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Synchronous generator for induced AC voltage test of single-phase and three-phase power transformers

***Abstract**. The paper presents the method of selection, calculation and measurements of generator that is built into the new transformer test station. The three phase cylindrical synchronous generator 800 kVA, 200 Hz with special damper bars is most suitable to be used as a power supply for testing of single-phase and three-phase power transformers. The emphasis is on the analysis of the armature winding connection and sizing of the damper winding due to unsymmetrical load of a generator in the induced AC voltage test. The results indicate that D-connected generator with skewed stator slots is the best solution. Special temperature sensors were mounted in the rotor.*

***Streszczenie.** W artykule przedstawiono metodę wyboru, obliczeń oraz pomiarów generator wbudowanego w nową transformatorową stację badawczą. Trójfazowy cylindryczny generator trójfazowy o mocy 800 kVA i częstotliwości 200 Hz ze specjalną szyną tłumiącą jest najdogodniejszy jako urządzenie zasilające do prób transformatorów jedno- i trójfazowych. Szczególną uwagę zwrócono na połączenie uzwojeń i wielkość uzwojenia tłumiącego z powodu niesymetrycznego obciążenia generatora w przypadku próby indukowanym napięciem. Wyniki wskazują na to, że generator z uzwojeniami połączonymi w trójkąt i skoszonymi żłobkami statora jest rozwiązaniem najlepszym. Specjalne czujniki temperatury zostały zamontowane w wirniku. (**Generator synchroniczny do prób napięciem indukowanym jedno- i trójfazowych transformatorów mocy**).*

Keywords: synchronous generator, induced AC voltage test, power transformer
Słowa kluczowe: generator synchroniczny, próba napięciem indukowanym, transformator mocy

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Introduction

Generators for power transformer test facilities are used for testing both three-phase and single-phase power transformers. For induced AC voltage test (ACSD - AC Short Duration) and partial discharge measurement of transformer, a source that is sinusoidal as nearly as possible is needed. Its frequency has to be sufficiently above the rated frequency, three to four times higher than the rated frequency. The induced voltage test, along with the monitoring of partial discharges during the test, is one of the most important tests to demonstrate the integrity of the transformer insulation system.

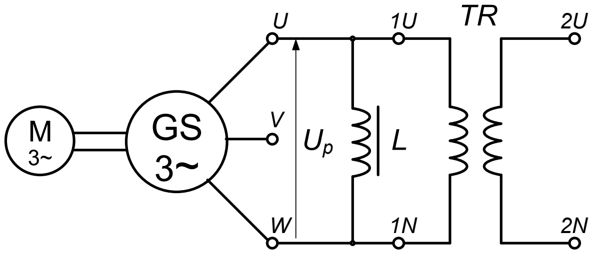


Fig. 1. Simplified test circuit for induced voltage test

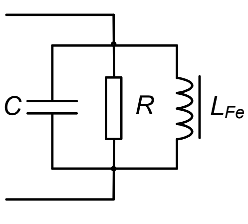


Fig. 2. Simplified equivalent scheme of the transformer in no-load

The purpose of the induced overvoltage withstand test for transformers is to ensure that the insulation terminals, turns, tapping leads can withstand the temporary overvoltages and switching overvoltages to which the transformer may be subjected during its lifetime [1]. For equipment with the highest voltage U_m = 36 kV the ACSD test voltage is 70 kV. Since the test voltage U_p for the induced voltage test is often higher than twice the rated voltage, the test frequency must be at least doubled to avoid over-excitation of the iron core. The principle of the induced voltage test is shown in the

Fig. 1. Inductor L should be connected parallel to the tested transformer TR since transformer in ACSD test represents RC load due to lower magnetic flux in TR. The voltage is increased by factor of 2 and frequency is increased by factor of 4 so that with the lower magnetic flux, no-load magnetizing current is lower than the no-load capacitive current (

Fig. 2). This is especially valid for modern transformers which at the rated voltage and frequency have no-load current value less than 0.1 % of rated current due to high-quality core material and good core sheet overlapping (e.g. step-lap). During this test the partial discharge (PD) measurement is normally performed [2][3].

