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Impact of generator and power grid on unit transformer reliability

Summary. *Unit transformer is usually connected directly to synchronous generator. Transformer windings are subject to all perturbations, coming from both generator and power grid. The paper lists different types of possible perturbations and presents example of unit transformer failure which occurred in one of thermal power stations.*

Streszczenie. *Transformator blokowy najczęściej jest połączony bezpośrednio z generatorem synchronicznym. Na uzwojenia transformatora działają wszelkie zaburzenia, tak od strony od strony generatora jak i systemu elektroenergetycznego. W artykule wymieniono rodzaje możliwych zaburzeń i podano przykład jednej awarii transformatora blokowego, która miała miejsce w jednej z elektrowni cieplnych.* ***(Wpływ generatora i sieci elektroenergetycznej na niezawodną pracę transformatora blokowego).***

Key words: Unit transformer, transformer failure, transformer repair, transformer protection
Słowa kluczowe: Transformator blokowy, awaria transformatora, naprawa transformatora, zabezpieczenie transformatora

Introduction

The unit transformer is usually directly connected to synchronous generator. The primary winding of unit transformer (T) is connected either by cable or by bus to generator's armature winding. The unit circuit breaker (CB) is installed close to transformer at "upper" voltage side – Fig.1. In this circuit any generator perturbations and power grid (PG disturbances affect the transformer. In case of power grid (PG) side the transformer is partially protected and during emergencies it may be disconnected from grid completely. However, the connection between transformer and generator is fixed and all possible generator perturbations affect the transformer without possibility of disconnection. The paper is focused on possible disturbances and their influence on unit transformer. We also present and discuss failure of unit transformer caused by these perturbations.

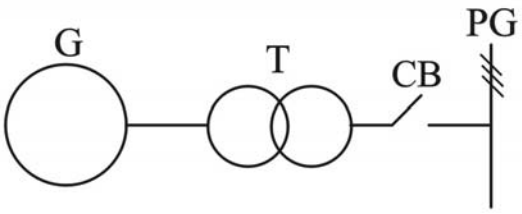

Fig.1. Power unit circuit: G – synchronous generator, T – transformer, CB – circuit breaker, PG – power grid

Perturbations in power unit during normal operation

Perturbations in synchronous generator operation

Types of synchronous generators perturbations are listed in relevant service manual (Ramowa Instrukcja Eksploatacji Generatorów Synchronicznych) [2]. This manual identifies all possible disturbances in generator operation together with the protective devices. These disturbances are:

- short-circuiting of stator windings, phase-to-phase and phase-to-ground, in wires connecting to buses and in external network,
- overloading of stator and rotor windings,
- over-excitation and loss of excitation,
- increased stator voltage,
- non-symmetrical loading,
- disconnection of driving system,
- loss of synchronism in excited generator,
- short-circuiting in unit transformer or outgoing power unit line.

Generators rated above 100 MW and operating with distribution or transmission grid may also be equipped with protections ensuring their disconnection from the network in following cases:

- frequency falling below 47.5 Hz, ,
- loss of stability,
- decrease of voltage at transformer's "upper" voltage terminals – below 80% of rated voltage,
- short-circuit in grid lasting more than 150 ms.

The protections mentioned above affect also unit circuit breaker W causing its tripping (switch-off).

Generator voltage may rise relatively fast. If generator operates with nominal excitation and power unit is switched off with circuit breaker CB - (Fig.1), then no-load voltage increases. The maximum value of this voltage may be evaluated basing on standard no-load curve of synchronous generators [6]. Generator's maximum no-load voltage, at nominal excitation, may be equal to:

$$U_{max} = 1{,}4U_N = 1{,}4 \cdot 15750 = 22050V$$

This voltage may result in turn-to-turn short-circuit if the dielectric strength of turn-to-turn insulation is reduced.

