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Unsymmetrical load of a three-phase synchronous generator

***Abstract**. The selection of a three phase synchronous generator most suitable to be used as a power supply for testing of single-phase and three-phase power transformers is described in the paper. 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 temperature rise test of single-phase transformers realized by the short-circuit method. The generator's output voltage waveforms in the case of unskewed and skewed stator slots are analyzed. The results indicate that delta-connected generator with skewed stator slots is the best solution.*

***Streszczenie.** W artykule opisano sposób doboru trójfazowego generator synchronicznego jako źródła zasilania dla testowanego transformatora jedno- i trójfazowego. Szczególny nacisk położono na uzwojenie twornika i rozmiary uzwojenia tłumiącego, ze względu na asymetrię obciążenia generatora przy wzroście temperatury w próbie zwarciowej transformatora jednofazowego. Wyniki analizy pokazują, że najlepszym rozwiązaniem jest generator ze skośnymi żłobkami stojana i uzwojeniach połączonych w trójkąt. (**Niesymetryczne obciążenie trójfazowego generatora synchronicznego**).*

Keywords: synchronous generator, unsymmetrical load, damper bar, transformer testing
Słowa kluczowe: generator synchroniczny, obciążenie niesymetryczne, pręt tłumiący, testowanie transformatora.

Introduction

Generators for power transformer test facilities are used for testing both three-phase and single-phase power transformers. In the latter case, the single-phase load (transformer) is connected between two line terminals of the generator (two-phase operation), and additional reactive power is obtained from parallel connected capacitor bank. The generator rated apparent power is defined similarly as for synchronous compensators (power factor cosφ = 0.05 ÷ 0.1), but rated reactive power of the capacitor bank can exceed generator's rated reactive power by a factor of 10 to 20. The active power supplied by the generator must cover relatively small losses of the transformer under test. Due to presence of a significant negative sequence component of the armature winding magnetomotive force (MMF) in two-phase operation, there will be a high current load induced in the rotor damper winding. In order to investigate the possible overheating of the damper winding and rotor of the generator, numerical calculations using finite-element method (FEM) of unsymmetrical (two-phase) load of an actual 5 MVA generator have been conducted.

The problem of unsymmetrical steady state load for a three phase generator is not adequately addressed throughout literature. However, various papers dealt with the problem of calculating the no-load voltage waveform for generator with damper winding [1]-[3]. Karmaker and Knight [4] presented experimental investigations and computer simulation of the field distribution, damper currents and rotor losses in a large salient-pole synchronous machine with skewed stator slots. Knight et. al. [5], [6] compared 2D FEA multi-slice method and "skew factor" method when dealing with machines which have skewed stator slots. Nica and Enache [7] investigated damper winding bar currents and the magnetic field in the different portions of the magnetic circuit for the generator-rectifier system.

Transformer Tests

Two basic tests performed on a newly built power transformer are the steady state short-circuit test and the temperature rise test. The purpose of the temperature rise test is to verify guaranteed temperature rise for oil and windings. The synchronous generator needs to provide the voltage (typically 10-20 %, sometimes up to 40 % of the rated voltage) at which rated current flows through the transformer with short-circuited secondary winding. If the required voltage is higher than rated voltage of the generator, an auxiliary transformer is used.

The transformer impedance is mainly inductive, so a capacitor is used to compensate the reactive power and minimize the required power rating of the generator (Fig.1). The capacitance of the capacitor bank has to be adjusted in order to match the reactive power required by the largest transformer (with the largest short-circuit voltage).

For performing short-circuit tests of regulation transformers (transformers with tap changer, e.g. +12·1.33% and -12·1.33%), it is advisable to run the test for all tap positions once the capacitor bank is selected. Ideally, the capacitance is tuned so that the generator operates at power factor 1 with tap changer in neutral position, while in positions with minimum and maximum voltage the power factor is close to zero (e.g. cosφ = 0.05).

