STATOR CORE VIBRATION AND TEMPERATURE ANALYSIS OF HYDROPOWER GENERATION UNIT AT 100 HZ FREQUENCY

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Abstract. The report presents stator core vibration and temperature analysis of a slow-speed salient poles synchronous generator specifically at 100 Hz frequency. The hypothesis of the study states that stator core 100 Hz vibration varies depending on the generator design, slot number, temperature, air gap and generation mode. To verify the hypothesis, measurements in different generation operation modes were taken for the synchronous generator with rated data in March and November of 2014. Research design of the given study includes both analytical calculation of stator core vibration from electromagnetic forces and a case study on site. The report will provide review of the existing standards and publications for stator core vibration and temperature for hydropower generation units. Root causes for increased vibration at 100 Hz will be discussed. The case study results will be presented for different operating modes, including no-load mode and modes with reactive power. Spectrum analysis and timeline charts will be used to present the obtained data.

Keywords: slow-speed generator, stator core, air gap, 100 Hz.

Introduction

Vibration at 100 Hz is an important parameter for hydropower generator condition assessment. The main advantage of detection of vibration causes for each particular machine is a possibility to regulate and fix the vibration levels without extensive repair of the generator, which saves costs for electricity producers. By evaluating the vibration at 100 Hz one could monitor number of parameters of hydropower generation unit, including generator stator winding vibration assessment, winding looseness assessment and stator core radial vibration assessment. In partial discharge measurements 100 Hz is the resonant frequency for current carrying parts vibration. It is known from the operational manuals that vibration of the stator core and frame can cause fretting and damage to the winding insulation, which consequently results into corrosion. The stator core vibration is the main subject of the research in this paper.

The handbooks, which represent fundamental knowledge about rotating electromachinery, state that vibration of 100 Hz of the stator core (or 120 Hz for machines with 60 Hz excitation) is caused by excitation forces [1] and is determined by the generator design, like the number of generator poles and slots [2; 3]. As a particular example, Arrow Lakes unit in Canada experienced such vibration [4; 5]. According to Mike Hoffer, the stator vibration study revealed that the primary frequency of the noise was 120 Hz with an elevated contribution at 240 Hz, and the generators exhibited a high magnetic noise level when the power exceeded 60 MW [5]. The authors noted that the stator vibration, thermal expansion and movements at field excitation need further study.

The specific framework to calculate vibration subharmonics created by electromagnetic force (EMF) on the generator anchor under different load condition exists in electrical machine theory [2; 3]. The authors of the framework suggest that subharmonics caused by the generator structure could have a great effect on stator vibration and could be eliminated accordingly.

Summing up the fundamental theories, the hydropower generator stator frame vibration always contains the following components.

1. 100 Hz vibration from excitation for units with 50 Hz (50 Hz times two) excitation or 120 Hz vibration for units with 60 Hz excitation;
2. 100 Hz vibration frequency determined by the number of poles. Thus, for particular generator with 68 poles and 1.47 Hz rotational frequency described further in this paper, the so called pole frequency would be equal to 68 times 1.47Hz;
3. Poliharmonic low-frequency EMF component (~sum of 1st to 5th harmonics).

The poliharmonic frequency is said to be low, because the hydropower generator is a slow-speed machine. Rotation speed is low, for the particular generator it is 1.47Hz. Then, second harmonic is equal to 2.94Hz etc. Taking into account the slow speed of hydrogenerators Petrov, 1976 in his thesis argued that this fundamental framework is not applicable to them as well as for turbomachinery [6].

There are a number of factors except EMF which affect stator core vibration at 100 Hz like an uneven air gap, hydropower unit design and loose stator parts. Indeed, the uneven air gap can cause the stator core to vibrate. Mike Hoffer noted that generators like those in Arrow Lakes, with small air gaps and 2 circuits/phase stator windings, are sensitive to magnetic imbalance from air gap irregularities [5]. GE stated [7] that by measuring the generator air gap one can detect stator core shifts, stator flexing, loose stator laminations and eliminate vibration. This means that stator frame vibration and the air gap should be changing in a similar manner. Bissonnette in his case studies [8] showed that air gap measurements can be used to evaluate relative displacement of the stator as long as the rotor axis and rim do not move. It was also shown in our previous studies that there are some similarities in the spectrum of the air gap and stator core vibration at 100 Hz [9]. Finally, there could be design specifics of the turbine which cause 100Hz vibration of the unit. Prokopenko in his thesis [10] showed that 100 Hz vibration of the guide bearings could occur as doubled vibration frequency of turbine blades. Also, stator columns could have self-excitation vibrational frequency close to 100 Hz. I.E. Saharov quoted by Petrov (1976), proposed the following equation for stator self-excitation frequency calculation [6]:

$$\omega = \sqrt{\frac{j^2 (j^2 - 1)^2}{j^2 + 1} \cdot \frac{EJ}{mR^4}}\,, \tag{1}$$

where $j = 2p$, and p is 34 (number of pole pairs, 68/2);
m – stator core weight, ≈ 260000 kg;
R – stator core radius, ≈ 5.955 m;
EJ – stator core material properties, usually considered equal to $2 \cdot 10^{11}$ N·m^{-2}, but could be up to ten times less depending on the quality of stator segment connections [6].

In Petrov's thesis [6] some laboratory experiments are quoted where stator core self-excitation vibration was calculated. It was shown that vibration could lay in wide frequency range, and it could also be very close to 100 Hz.

The hydropower generation station maintenance standard suggests that particular attention should be paid to 100 Hz vibration condition depending on the generator temperature [11], therefore in this study vibration and temperature are measured simultaneously. The objective of the paper is therefore to investigate the relation of vibration of the stator core at 100 Hz and temperature. The hypothesis of the study states that stator core 100 Hz vibration varies depending on the generator design, temperature and generation mode. Meanwhile, principal results of the study show that the 100 Hz vibration could not be predicted by calculating subharmonics produced by the generator, and the temperature has only secondary effect on 100 Hz vibration. The primary cause of 100Hz vibration in the given study was the active and reactive load.

Materials and methods

The methodology of the study included experiments on site. Experimental results were obtained on a synchronous slow-speed hydropower generator with salient poles of vertical shaft, umbrella type, driven by a Francis turbine rated at 105 kVA, 88.2 rpm. The hydropower generator of type SAV 1191/147/68 was used for this study. The generator has 504 slots, double windings. The stator has 6 segments. The stator core is built up of silicon steel plates, insulated on both sides with a special varnish and fastened to the frame by means of dovetailed keys.

The measurements were made in different modes, including Runout, speed no load (SNL) mode, synchronous compensator mode (SC) etc. For bearing absolute vibration and general vibration assessment, generator bearings were equipped with two accelerometers, 90º apart, to measure radial vibration, while the turbine bearing was equipped with four accelerometers to measure radial and axial vibration. For shaft displacement, two inductive probes were installed 90º apart on both generator and turbine bearings to measure radial relative displacement. The 3 minutes long signal obtained in each mode was analyzed to ensure statistically correct data. Capacitive proximity probes were chosen for the air gap measurement for the reasoning explained in the previous paper [9]. The statistical and standard deviation analysis of the data was discussed previously [12]. Air gap measurement was highly important during the study because the stator is a flexible assembly that can become distorted or off center [7]. Since we were not sure that the rotor axis is not displaced and rotor rim is connected with spider uniformly, we performed a separate set of tests to measure stator displacement. It is known form the construction specifics of the hydropower generation unit that the upper end of the stator is less flexible, while the lower end expands.

In addition, a laser tachometer kit was used to synchronize the measurement inputs with unit rotation. Stator core vibration was measured by mounting 3 vibration transducers on the stator core/frame upper, middle and lower end on the right side of the 4th segment as shown in Fig.1.