Perturbations coming from the power grid

Overvoltages (voltage waveforms) may occur in the power grid, they are characterised by high voltage over time rates of change and short durations (microseconds). These waves may be traced back to atmospheric discharges or operation of current-limiting circuit breakers, switching off large inductive loads e.g. transformers supplied from 110 kV, 220 kV or 400 kV grids, or emergency shut-downs of PG sections. These microsecond-long overvoltages are not recorded by measurement apparatus, because they are attenuated by instrument transformers. Theory of transformers [5] demonstrates that external voltage waveform U_X incoming to transformer winding will be distributed non-uniformly among individual turns of winding. This voltage distribution among turns depends on the ratio of winding's capacitance to earth C_0 to equivalent turn capacitance C_Z. Its maximum value is assigned to foremost turns looking from the phase side.

$$(\Delta U_X)_{max} \approx \frac{U_X}{Z}\alpha$$

$$\alpha = \sqrt{\frac{C_O}{C_Z}}$$

where Z denotes winding's number of turns.

For instance, in power unit transformer 270 MVA, 15750 V / 250000 V the capacitance of insulation to ground high-voltage (HV) of winding and in relation to low-voltage (LV) of winding and core is equal to C_0= 13,6 μF. The turn capacitance C_Z has not been measured during commissioning tests of the transformer, and therefore coefficient α cannot be calculated. Reference [5] states that α may vary from 5 to 20. The windings were specially transposed in order to increase turn-to-turn capacitance C_Z, and therefore coefficient's lower limit may be adopted, α = 5. This voltage value will occur at the first instance of voltage waveform input. In case of voltage waveform the transformer winding must be expressed by distributed parameters (capacity, inductance and resistance) and this fact triggers electromagnetic damped oscillations. The maximum voltage decreases with time and travels along turns distributed down the transformer leg. These over voltages create hazard to turn insulations, and in particular to insulation of first few turns from the phase side. Even if voltage waveform is not high, then if dielectric strength of insulation is decreased, turn-to-turn short-circuit may be initialised, mostly in the first few turns of HV winding.

A failure of unit transformer 725 MVA, 23 kV/345 kV is quoted in reference [4]. It occurred during synchronisation of power unit with the power grid. Synchronisation was manual and operator made a mistake by switching generator on when the voltage phase shift of power unit transformer in relation to PG voltage was equal to 120°((it is probable that he compared phase shifts of different phases). The consequences of this mistake for the transformer were as follows: all windings were dislocated in relation to the core, all winding clamps were loosened or broken; phase "B" winding was damaged most of all, with shreds of insulation and parts of clamps floating in oil, with turn-to-turn and earth faults.

Example of power unit transformer failure

We will present example of failure of new power unit transformer, rated at 270 MVA, 15750 V/250000 V. The failure occurred during pilot (test) operation of the power unit. Transformer was built in 1971 with power rating 240 MVA. In 1996 it was modernised, but only original core and tank were used, all other constructional elements were replaced. The power rating was increased to 270 MVA and so a new transformer was built. The construction was carried out by PPRE Energoserwis Lubliniec (Poland) company, at present it is called TurboCare (Siemens). The construction was correctly accomplished. Independent supervision and control of transformer engineering and some specialised measurements were carried out by independent external company ZPBE Energopomiar – Elektryka, Gliwice (Poland).

Tests of power unit transformer carried out during production stage

Transformer tests consisted of process engineering tests during production stage and final tests carried out with completed transformer. Transformer was designed and constructed in accordance with (then) valid standard PN-83/E-06040 [1]. The scope of process engineering embraced:

- disassembling of transformer and its active part,
- relocation of core, together with modernisation and change of clamping method,
- replacement of copper screens with magnetic plates screens,
- replacement of insulation to ground with hard-type insulation
- execution of new end systems for controlled oil circulation
- execution of new modernised windings,
- modification of cooling system -adaptation to controlled oil circulation,
- equipping the transformer with new pumps, flow meters and free-standing control box,
- drying of active part in vacuum stove and impregnation with new oil,
- final tests and measurements.

Supervision and control embraced the following:

- verification of technical specifications (construction, process engineering),
- control of core and windings, conducted in the midst of different engineering processes,
- control of insulation system drying and impregnation processes; check-ups of moisture content after drying,
- supervision of process engineering,
- commissioning of transformer.

