is significant, while this factor for phase-to-phase voltage is five times less and lies in the range allowed by Ministry of Economy Decree pertaining to quality of electrical energy.

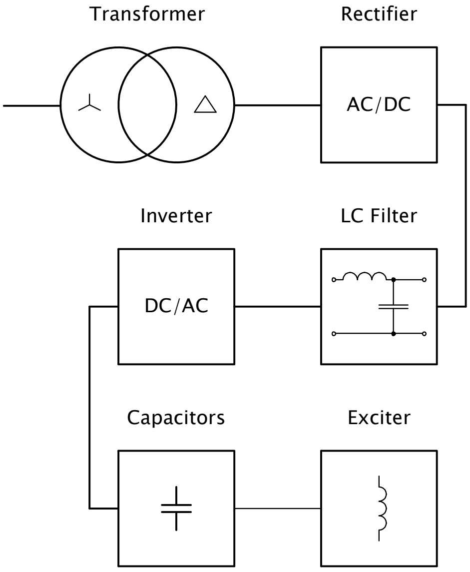

Fig. 1. Induction furnace supply scheme

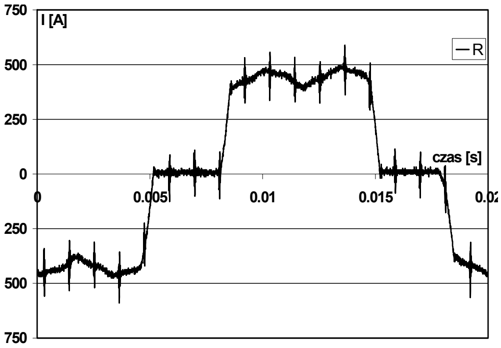

Fig.2. Transformer output phase current

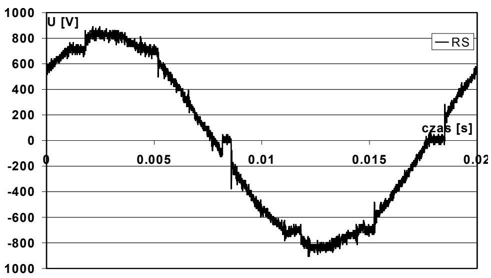

Fig. 3. Transformer output phase-to-phase voltage

Instantaneous (step-like) variations in current waveform may be observed in Fig.2; these are due to rectifier commutation and are not accounted for in THD_i coefficient. Current derivative at commutation time instant generates voltages influencing windings insulation circuit. Voltage occurring between transformer tank and winding phase is shown in Fig.4. Transformer's insulation system is subjected to this voltage. The THD coefficient for this voltage is THD_{uf} = 113%; however, it is not this coefficient which causes accelerated deterioration of insulation system, this is due to voltage rate of change. In this case, rise rate of voltage between phase and transformer grounding is equal to 115V/μs. We may compare it to maximum voltage rise rate in transformer's insulation system, when transformer operates with sinusoidal voltage:

– at the secondary side

$$(1)\left(\frac{\mathrm{d}u_{2f}(t)}{\mathrm{d}t}\right)_{\max}=\frac{\sqrt{2}\cdot U_{2N}\cdot\omega}{\sqrt{3}}=\sqrt{2}\cdot\frac{590}{\sqrt{3}}\cdot 314=0.15\,\mathrm{V/\mu s}\,,$$

– at the primary side

$$(2)\left(\frac{\mathrm{d}u_{1f}(t)}{\mathrm{d}t}\right)_{\max}=\frac{\sqrt{2}\cdot U_{1N}\cdot\omega}{\sqrt{3}}=\frac{\sqrt{2}\cdot 6000}{\sqrt{3}}\cdot 314=1.54\,\mathrm{V/\mu s}\,.$$

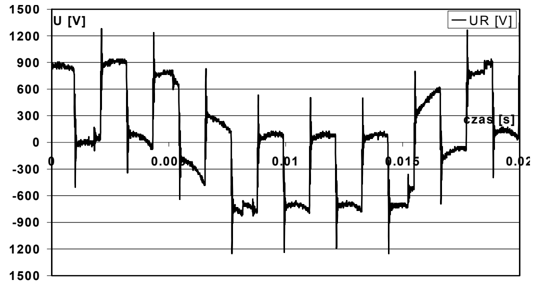

Fig 4. Voltage between transformer tank and secondary winding

Voltage pulses in insulation system recur with frequency of power electronics switches operation.

Tests of gases dissolved in oil of furnace transformer and power engineering transformer

Diagnostic tests of transformers insulation system are conducted routinely by chromatographic analysis of gases dissolved in oil; gas composition and concentration are identified. The tests are pretty much routine and run in accordance with Polish Standard PN-EN 60567, 2012. Table 1 shows exemplary results of oil tests for two transformers with similar ratings. Transformer rated at 1000 kV·A has operated for last ten years in power engineering distribution station; it has been supplied with sinusoidal voltage and loaded with sinusoidal current. Transformer rated at 670 kV·A has operated for 4 years and a half, supplying inverter of melting furnace. The transformer oil tests were run in 2012, the results are shown in Table 1. Transformer rated at 1000 kV·A is characterised by satisfactory (good) indicators, while most indicators of 670 kV·A transformer exceed allowable values.

