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DETECTING STATOR WINDING BAR VIBRATION WITH ON-LINE PARTIAL DISCHARGE MEASUREMENTS – TWO CASE STUDIES

1 ABSTRACT

In this paper two real-life cases of generator stator winding bar vibration problem and their consequent failures are discussed.

The emphasis is on the analysis of on-line partial discharge measurement results and how the bar vibration phenomenon affects the partial discharge phenomenon of a high voltage generator and how it can be recognized.

2 INTRODUCTION

2.1 Bar vibration phenomenon

In the context of this paper bar vibration phenomenon refers to unwanted and harmful vibration of high voltage stator winding bars inside the stator core slots of a relatively large turbo generator, as a result of forces created by the interaction of the magnetic field of the generator, the geometry of the stator core slot and the magnetic field created by the AC current in the vibrating bar. The term *bar bouncing* is also often used, having the same meaning.

Vibration of the winding ends of a generator is not discussed here, and that phenomenon has primarily different causes and different consequences than the bar vibration phenomenon.

The electromagnetic forces acting on the bars of a running generator as well as the nature of the bar vibration problem are well explained e.g. in reference [1]. The electromagnetic force is pulsating at twice the power frequency (2 x 50 Hz or 2 x 60 Hz).

The pulsating force component towards the slot bottom is maximal in slots where both bars belong to the same winding phase, in which case their currents have no phase angle difference. The force is proportional to the square of the current in the bars. The direct electromagnetic force experienced by the top bar is three times as much as the direct electromagnetic force experienced by the bottom bar. However the bottom bar of the slot is also affected by the pounding created by the top bar, if the top bar is able to move and apply force on the bottom bar. [1], [2]

There is also a tangential force component acting towards the side walls of the slot, but it is significantly weaker than the force towards the slot bottom and it affects only the top bar. [2]

In all cases experienced by the author the failed bar has been the top bar in a slot where both bars belong to the same winding phase.

2.2 Consequences of bar vibration

The consequences and failure mechanisms caused by bar vibration are extensively discussed in references [1], [3], [4], [5], [6] and [7].

The first obvious negative consequence is the abrasion and wear of the main insulation of the vibrating bar, which can be clearly seen both in Picture 1 of Case 1 and Picture 5 of Case 2. In both cases the steel lamination of the stator core has left a distinctive pattern on the main insulation of the failed bar. In Case 2 the main damage was on the bottom of the top bar, which has been pounding on the filler strip between the bars in the slot and was finally punctured.

The second possible consequence can take place in bars having relatively high voltage stress to ground, but not in bars near the star point. When the slot corona protection (graphite electrode) is mechanically damaged by abrasion caused by the vibration, high classic partial discharge activity (called slot discharges in this paper) may take place. Slot discharge phenomenon is also referred as capacitive slot discharges [1].

It is also expected that the nature of the partial discharge activity changes when the damage on the slot corona protection advances. The practical experience of the author is that when nearly all the graphite of the vibrating bar is lost the classic partial discharge magnitude will no longer increase but is stabilized or may even decrease compared to earlier situation where the slot corona protection electrode was only partially eroded.

The third possible consequence is the vibration sparking phenomenon, also called spark erosion or electro-erosion, where the main insulation of the bar is eroded by sparking when the surface of the vibrating bar periodically loses and remakes electrical contact with the slot wall. The electrical sparking is not powered by the phase-to-ground voltage stress but by the difference in electrical potential along the axial length of the stator core, caused by the normal flux of the operating generator. Therefore it is completely separate and different mechanism than slot discharges. Vibration sparking may take place in any bar of the stator winding, including bars near the star point. This phenomenon is also referred as inductive slot discharges [1].

The long term consequence of active bar vibration is almost certainly the puncture of the main insulation and consequent stator winding ground fault. This may be caused by abrasion and wear of the main insulation alone, or the combined effect of the above described mechanisms.

Failures have occurred in less than two years, making this one of the fastest stator winding failure mechanisms [3].

Well designed and fully functional protection system should be able to detect stator winding ground fault and disconnect the generator from the grid automatically. When the stator winding is electrically isolated from ground or grounded through a large impedance the fault current is relatively low and large scale damage to the stator core is unlikely. However, even a single ground fault prevents operating the generator before repair, excluding possible short term emergency operation.