The following tests and evaluations were run:

- windings resistance measurements,
- turn-to-turn insulation testing with 220 V voltage,
- measurement of transformer's voltage ratio by compensation method,
- measurement of insulation resistance,
- core testing,
- testing of moisture content after drying process in insulation samples.

Transformer's final tests were executed in accordance with then valid Polish standard PN-83/E-06040 [1]. These tests included:

- voltage ratio and vector group test,
- windings resistance measurements,
- insulation tests:

— resistance and R60/R15 indicator,
— capacitances and tgδ,
— oil testing,
— insulation electrical strength tests:
- with input voltage HV – 230 kV, LV – 40 kV,
- with induced alternating 3-phase voltage, "lower" voltage winding was supplied with 24,9 kV; 200 Hz voltage,
- with induced 1-phase voltage, partial discharges measurements,

- no-load test - current and power losses,
- short-circuit test,
- leakage reactance and zero-sequence component reactance measurements,
- magnetising currents measurements at low voltages,
- chromatographic analysis of gases dissolved in oil (DGA),
- tank leakproofness test.

The following tests recommended by standard [1] were not carried out:

- surge voltage test (surge voltage generator was not operable),
- heat run test at rated current (unfulfilled test conditions).

The final tests and process engineering tests results were positive. The transformer was commissioned with one reservation, that heat run test would be carried out with transformer operating in the power unit. The transformer was declared to be correctly built and its technical condition was equivalent to that of brand new transformer.

Transformer's operation and failure

Transformer was conveyed by train to the power plant and installed. The ratings of power unit transformer were: 270.6 MVA; 230 MW; 15,75 kV. The operation of power unit before the failure ran as follows (this data was obtained from electric power plant operator):

- On 13th Dec., 1996, the power unit was switched on and synchronized with the power grid. On 15th Dec.1996, after *c.* 65 hours of operation the power unit was disconnected from the grid. Before switch-off the generator operated with 145MW load at power factor cosφ = 0.877. The reason given for disconnection was loss of excitation by generator and its subsequent transit to asynchronous mode of operation.
- On 30th Dec., 1996, the power unit was again synchronized with the power grid and after 32 hours of operation it was switched of (on 31th December) because of turbine trouble.
- Once again the power unit was synchronized with the power grid on 12th January, 1997. The unit operated correctly at 160MW load and reactive power load equal to 80 MVAr. After several hours the unit transformer failed.

Total time of transformer operation was 135 hours, its maximum load (apparent power) was 225 MVA, i.e. 83% of its rated power.

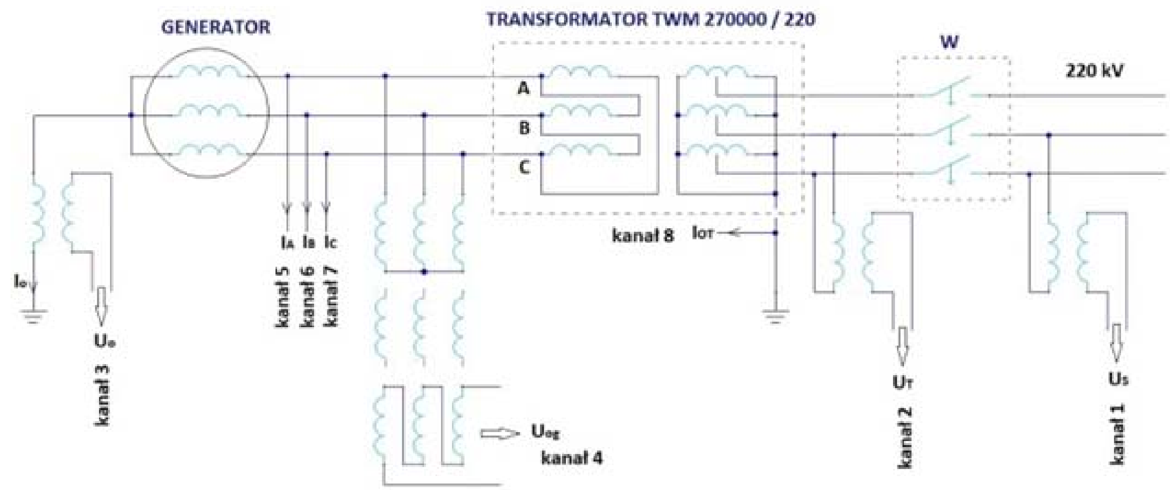

Fig.2. Electrical scheme of power block "generator-transformer" with measurement points marked