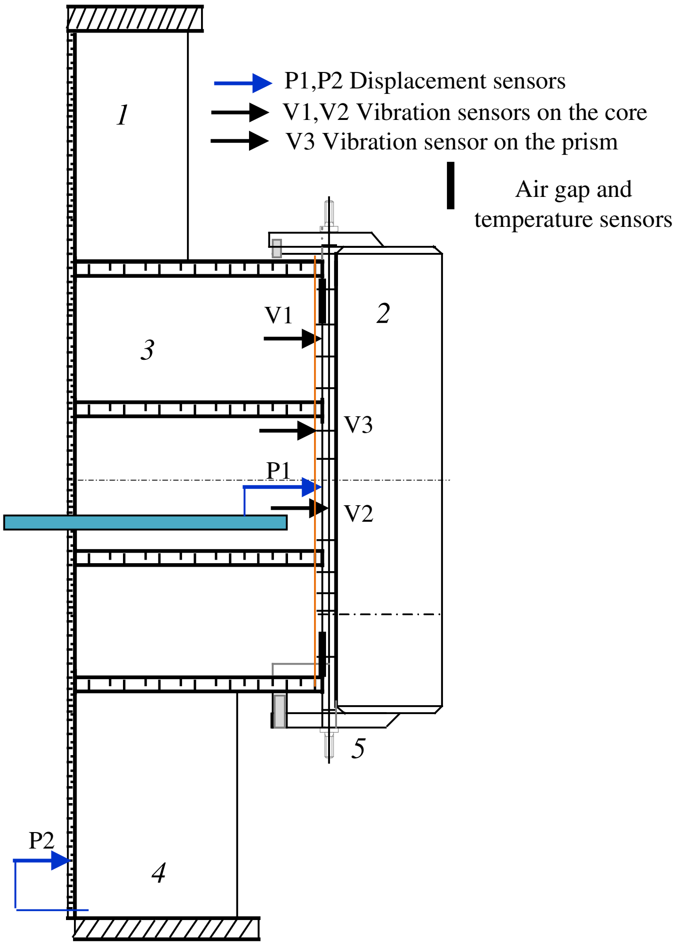

Fig. 1. **Position of the sensors for the measurement:** 1 – stator frame; 2 – stator core; 3 – openings in the shell plate for cooling air flow; 4 – sliding feet plates and foundation plates; 5 – pressure segments and non–magnetic pressure fingers

Temperature was measured separately, using probes (in stator slots and air cooler inlet and outlet) and obtaining pole temperature readings from the SCADA system. Data acquisition was accomplished using National Instruments device on PXI 1031 platform with 16 channels and LabVIEW 8.5, Sound and vibration suite 5.0 software.

Results and discussion

To eliminate seasonality effect measurements were taken in March of 2014 and in November of 2014. The obtained results of stator vibration at 100 Hz temperature in different generation modes are presented in Table 1. From Table 1 the evaluation of the condition could be done. According to the standard [11], vibration is not exceeding the allowed limits. According to STO, the stator core radial vibration, peak-to-peak value in nominal load up to 30 micrometers (μm) is allowed. Vibration up to 50 μm in SNL mode is also considered satisfactory, if only the visual assessment results confirm that corrosion of the stator core and contact surfaces is not significant. However, such assessment is subjective. The recent visual assessment on site revealed that corrosion appears both on the stator core and contact surfaces, while the vibration is far below the allowed limit. Vibration of 100 Hz could be exceeding the allowable limits, because the stator core consists of sheets, and insufficient density of the construction could lead to increased vibration. Table 1 shows that stator core vibration, which is obtained from spectrum, does not exceed 30 µm. In our case vibration is not exceeding the allowable limits [11], but significant corrosion raises some concerns.

Table 1

Comparison of hydropower stator vibration at 100 Hz temperature in different generation modes

Mode	Vibration of stator core, µm, November		Vibration of stator core, µm, March	
	Upper end	In the middle	Upper end	In the middle
SNL with 13.8 kV excitation	1	1	1	0
90 MW 0 MVAr	7	4	7	3
90 MW 20 MVAr	7	4	7	3
90 MW -20 MVAr	6	3	6	2
90 MW -50 MVAr	6	3	6	3
SC -50 MVAr	6	4	8	4
SC -20 MVAr	7	4	6	2
SC 0 MVAr	6	4	6	0
SC 20 MVAr	7	4	6	2

Table 1 also shows that vibration decreases with reactive load, but increases at -50 MVAR in SC mode. Such increase at full reactive load could be explained by vibration of the end-winding region [5], but it is not the main subject of concerns, since generation modes with large reactive power are not typical for hydropower plants.

It should be noted that measurement at SNL mode without excitation was also taken in November, 2014. It was expected that stator core vibration would increase when excitation is added. Instead, it only grew from 0 µm to 1 µm. It means that 100 Hz vibration from excitation (13.8 kV) is equal to 1 µm only, while vibration from active or reactive load is equal to 5-6 µm.

From Fig. 2 a conclusion could be drawn that 100 Hz vibration increases particularly when the active or reactive load is added to the generator.