Repair options are in practice partial or complete rewinding or complete new stator.

3 CASE 1

3.1 Introduction and failure

The generator of Case 1 is a 230 MVA air cooled turbo generator with rated voltage 15,75 kV manufactured in 2009.

The generator experienced a stator winding failure in 2014, which was confirmed to be caused by puncture of the main insulation of a vibrated stator winding top bar. The generator was repaired by replacing the failed top bar and returned in operation.

Picture 1. Failed stator winding bar of Case 1. The crater-like appearance is clear sign of sparking, caused by slot discharges or more likely vibration sparking.

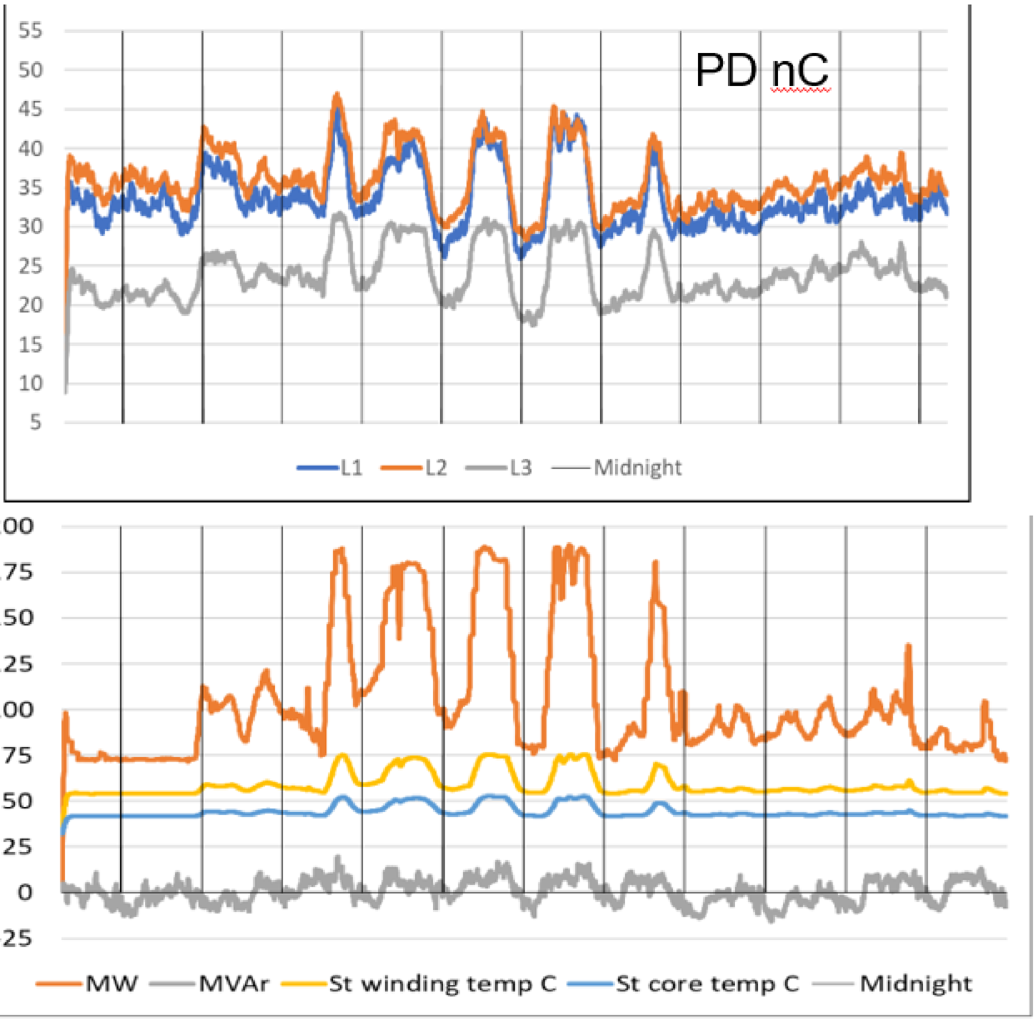
The partial discharge measurements performed after the repair and recommissioning are discussed in this paper, and they strongly suggest that the bar vibration phenomenon further continues in the generator. Unfortunately no on-line PD measurements were performed before the failure.