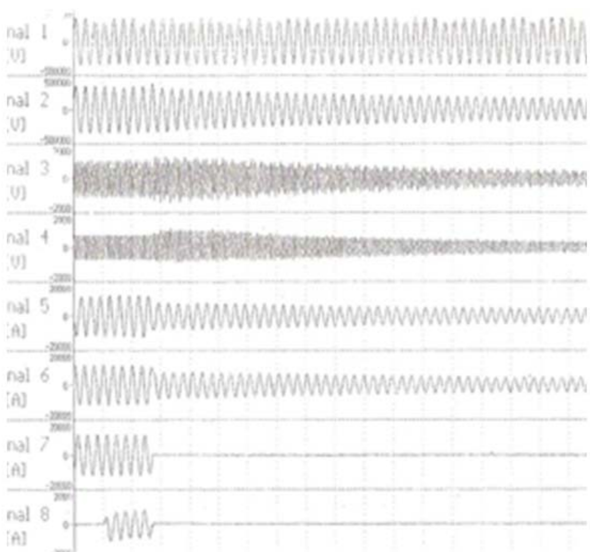

Fig. 3. Voltages and currents - waveforms recorded during failure; different channels are marked as shown in Fig.2

Scope of transformer damage

The sequence of events during transformer failure was recorded by disturbance recorder. The committee working on transformer failure was therefore acquainted with record of basic power unit parameters encompassing interval of 0.5 s before the failure, emergency shut-down of power unit and voltage and current decay after transformer shut-down (see Figs. 2 and 3). Total recording time of the failure is equal to almost 6 seconds. Power unit parameters before shut-down were as follows: grid voltage 245 kV, generator voltage 15444 V frequency 49.760 Hz, generator phase currents 8389 A; 8467 A; 8467 A, active power 209.22 MW. Current appeared in zero-lead of 220 kV winding (see Fig.2), its maximum reached about 570 A, that is *c.* 0.8 of primary winding rated current value. Zero-lead current could be caused by turn-to-turn short-circuit in one of the phases. The oscillogram shows that after roughly four periods (80 ms), the transformer was disconnected from 220 kV grid by differential protection; simultaneously, the generator was de-excited. Apart from transformer's differential protection, other protective devices were also actuated, among them the Buchholz relay (device) (both sets of contacts). Synchronous generator currents in phase "C" and in zero lead were stopped; currents in phases "A" and "B", while still flowing, decreased steadily until complete de-excitation of generator was reached. This indicated arcing in transformer.

The electric plant personnel found gas in Buchholz relay and identified its combustibility. The measurements conducted after transformer failure in accordance with the transformer operation manual (Instrukcja Eksploatacji Transformatorów) [3] showed: anomaly in phase B of 220 kV voltage, consisting of 100% increase in resistance in relation to original value and change of leakage reactance. Investigation of oil properties did not show any changes in basic dielectric physico-chemical parameters; however, traces of opalescent pyrolytic carbon were identified.

Chromatographic analysis of gases dissolved in oil showed characteristic composition of gases, corresponding to internal short-circuit characterized by high energy density (code IEC 102). Table 1 shows results of chromatographic tests run after transformer has been assembled and after it failed.

Table 1. Composition and concentration of gas dissolved in oil.