Along with the synchronous generator for the increased frequency (200 Hz) the test facility is equipped with the synchronous generator for rated frequency (50 and 60 Hz) for conducting other tests on three-phase and single-phase transformers. The side-effect of supplying single-phase transformer is unsymmetrical load [4] and therefore the damper winding must be dimensioned accordingly. Both generators must be able to supply the single-phase transformers without overheating of the rotor due to unsymmetrical load. The armature winding can be connected in either Y (most common connection type for synchronous generators) or D (due to requirement for two-phase operation). The third harmonic phase currents are present even in no-load operation in D connection, but this type of connection is favoured due to the reduced negative sequence MMF component. An equal two-phase load with D connection will produce only 77 % of negative sequence component when compared to Y connection. In order to avoid problems with negative sequence component, a single phase synchronous generator can be built solely for testing single-phase transformer [5].

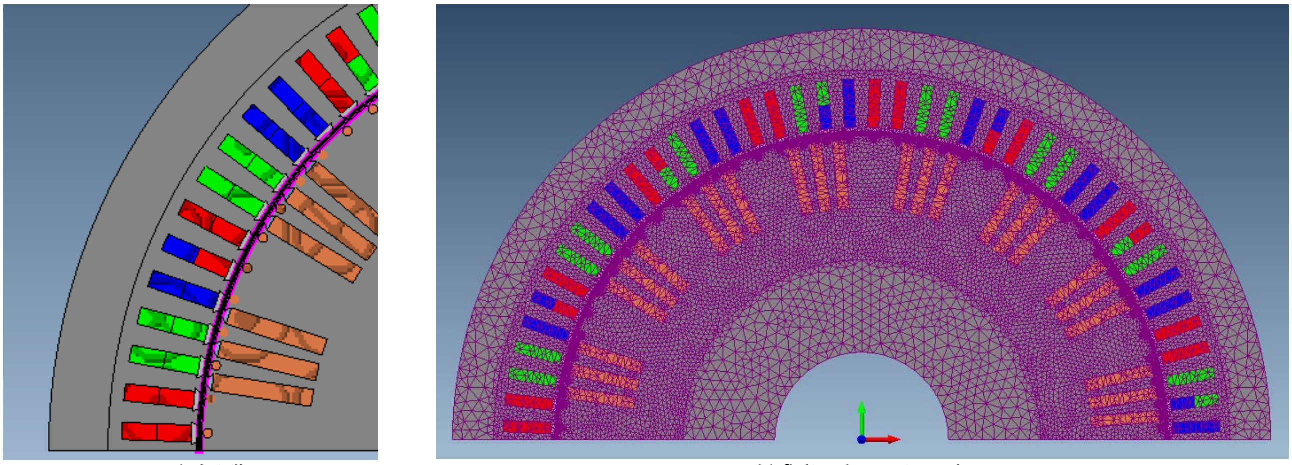
Synchronous Generator Parameters, Calculations and Measurements

For the purpose of testing three-phase power transformers up to 100 MVA and single-phase transformers up to 100/3 MVA the generator manufacturer suggested a cylindrical generator rated 800 kVA (three-phase load), 200 kVA (single-phase load), 200 Hz, 3 kV, 16 poles, power factor 0.05 lagging. This generator is used primarily for the following tests: Induced AC Voltage Test (ACSD) and Partial Discharge Measurement. The form of the generator voltage must be quite sinusoidal and its frequency has to be sufficiently above the rated frequency to avoid excessive magnetizing current during the test. Typically, the generator has a frequency of 200 Hz to test transformers with rated frequency of 50 and 60 Hz.

In the initial generator design conducted by classical analytical methods, the rotor of the generator was supposed to have 96 damper bars of 4 mm in diameter and 96 symmetrically punched slots but with only 64 of them filled by the field winding. FEM calculation showed that some damper bars were loaded with current density higher than 20 A/mm^2 due the unsymmetrical two-phase load. The design calculation was repeated and the new design had 80 damper bars of 6 mm in diameter, 80 symmetrically placed field winding slots, with 48 of them wounded. According to the FEM calculations, the current density was almost halved. The skewed stator has 84 slots.

