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OIL-FILLED TRANSFORMER SUPPLYING POWER ELECTRONICS CIRCUIT

Abstract: Oil-filled transformers with paper insulation are used in power electronics circuits, in power engineering based upon renewable energy sources and in electric heating engineering. The paper insulation of these transformers deteriorates very rapidly, due to commutation of diodes, transistors and other power electronics elements. Impulses of commutation currents generate tank-to-phase voltages with voltage rise rates exceeding 100 V/μs.

Key words: oil-filled transformers, oil testing, power electronics circuits.

Introduction

Oil-filled transformers have been used in power engineering for over a hundred years. In power engineering, transformers operating conditions are stable: supply voltage is sinusoidal, frequency is constant and load current is sinusoidal. Under such conditions, the life span of transformers is thirty years or more. 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. Main insulation consists of oil plus insulating barriers made of insulating boards. Insulating boards used in electrical circuits are chemically stabilised, they are characterised by diminished moisture absorption capacity and increased resistance to heat. 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.

During last years we have seen dynamic development of renewable energy sources. Wind power farms, solar farms, biogas power stations, small wind power plants are being built. The solar farms are sources of dc voltage, while other renewable energy sources generate ac voltage with variable frequency, since turbines' rotational speed is adapted to their maximum capacity. The energy sources mentioned above are connected to the power grid via voltage inverters and oil-filled transformers. The oil-filled transformers are also used in foundries to supply induction melting furnaces (frequency converters are used).

Operational practice shows that life time of oil transformers working in power electronics circuits is short, about 5 years maximum. Investigation of oil transformers voltage and current waveforms recorded at inverter side in solar farm and foundry with induction furnace has been conducted. The research has made possible identification of accelerated ageing of oil-paper insulation system in these transformers.

Assessment of age deterioration in transformer insulation system

The transformer's insulating system is characterised by following parameters: dielectric strength, resistivity, loss tangent and susceptibility to partial discharges. The dielectric strength of insulating paper impregnated with oil is highly dependent on residual moisture content and temperature. If moisture content is greater than 3%, the paper's dielectric strength falls by over 10%. The influence of temperature on paper and oil deterioration is even more significant. Allowable oil temperature (if oil is in constant contact with air, i.e. oxygen) and with continuous duty should not exceed 95°C. Temperature of 110°C causes substantial acceleration of oil ageing, and if temperature is higher, then paper is degraded and oil is chemically decomposed. Dielectric strength and insulation resistivity are decreased, loss tangent is increased, and electric field intensity starts to excite partial discharges. Insulation system is subjected to gradual degradation, gases such as hydrogen (H), methane CH_4, ethane C_2H_6, ethylene C_2H_4, propane C_3H_8, propylene C_3H_6 and others are released. Concentration of flammable gases in oil rises.

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. Use of gas chromatograph makes it possible to separate gases from the oil in the vacuum and to analyse them. For diagnostic purposes the concentration of following gases is calculated: hydrogen, carbon monoxide and dioxide and content of carbohydrates such as methane, ethane, ethylene, acetylene, propane, propylene and butane is found as well. The quantity of gases extracted from the oil and concentration of different components are then calculated and converted to reference pressure 101.3 kPa and reference temperature 200°C. The quantity is given in microliters of gas volume per one litre of oil [µl/l (ppm)]. Analysis results constitute the basis for diagnosing and forecasting duration of further failure-free operation of transformer. Table 1 shows exemplary results of oil tests for two transformers with similar ratings. Transformer rated at 1000 kV·A is characterised by satisfactory (good) indicators, while most indicators of 670 kV·A transformer exceed allowable values.

Table 1.Results of oil tests for transformers operating in different circuits

No.	Gas component	Chemical formula	Allowable value [$\mu l/l$ (ppm)]	Transformer 1000kVA 6kV/400V [$\mu l/l$(ppm)]	Transformer 670kVA 6kV/590V [$\mu l/l$ (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

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. 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 oil of 670 kV·A transformer was subjected to further tests, and furan compounds were looked for. 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.

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

* Value of 2FAL > 5 indicates very high degree of cellulose degradation.

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. These values have been determined on the basis of statistical tests of about 1000 power engineering transformers. They are shown in Table 3.