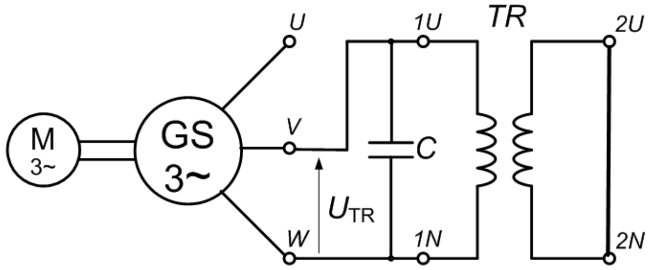

Fig. 1 Connection of a synchronous generator and a single-phase transformer during short-circuit test and the temperature rise test of the transformer

Synchronous Generator Parameters

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 salient-pole generator rated 5 MVA (three-phase load), 1.5 MVA (single-phase load), 50/60 Hz, 3000 V, 4 poles, power factor 0.05 lag. In the design stage, the most suitable armature winding connection had to be determined. The armature winding can be connected in either wye (most common connection type for synchronous generators) or delta (due to requirement for two-phase operation). The third harmonic phase currents are present even in no-load operation in delta connection, but this type of connection is favoured because of reduced negative sequence MMF component. An equal two-phase load with delta connection will produce only 77 % of negative sequence component when compared to wye connection.

Numerical calculations

The generator has a total of 72 stator slots and 13 damper bars per pole. The axial ventilation ducts are positioned inside each stator tooth and on every pole (three holes). The rated operating point is defined with rather small active power load: $5 \cdot 0.05 = 250$ kW and therefore magnetic flux plot is only slightly different than in open circuit due to very small load angle. The flux plots are shown in Fig. 2 for rated three-phase load and Fig. 3 for unsymmetrical load (two-phase connected single-phase load, power factor 0.05).

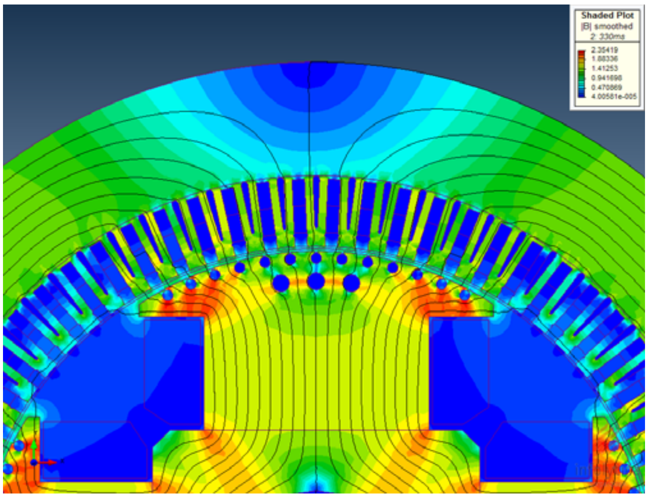

Fig. 2 Magnetic flux of a synchronous generator at rated load

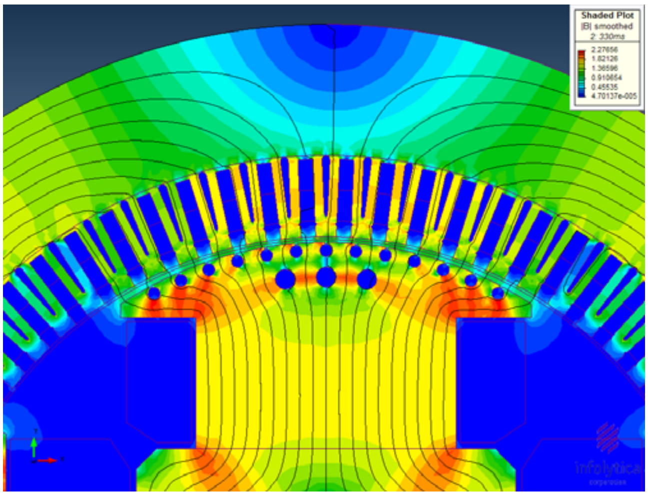

Fig. 3 Magnetic flux of a synchronous generator at unsymmetrical load

The differences in damper bar current distributions between wye and delta connection are shown in Figs. 4 and 5. Damper bar No. 7 is placed in the middle of the pole shoe, and damper bar No. 1 is the first on the left (the rotor rotates counterclockwise).

It can be noted that damper bar currents are approximately two times larger in wye-connection. The largest currents occur in the outermost damper bars.

The differences in frequency spectrum of phase currents between wye and delta connection are shown in Fig. 6 and Fig. 7.