Numerical calculations

Two-dimensional finite element model was built with software package Infolytica MagNET 7.1. Model details and finite element mesh are shown in Fig. 3. Transient simulations with 400 data points per period were conducted. It was required to determine the field current within iterative procedure in order to obtain rated voltage on a passive load for both three-phase and single phase load (two phase operation). Based on the data shown in Tables 1 and 2 and Fig. 4, it can be concluded that D-connection of the stator winding imposes less load on damper bars during unsymmetrical load.



a) detail b) finite element mesh

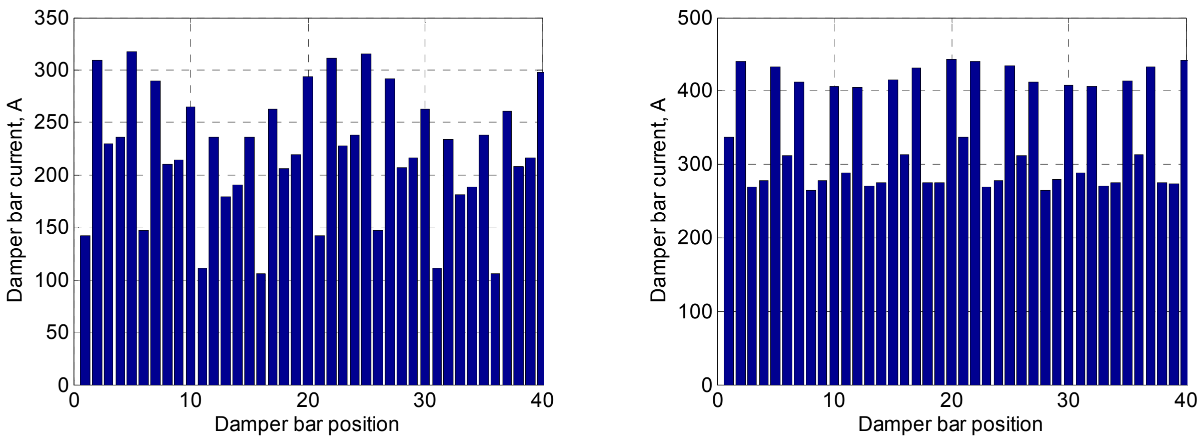
Fig. 3. Finite element model

Table 1 Disposition of currents and current densities in damper bars – D-connection

Bar No.	1	2	3	4	5	6	7	8	9	10
I, A	142	309	230	236	318	147	289	210	214	265
J, A/mm^2	5,03	10,93	8,13	8,33	11,24	5,19	10,24	7,42	7,56	9,37

Table 2 Disposition of currents and current densities in damper bars - Y-connection

Bar No.	1	2	3	4	5	6	7	8	9	10
I, A	337	440	269	279	435	312	412	264	279	408
J, A/mm^2	11,94	15,55	9,51	9,85	15,37	11,04	14,56	9,35	9,87	14,43



a) D-connection b) Y-connection

Fig. 4. Single-phase 200 kVA load, damper bar currents vs. damper bar position

Fig. 5. Rotor with temperature sensors

Fig. 6. Induction motor (left) and synchronous generator (right) on site

Measurements

Temperature measurement probes are thermocouples TS-06, type J for temperatures up to 750 °C and together with remote measurement system TC-link OEM by MicroStrain are used as a rotor temperature monitoring system. The primary use of this system is to monitor the rotor damper bar temperatures during unsymmetrical load when testing single-phase transformers.

The rotor is equipped with 8 thermocouples in total - 4 placed on each side. In Fig. 5 one can observe the temperature probe placed in the rotor wide tooth. In two-pole area of the rotor, two adjacent rotor slots are filled with the iron core material and they represent wide rotor tooth. Of 80 punched slots, 48 are wounded with field winding, and the remaining 32 (2 in each of the 16 poles) have iron inserted in the slots. Rotor has 60 axial cooling ducts. Induction motor - synchronous generator set is shown in Fig. 6. Rotor temperature change during rated symmetrical three-phase load with low power factor is shown in Fig. 7.

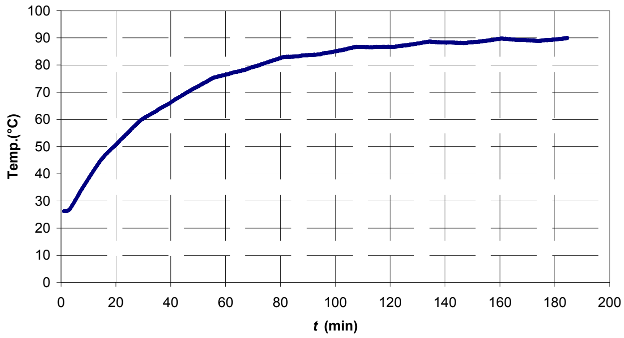


Fig. 7. Measured temperature of the rotor, rated load 800 kVA

Conclusion

Temperature measurement was conducted also for two-phase operation by loading single-phase transformer of 95 kVA at low power factor. The transformer with larger rated power was not available at the test facility. This is less than half of rated load (200 kVA). Therefore rotor temperatures did not exceed 60 °C. The test will be repeated according to the availability of the larger transformer to check the rotor heating at full unsymmetrical load. Besides the above mentioned tests, this synchronous generator was thoroughly tested both in the generator manufacturer's test facility and in the transformer test facility. All tests were performed on both 50 and 60 Hz while only some tests were performed on 16⅔ Hz. Calculated parameters for the rated frequency were confirmed by the tests.