Table 3. 2FAL indicators of paper insulation condition

2FAL content in oil [ppm]	Evaluation of degree of ageing of paper insulation
0.00	Healthy insulation, lack of ageing
0.01 – 0.20	Initial stage of ageing, no negative changes in cellulose mechanical strength
0.20 – 1.00	Natural ageing causing gradual changes in cellulose mechanical strength. Typical of most operating transformers
1.01 – 2.00	Considerable degree of deterioration in long-operating transformers, with rather common defects such as low-temperature internal overheating. Different compounds are present (*cf.* Table 2).
>2.01	Advanced degree of deterioration, usually with accelerated rate and significant increase of furans content
>5.00	Almost full deterioration (rare), indicating very high degree of cellulose degradation due to internal high-temperature overheating of transformer.

Operating conditions of transformer working in power electronics circuit

What was the reason for the fast deterioration of 670 kV·A transformer? The only possible causes were transformer's operating conditions, i.e. supply voltage and load current. The transformer supplies power electronics circuit of induction melting furnace, consisting of three-to-one phase converter. The output frequency of the inverter may be set in the range of 70 Hz to 9600 Hz. Transformer is fitted with delta-connected primary winding and star-connected secondary winding; the neutral point of star winding is isolated from the ground. This is due to specific design of water-cooling system of furnace excitation coil circuit. Load current (rectifier current) waveform is shown in Fig.2 and its harmonic spectrum in Fig.3. The THDi coefficient is 26%. Fig.4. presents phase-to-phase voltage waveform, voltage at secondary winding terminals and its harmonic spectrum are given in Fig.5. Voltage THD coefficient is equal to 5.5%.

Even though transformer output current is substantially distorted (which is due to rectifier operation), the phase-to-phase voltages are nearly sinusoidal and their distortion is slight, about five times less than in case of current.

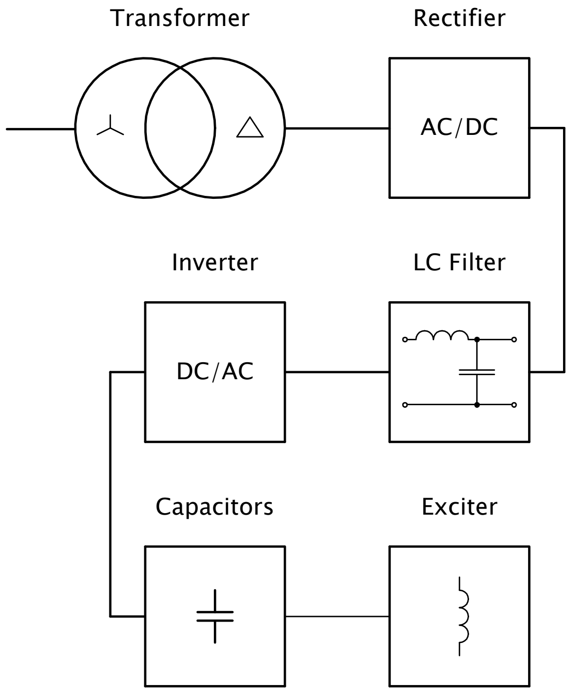

Fig.1. Melting furnace supply circuit

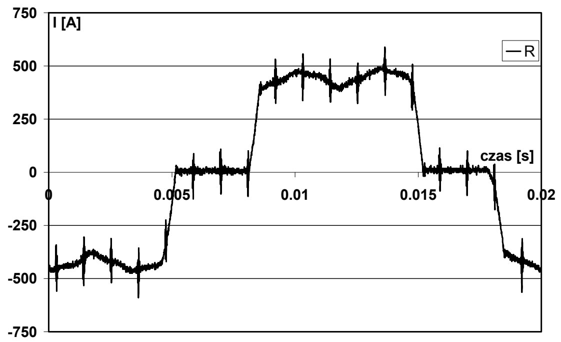

Fig.2. Transformer current waveform, one phase

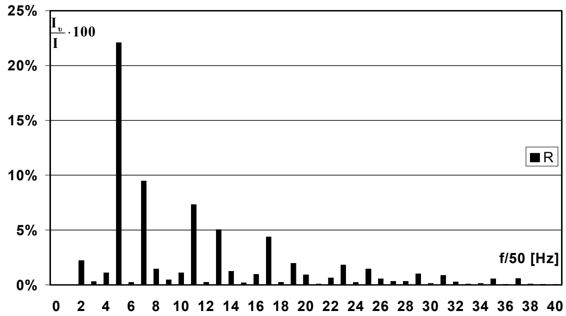

Fig.3.Higher harmonics spectrum (fundamental harmonic is not shown) of transformer current, calculated on the basis of waveform shown in Fig.2