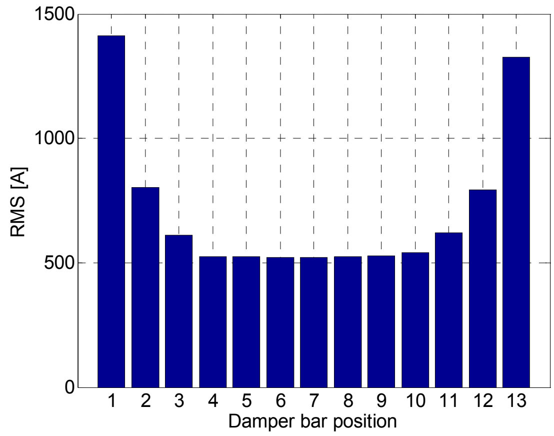

Fig. 4 Damper bar current distribution of one salient pole, two-phase load 1.5 MVA, delta connection

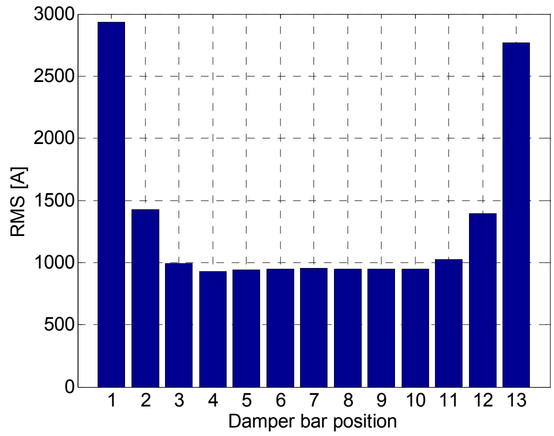

Fig. 5 Damper bar current distribution of one salient pole, two-phase load 1.5 MVA, wye connection

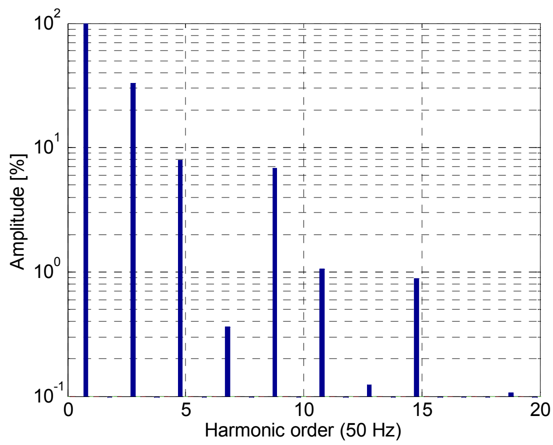

Fig. 6 Phase current frequency spectrum, two-phase load 1.5 MVA, delta connection

The line-to-line voltage waveforms with unsymmetrical load for wye and delta connection are shown in Figs. 8 and 9 with unskewed stator slots.

By skewing the stator slots for one slot pitch, the higher harmonics due to slotting on stator and rotor are substantially reduced. This effect is clearly demonstrated in Figs. 10 and 11.