Gas components		Measured values [ppm]	
		Before start-up	After failure
Hydrogen	H_2	Trace	2454
Methane	CH_4	none	607
Ethane	C_2H_6	none	20
Ethylene	C_2H_4	none	350
Acetylene	C_2H_2	none	599
Propane	C_3H_8	none	1
Propylene	C_3H_6	none	30
Carbon monoxide	CO	3	250
Carbon dioxide	CO_2	47	2324
Sum of combustible gases		3	4311

Fig.4. Phase "A" leads

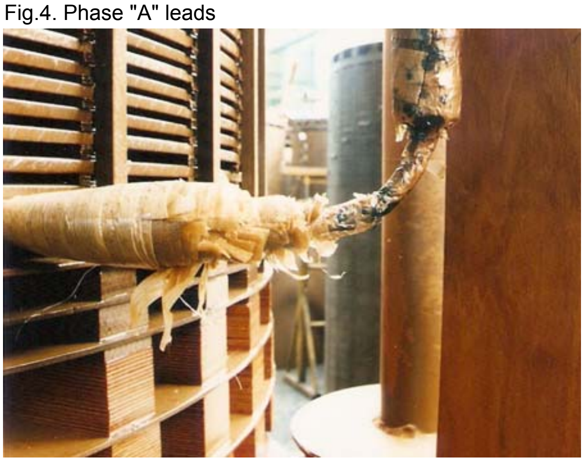

Fig.5. "0" point leads

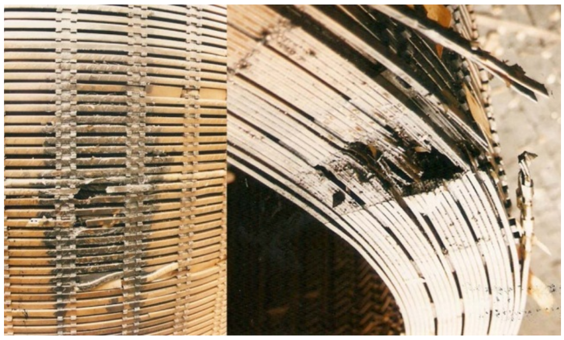

Fig.6. Location of phase "B" winding damage

Transformer was moved to PPRE Energoerwis Lubliniec for repairs. After taking it out of the tank and disassembling HV winding, detailed visual inspection was conducted in order to localize damages and determine extent of necessary repairs.

Visual inspection showed:

- Deep arc burn of phase "B" winding (45 discs). Burned discs were found in the middle section of the leg, i.e. at the side near phase lead. The terminal was broken.
- The leads of "A" and "0" phases showed charred inner insulation layers (i.e. close to copper wire) and partial overheating of insulation at internal terminals of "0" (neutral) point.
- Insulating (shielding) sleeves of all phases were shattered and displaced at the point of gluing contact.

The LV winding did not show traces of damages and transformer core likewise was not damaged.

Figures 4-6 display characteristic locations of damages.

Damages in GN winding were undoubtedly generated during turn-to-turn short-circuiting in phase “B”. However, turn-to-turn short-circuit and short-lasting current in zero-lead could not overheat insulation in this wire. Charring of insulation in zero-lead and “A”phase show that copper temperature reached at least 250°C. During short-circuit this temperature in zero-lead could not be attained. Similarly, overheating of phase “A” terminal could not happen during failure, since short-circuit current flowed through phases “A” and “C” and phase “C” terminal was not overheated. Therefore overheating of insulation in “0” and “A” leads must be due to other, hitherto unexplained reasons. Information on power unit operation obtained from power plant operator does not therefore seem credible, since it does not justify overheating of these wires. Authors may quote from their own experience instances where unreliable information on operation and failure of electrical machines was provided by operators, in particular on occasions when machines’ guarantee period had not expired or when failure was due to employees’ fault. In this particular case the authors are acquainted with the event occurring on 21st Dec., 1996 in nearby plant supplied by the very switch house where transformer in question was connected. Due to sudden rise in voltage different manufacturing devices were damaged (overall costs reaching 48000 DM) together with 100 lamps costing 5000 PLN.