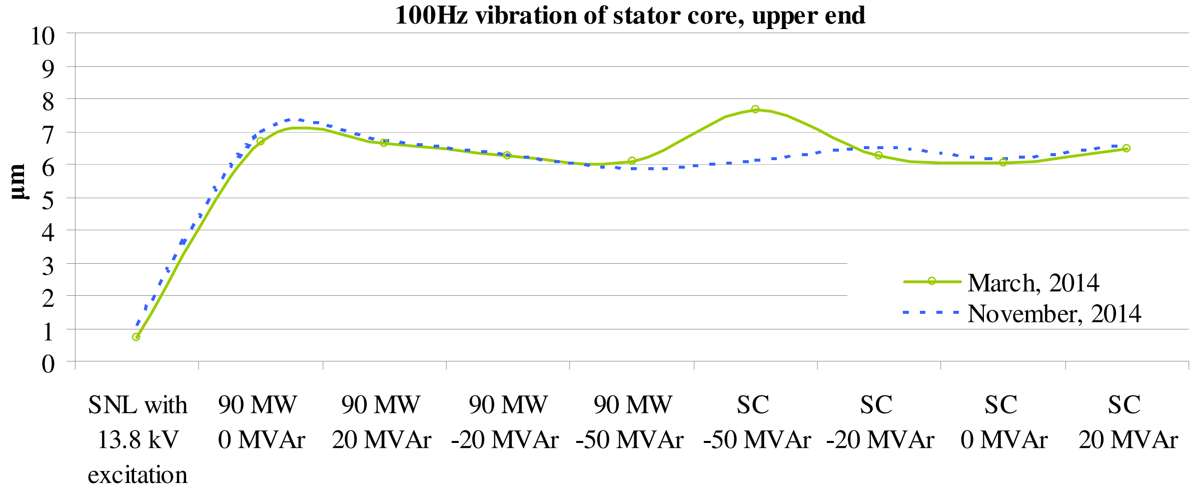

Fig. 2. **Stator core vibration in different modes**

The poliharmonic frequency component was calculated analytically according to fundamental electromachinery frameworks quoted in the Introduction [2; 3] and registered in the vibration spectrum, but the values of the harmonics were very small. The main calculated values are presented in Table 2.

A similar conclusion could be drawn from the spectrum diagrams, where the horizontal axis stands for the frequency of vibration, and the vertical axis stands for the amplitude of vibration. Fig. 3

shows that poliharmonic frequency components do exist near the basic poles frequency (68), but they are smaller than 0.3µm.

Table 2

Vibration of hydrogenerators induced by magnetic waves

Harmonic number	**4**	**8**	**12**	**16**	**20**
Main magnetic wave	7E-10	4E-11	8E-12	2E-12	1E-12
Mechanical resistance	-2E+06	-4E+07	-2E+08	-7E+08	-2E+09
Vibration velocity, $\mu m \cdot s^{-1}$	2.4E-02	1.3E-03	2.5E-04	7.9E-05	3.2E-05

It is shown in Fig. 4 that poliharmonic frequency components remain small, when the active load is added to the generator. One could say that in the majority of the generation modes poliharmonic frequency components are not significant comparing to basic poles frequency (68).

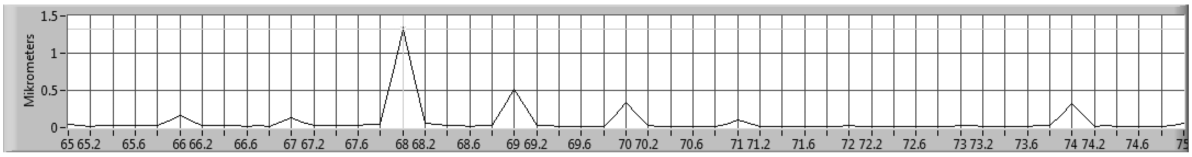

Fig. 3. **100 Hz vibration spectrum at SNL with 13.8 kV**

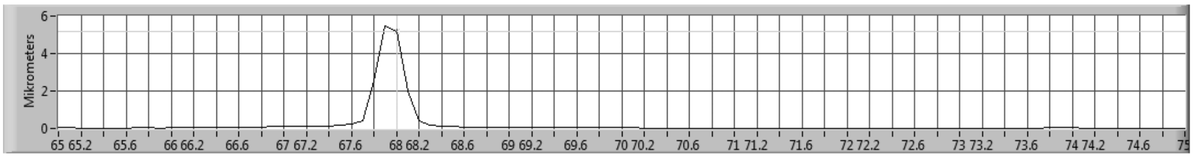

Fig. 4. **100 Hz vibration spectrum at 90 MW load with 0 MVAr**

According to Petrov [6], when the main cause for 100 Hz vibration is non-uniform air gap, the vibration would be the most severe in SNL mode. The air gap is inspected in more details in previous studies [9], and it is relatively uniform for the given unit. Figure 5 shows that the air gap is changing because the stator expands after the heat-up. The change is equal to approximately 2 mm, which is acceptable according to the generator design documents.