The quotients of flammable gases concentration prove that locally insulation temperature ranged from 300°C to 700°C; this caused overheating of paper insulation and decomposition of oil. The results show that paper insulation is worn, perhaps even within some restricted localization, still it may jeopardize further transformer operation. Paper's electrical strength is correlated to paper's breaking strength (mechanical), which in turn depends on length of cellulose chain, i.e. degree of polarization (DP). Decreasing paper's breaking strength by 50% in relation to strength of new paper corresponds to 50% wear of insulation; decreasing this strength down to 20% is assumed to be equivalent with 100% insulation wear.

Furan compounds are oil-dissolved products of thermal and hydrolytic degradation of cellulose. The amount of furan in oil characterises degree of ageing of transformer's cellulose insulation. The investigations were run by extracting furans with the help of acetonitrile in accordance with IEC 61198 standard. Afterwards the extract was subjected to analysis with the help of a high-resolution liquid chromatograph in order to find different furan compounds: 2-furaldehyde (2FAL), 5-hydroxymethyl-2-furfural (5HMF), furfuryl alcohol (2FOL), 2-acetylfuran (2ACF), 5-methyl-2-furaldehyde (5M2F). Levels of these compounds were found (in [μl/l (ppm)]) and compared with standard values. The results are given in Table 2.

Furan derivatives are produced only when paper is degraded and it is possible to find them in oil. It is therefore possible to obtain information on condition of paper insulation without running invasive tests (degree of polymerization (DP) tests of paper insulation itself taken from transformer windings). The most important indicator in diagnosis is 2FAL factor, which is correlated to cellulose mechanical strength.

The Energopomiar –Elektryka Company, Division of Transformers and Oil Insulation, has identified 2FAL indicators characterising degree of ageing of paper insulation. For instance, 2FAL>5 ppm testifies to almost complete insulation wear, which does not occur often; it indicates very high cellulose degradation due to internal high-temperature transformer overheating.

Table 1.Results of oil tests for transformers operating in different circuits (all values converted to reference conditions, pressure 101.3 kPa, temperature 200ºC). Tests were run in 2012.

No.	Gas component	Chemical formula	Allowable value [μl/l (ppm)]	Transformer 1000kVA 6kV/400V [μl/l(ppm)]	Transformer 670kVA 6kV/590V [μl/l (ppm)]
1	Hydrogen	H_2	350	8	166
2	Methane	CH_4	200	2	3528
3	Ethane	C_2H_6	170	1	6195
4	Ethylene	C_2H_4	260	none	10860
5	Acetylene	C_2H_2	70	none	10
6	Propane	C_3H_8	30	1	2280
7	Propylene	C_3H_6	40	2	32720
8	Butane	n-C_4H_{10}		none	620
9	Carbon monoxide	CO	260	89	269
10	Carbon dioxide	CO_2	4000	1761	3541
11	Air			52836	54211
12	Sum of flammable gases		2500	103	56648
13	Sum of gases in oil			54700	114400
14	Quotients of concentration of flammable gases	C_2H_2/C_2H_4	<0.1		$0.92\ 10^{-3}$
15		CH_4/H_2	>1	0.25	21.3
16		C_2H_4/C_2H_6	for interval from 1 to 4		1.75

Table 2.Results of chromatographic analysis – furan compounds contents

Furan compound	Test result [μl/l (ppm)]
2FAL (2-furaldehyde)	6.96*
5HMF (5-hydroxymethyl-2-furfural)	0.21
2FOL (furfuryl alcohol)	0.40
2ACF (2-acetylfuran)	0.05
5M2F (5-methyl-2-furaldehyde)	0.16

Conclusions

Oil-filled transformers with paper turn-to-turn insulation are graded in temperature class A (105°C). Transformer insulation does not pose any operational problems in power engineering networks, that is with sinusoidal voltage supply and sinusoidal current load. Under such conditions oil-filled transformers operate for 30 or more years without failure. However, when oil-filled transformers operate in power electronics circuits (small renewable energy power plants, induction melting), the existng insulation system is not immune to conditions set by power electronics. The investigations have shown that current distortions at converter side are significant and due to commutation of rectifier elements. The harmonic content in current shown in Fig.2 is characterised by THDi coefficient equal to 26% and this value does not cause degradation of insulation. The dominant harmonic in the current is harmonic of the 5th order; this is of course due to the fact, that 6-pulse rectifier is used. The phase-to-phase voltages are distorted only slightly. The principal threat to paper-oil insulation is posed by voltage rise rate (of phase-to-transformer tank grounding voltage) which is equal to 115 V/μs. This is the main cause of accelerated deterioration of paper-oil insulation. We may compare this rate to maximum voltage rise rate in transformer's insulation system of transformer operating with sinusoidal voltage, which is equal to c. 0.15 V/μs at secondary side and 1.54V/μs at primary side. The original reason may be traced to commutation processes in the PWM converter and generation of high winding-to-tank voltage rise rates by commutation currents. The use of paper-oil insulation is not appropriate in circuits with high voltage rates.

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