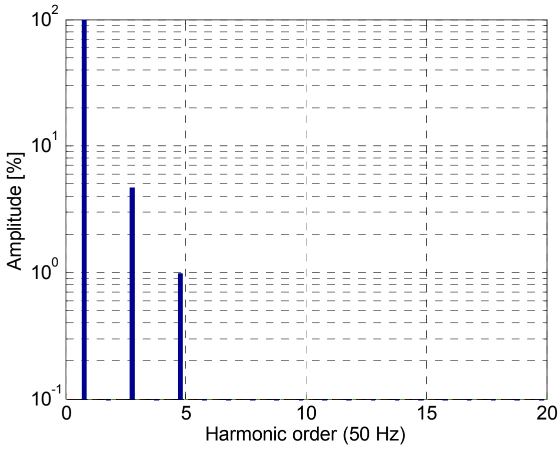

Fig. 7 Phase current frequency spectrum, two-phase load 1.5 MVA, wye connection

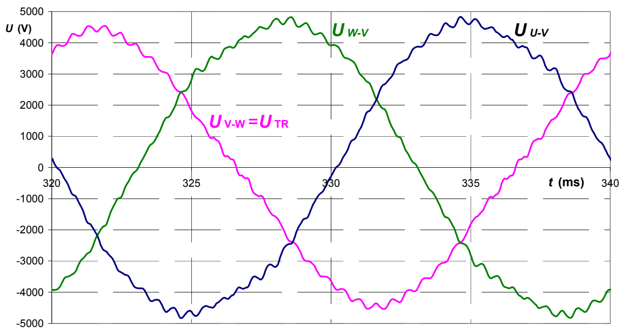

Fig. 8 Line-to-line voltage waveform, two-phase load 1.5 MVA, delta connection

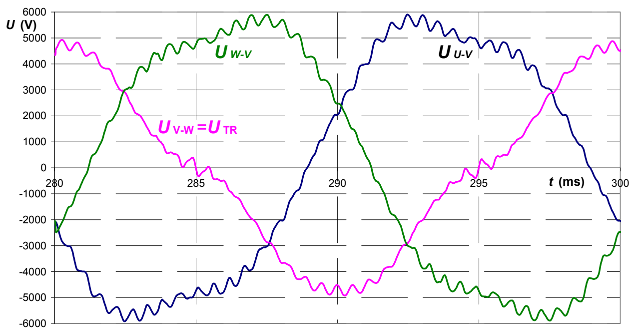

Fig. 9 Line-to-line voltage waveform, two-phase load 1.5 MVA, wye connection

By conducting a series of finite-element method calculations, it has been shown that it is better to choose delta connection for testing single-phase transformers. It is interesting to see that even in no-load operation the damper bar currents cannot be neglected (Fig. 12).

It can be noted that the largest currents in no-load operation flow in the centre of the pole, which is not the case in unsymmetrical operation (Figs. 4 and 5.). For orientation, the current of 76 A corresponds to the current density of 0.67 A/mm^2.

In no-load operation and wye connection the armature winding current equals zero, while the field winding is excited producing magnetic field in the generator. Due to presence of the stator slots, a slight variation of the total magnetic reluctance seen by the field winding occurs, and thus the variation of the air-gap flux density occurs as well as the rotor rotates. Consequently, a variation of the flux linked by the damper winding bars also occurs, which induces voltage in the bars, and since they are all short-circuited, the current can flow. Since bars located in the centre of the pole link the highest flux, those bars will also exhibit the highest flux variation and thus the highest induced voltage and current. In the case of delta connection, the small amount of zero sequence current will be induced which can circulate inside the closed delta connection. This current produces an additional field component which is reflected on the damper winding, thus additionally increasing the damper bar currents by approximately 10 %.

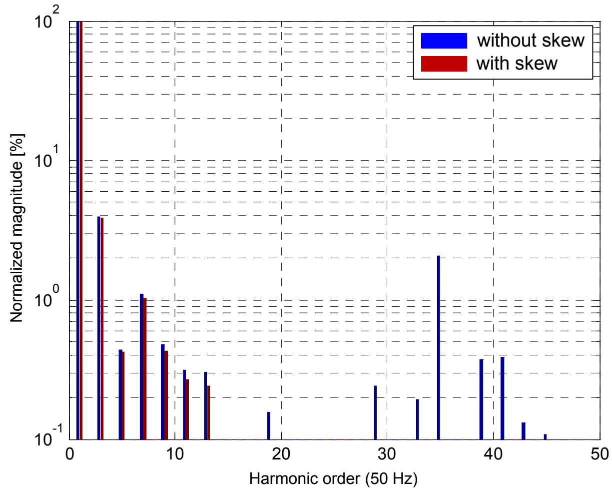

Fig. 10 Single phase load 1.5 MVA, line-to-line voltage, frequency spectrum, delta connection

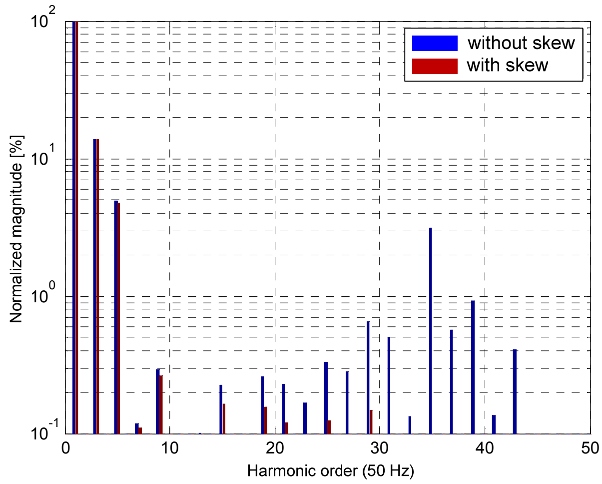

Fig. 11 Single phase load 1.5 MVA, line-to-line voltage, frequency spectrum, wye connection

The damper bar current distribution under rated three-phase load is very similar to no-load operation due to low power factor and small load angle (Fig. 13). The maximum bar current of 264 A corresponds to the current density of 2,33 A/mm^2. It should be noted that currents in the bars 8 to 13 are slightly higher than currents in the bars 1 to 6 because under load the air-gap field axis is shifted towards bars 8 to 13 by the amount of load angle with respect to the centreline of the pole, thus causing higher induced currents in those bars.