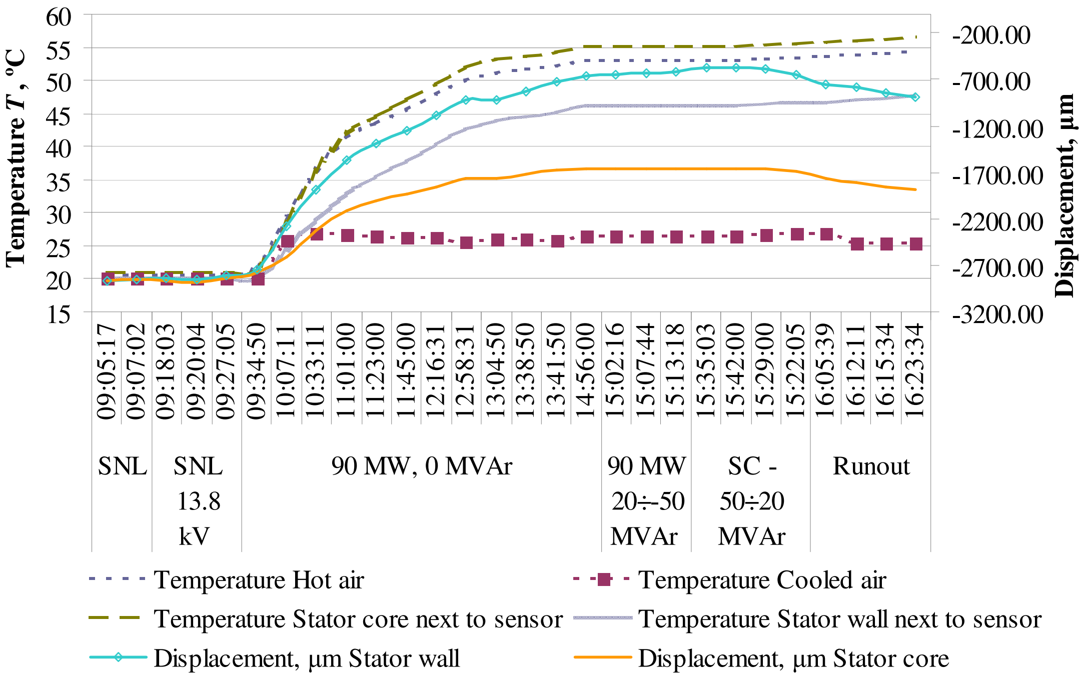

Fig. 5. **Stator wall displacement depending on temperature**

The stator self-excitation frequency requires further research, since information about the material properties E and J from equation (1) are not available up to date. Assuming that the stator wall is a uniform structure means ignoring the important construction specifics, because it is actually composed of sheets. The calculated preliminary self-excitation frequency for uniform structure is too high to cause the resonance effect. Further study is suggested to calculate the material properties of the stator core.

Conclusions

4. Hydrogenerator stator core 100 Hz vibration causes fretting corrosion of the contact surfaces and should be eliminated to avoid hydropower unit damage, since the fatigue cracks and structural damages occur faster on corroded areas and parts of the stator.
5. During the case study it was shown that 100 Hz vibration does result from the generator slot number design. Contradictory to fundamental frameworks the poliharmonic EMF component resulting from uneven number of slots (calculated for poles and phases) has no great effect on 100 Hz vibration. Vibration velocity due to uneven slot number is small, compared to actual vibration.
6. According to the case study results, active load has the most effect on stator core 100 Hz vibration, whereas excitation and temperature has no direct effect on it. Temperature has some minor effect on 100 Hz vibration, because it affects the size of the air gap. It was shown that the stator expands for 2 mm after heat-up, but it expands uniformly, and the air gap is relatively uniform, therefore it is not the main cause of increased 100 Hz vibration.
7. The stator core self-excited frequency could be the reason for resonance, but it should be proven on-site after the mechanical properties of the stator core would be studied.

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