3.2 Symptoms

Positive correlation between partial discharge magnitude and the power or stator current of the generator is considered to be a well-known symptom of bar vibration. However there are also other mechanisms that can cause that correlation in special conditions. [8]

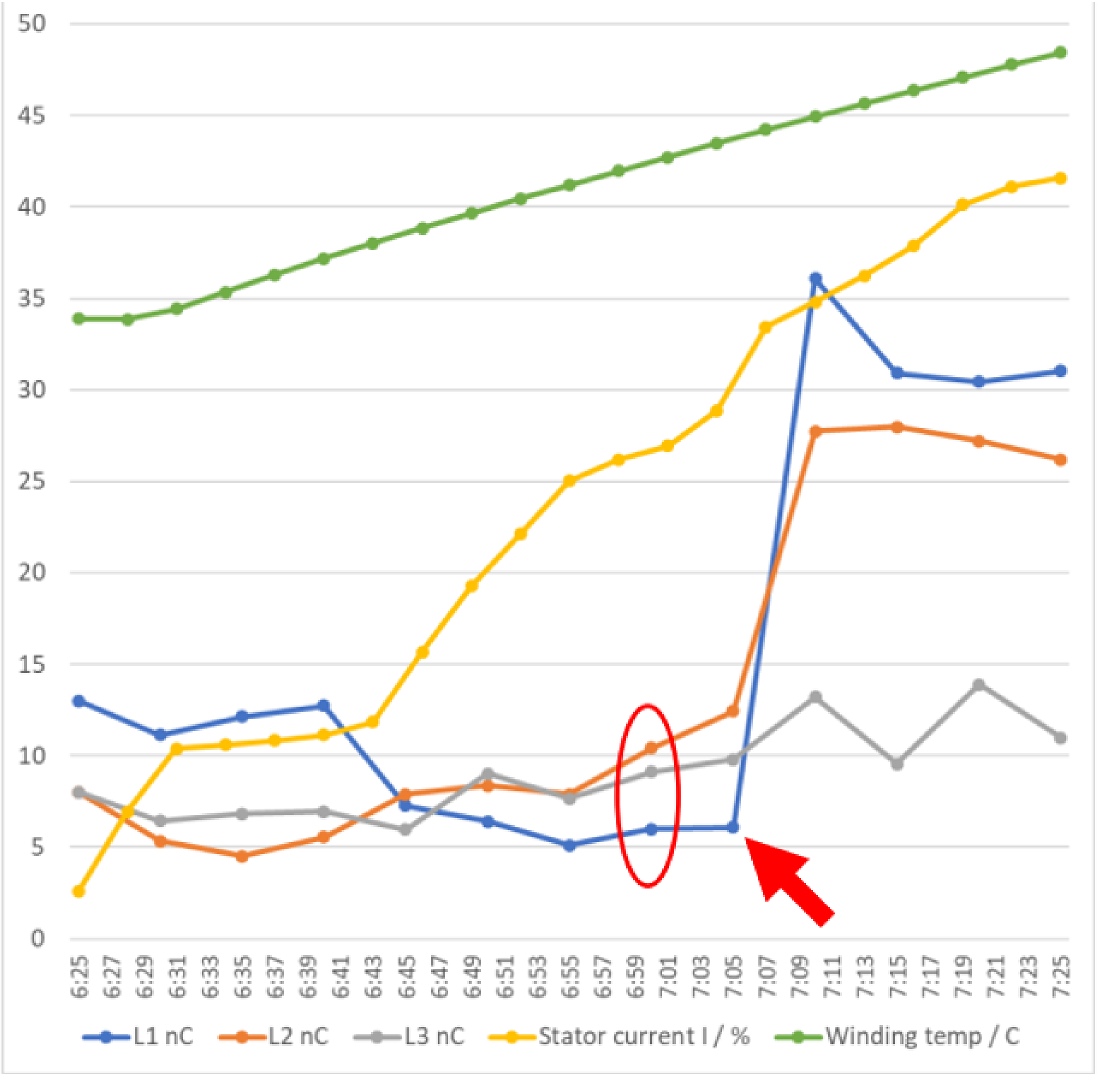
The generator of Case 1 shows clear and strong positive correlation between on-line partial discharge magnitude and the power or stator current, as shown in Picture 2.