Conclusions

Power unit transformer is directly connected to the generator and via circuit breaker to the power grid. The transformer is affected by generator perturbations and perturbations induced in the power grid. These events greatly influence reliability of the transformer. The authors present example of power unit transformer failure (transformer ratings: 270 MVA, 15750 V / 250000V), which took place during pilot (test) operation of modernised power unit. The modernisation encompassed power unit consisting of turbine, generator and transformer and was aimed at both restoration and increasing nominal power of the power unit. Perturbations in generator operation accompanying start-up tests could and did influence subsequent transformer failure. The burn of phase "B" lead terminal, caused by arcing (Fig.4) and overheating of phase "A" and "0" lead terminals insulation (Figs 5 and 6, respectively), indicate that the transformer had to operate at least twice and for a prolonged period of time at asymmetrical, one-phase load (phase "B" and phase "A") and with currents greatly exceeding rated current. This condition could be due to, for instance, single phase short-circuit. During prolonged single phase short-circuit the leads and turn-to-turn insulation of phases "A" and "B" overheated. The overheated turn-to-turn insulation is characterised by decreased voltage dielectric strength. The turn-to-turn short-circuit at failure time was probably caused by short-time (impulse-type) overvoltage in power grid. Such overvoltages occurring in the grid are generated usually by circuit breakers and not recorded, since they are not transmitted by instrument transformers.

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REFERENCES

[1] Polish Standard PN-83/E-06040. Transformatory. Wymagania ogólne.
[2] Ramowa Instrukcja Eksploatacji Generatorów Synchronicznych (*Manual operation of synchronous generators*). Tabela 3.9.3. Energopomiar, Gliwice, 2009r.
[3] Ramowa Instrukcja Eksploatacji Transformatorów (*Manual operation of power transformers*). ZPBE Energopomiar-Elektryka, Gliwice, 2012r.
[4] Pasternack B.M., Provanzana J. H., Wagenaar L. B.: Analysis of a Generator step-up Transformer failure following faulty synchronization. IEEE Transactions on Power Delivery. Volume 3. No. 3 July 1988.
[5] Васютинсқий С. Б.: Вопросы теории и расчета трнсформаторов. (Глава 7-4 Перенапряҗеия в трансформаторах. Стр. 310-325). (*Theory and calculation transformers; Chapter 7.4 - Overvoltages transformers – pp. 310-325*). Издательство „Энергия" 1970г.
[6] Koter T., Pełczewski W.: Maszyny elektryczne w zadaniach – str. 308. (*Electrical machines in the exercises – pp. 308*). PWT. Warszawa 1961r.
[7] Florkowski M., Furgał J.: Rozpoznawanie uszkodzeń uzwojeń na podstawie funkcji przenoszenia transformatorów. Przegląd Elektrotechniczny, ISSN 0033-2097. Nr 12/2007, pp. 60-63.
[8] Chojnacki A.: Parametry i właściwości niezawodnościowe transformatorów SN/nn Przegląd Elektrotechniczny, ISSN 0033-2097. Nr 04/2008.
[9] Glinka T., Glinka M.: Steel plant transformer operational issues. Przegląd Elektrotechniczny, ISSN 0033-2097, Nr 7a/2012, pp. 193-195.
[10] Gutten M., Kucera S., Šebök M.: Analiza niezawodności transformatorów mocy z uwzględnieniem przetężeń i prądów zwarciowych. Przegląd Elektrotechniczny, ISSN 0033-2097. Nr 07/2009.
[11] Mosiński F., Bocheński B., Piotrowski T.: Nowe trendy w diagnostyce izolacji transformatorów energetycznych. Przegląd Elektrotechniczny, ISSN 0033-2097. Nr 03/2006
[12] Stobiecki A.: Analiza czasu trwania awarii transformatorów SN/nn oraz ocena czasu przerwy w dostawie energii elektrycznej do odbiorców. Przegląd Elektrotechniczny (Electrical Review), ISSN 0033-2097. Nr 07/2008.
[13] Sołbut A., Sołbut T.: Stany przejściowe w transformatorach trójfazowych Przegląd Elektrotechniczny, ISSN 0033-2097. Nr 02/2008
[14] Zakrzewski K.; Szczerbanowski R.: Obliczanie strat we współczesnych blachach transformatorowych; Przegląd Elektrotechniczny, ISSN 0033-2097. Nr 6/201.