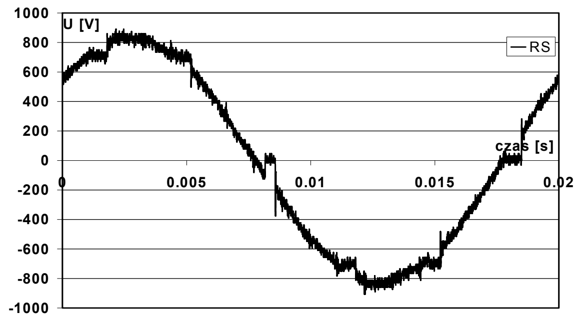

Fig.4. Phase-to-phase voltage, transformer's secondary winding

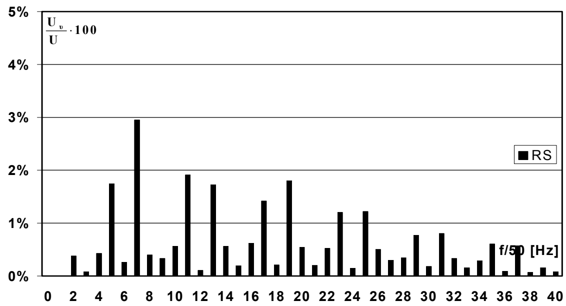

Fig.5. Higher harmonics spectrum (fundamental harmonic is not shown) of phase-to-phase voltage, calculated on the basis of waveform shown in Fig.4.; secondary windings of transformer

Sudden (step-like) variations in current waveform may be observed in current course shown in Fig.2; these are due to rectifier commutation and are not accounted for in THDi coefficient. Current derivative at rectifier commutation time instants generates voltages influencing windings insulation circuit. Voltage occurring between transformer tank and winding phase is shown in Fig.6, and its harmonic spectrum is shown in Fig.7. Transformer's insulation system is subjected to this voltage. The THD coefficient for this voltage is $THDu_f$ = 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:

- for secondary side winding

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

- and for primary side winding

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

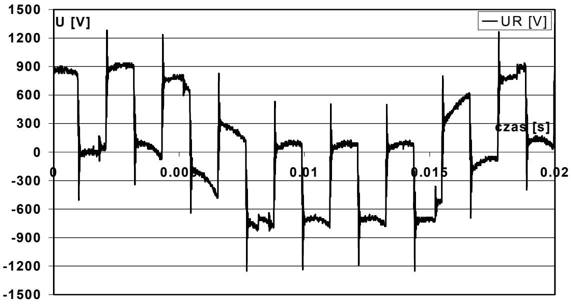

Fig.6. Voltage between transformer tank and secondary winding

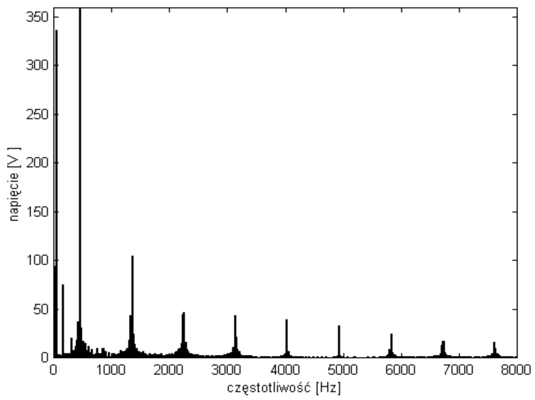

Fig.7. Harmonic spectrum of transformer's secondary winding phase voltages (transformer as in Fig.6)

Conclusions

Oil-type transformers operating in power electronics circuits are equipped with insulation systems not resistant to conditions set by power electronics converters. This is supported by tests run on transformers operating in solar farms in Czech Republic, Italy and Germany and by transformers supplying induction furnaces in the foundries. 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 harmonic content in phase-to-phase voltage (THDu) is equal to 5.5% and this is allowable by appropriate regulations. Distortion of voltage between phase and grounding of transformer tank (Fig.6) is much higher and equal to 113%. 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 rectifier 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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Transformator olejowy zasilający układ energoelektroniczny

Streszczenie. Transformatory olejowe z izolacją papierową są stosowane także w układach energoelektronicznych: w elektroenergetyce odnawialnej i w elektrotermii. 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.
Słowa kluczowe: transformatory olejowe, badania oleju, układy energoelektroniczne.

Reviewer

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