In the case of unsymmetrical single-phase load a negative sequence field component emerges which travels at a speed twice the synchronous speed with respect to the damper winding. Since damper winding has no conductors in the interpolar space and the short-circuit rings connect all the bars in all pole shoes, with respect to the negative sequence MMF it behaves similar to a squirrel-cage of an induction motor with broken bars. When one or several consecutive bars are broken, the bars adjacent to the broken ones exhibit higher current loads. This is what happens in the generator as well, so the bars closest to the interpolar space have the highest current load as shown in Figs. 4 and 5. Therefore, these bars should have a larger cross-section than the bars in the middle of the pole shoe. This is a somewhat contradictory requirement from the mechanical perspective because the end of the pole shoe has the smallest cross-section and placing a bar with larger diameter in that location yields higher mechanical stress due to centrifugal forces unless the entire pole shoe is made thicker, which in turn increases its weight and reduces the available space for the field winding. This may lead to the necessity to increase the diameter and the cost of the entire machine in order to satisfy the mechanical constraints of the pole shoe, thermal constraints of the damper bars and provide the necessary space for the field winding.

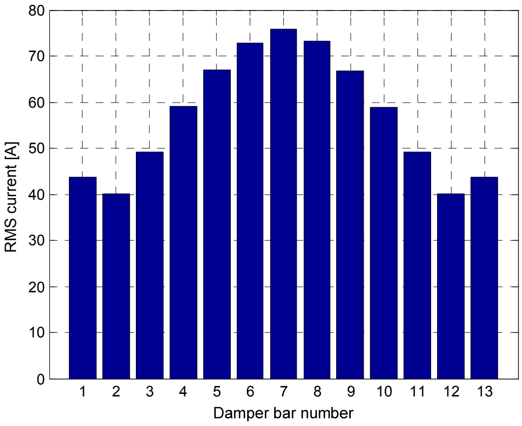

Fig. 12 No-load, RMS currents in the damper winding bars, delta connection

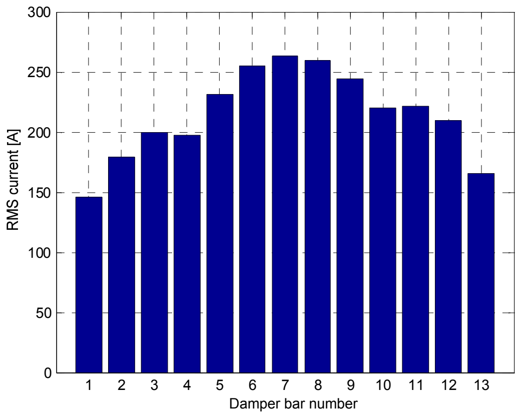

Fig. 13 Rated load, RMS currents in the damper winding bars, delta connection

Plot of the current density in the outermost damper bar vs. apparent power of the load in two-phase operation (power factor 0,05) is shown in Fig. 14. The line in the plot connects three points calculated for the following load conditions: no-load operation, two-phase load of 1500 kVA and two-phase load of 2500 kVA with constant voltage 3 kV connected in delta.

Conclusion

Synchronous generators for testing power transformers should be practically built as synchronous compensators. 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 wye connection of the armature winding is always the preference, in this case the delta connection is more preferable since in the case of the two-phase load it results in lower values of the damper winding currents. 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.

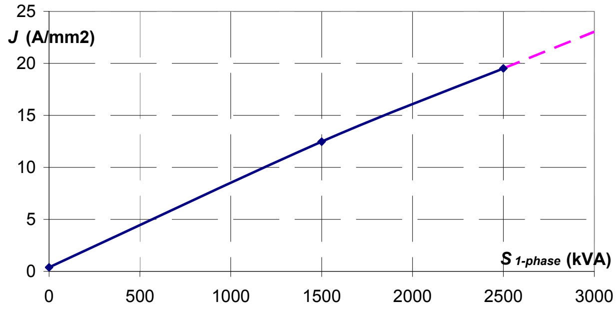

Fig. 14 Damper bar current as a function of two-phase load, delta connection

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