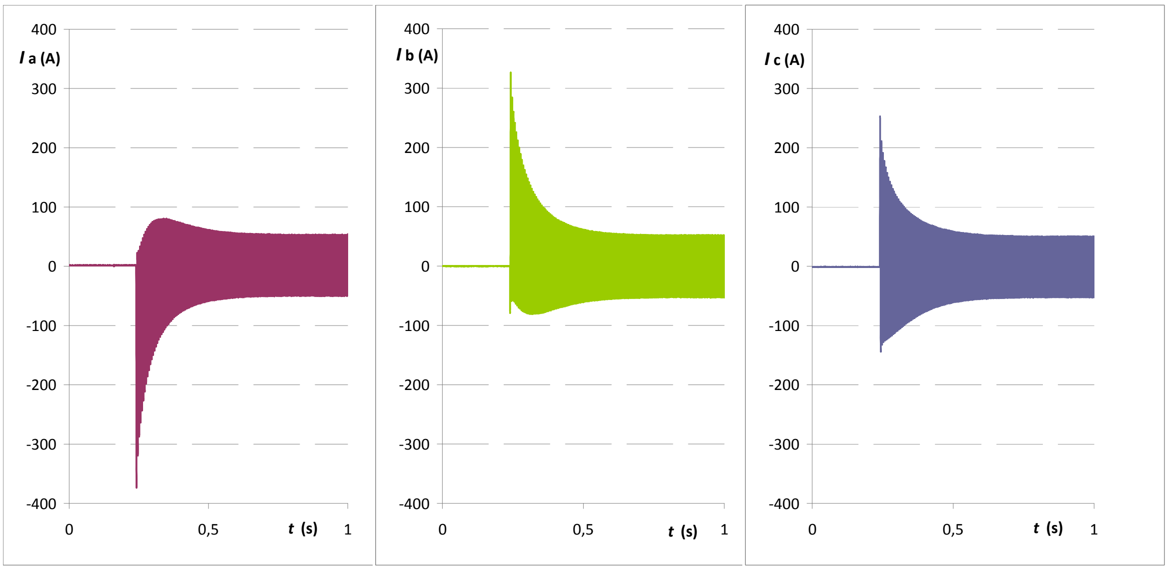


Fig. 8. Phase currents in sudden short-circuit test at 0,72 rated voltage (Y-connected generator)

Synchronous reactances were determined from the no-load test and short-circuit test: 146 % unsaturated and 131 % saturated synchronous reactance. The following parameters were determined from the sudden short-circuit test (Fig. 8): subtransient reactance X''_d = 35.7 %, transient reactance X'_d = 45 %, and time constants T''_d = 6.9 ms, T'_d = 104.2 ms and T_a = 104 ms. The sudden short-circuit test was performed with armature winding connected in Y at the voltage of 3060 V (72 % of rated voltage for Y). Rated voltage of the generator is 3 kV in D connection.

Synchronous generators for testing power transformers should be built practically as synchronous condensers. The practical experience indicates that power transformers of ratings up to 20 times higher than the rating of the generator can be tested. In order to make possible to test both three-phase and single-phase transformers, the damper winding of the generator must be sized to withstand higher values of induced current under two-phase load due to negative sequence component of the stator current. Unlike the standard generators where Y-connection of the armature winding is always the preference, in this case the D connection is more preferable since in two-phase operation it results in lower values of the damper winding currents. But in the case of D-connected stator winding, damper winding of the synchronous generator for transformer test facility must be robust enough to withstand the thermal load in single-phase transformer test. The basic requirement for these generators is to ensure the supply voltage for the transformer under test with low THD so the common solution is to skew the stator slots.

Total harmonic distortion of this generator is 0.467 % at rated line to line voltage. Such low value of THD is very important for a synchronous generator in test facility.

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