Also the PD magnitude itself is high, level below 10 nC could be considered normal or typical, at least in off-line measurements at rated phase voltage [9].



Picture 2. Results of continuous on-line PD monitoring 2021 showing clear correlation between on-line partial discharge magnitude and the power level of the generator. The time between two vertical lines is 24 h. Measured with Omicron MPD600 system (frequency range 100-400 kHz). The signal in winding phase L3 is mainly cross-coupling.

On-line PD measurement was performed also during start-up of the generator. The result in picture 3 shows a clear activation threshold of strong discharges, likely caused by bar vibration, with increased stator current. This can be explained by the fact that the forces on the winding bars causing vibration are proportional to the square of the current.



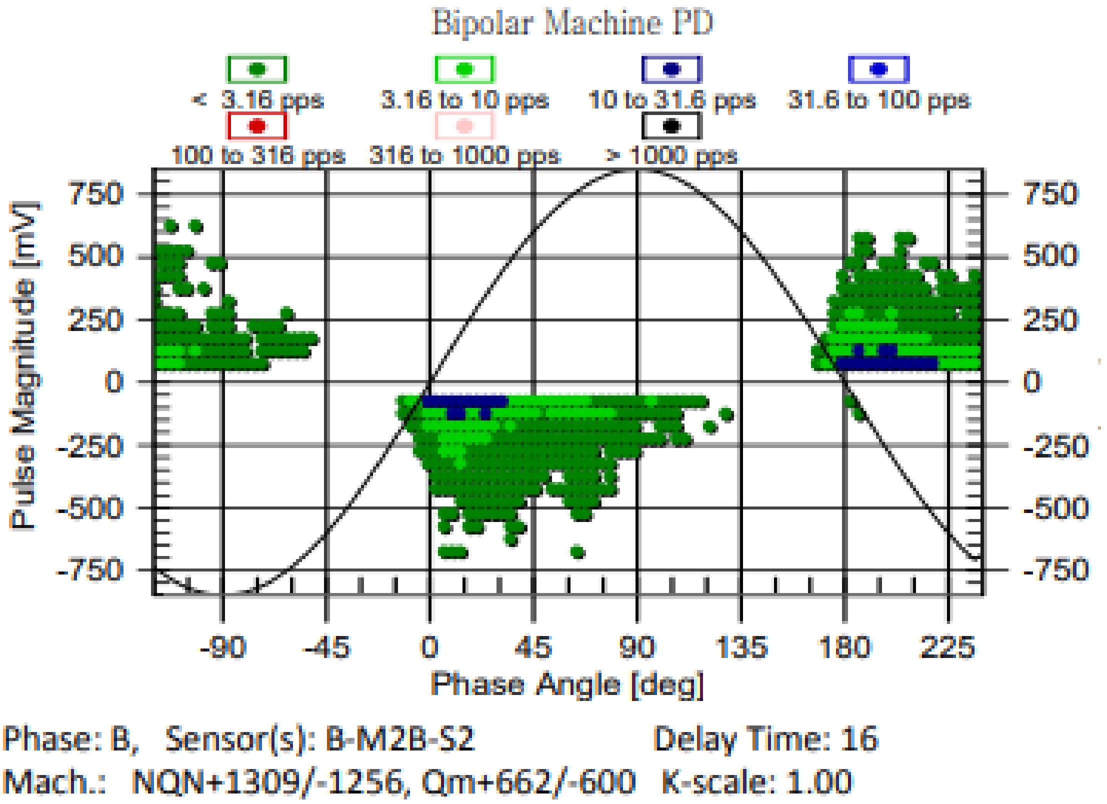
Picture 3. Results of continuous on-line PD monitoring 2021 showing the activation threshold (red arrow) of strong on-line partial discharges during start-up of the generator with increasing stator current. Measured with Omicron MPD600 system (frequency range 100-400 kHz). The signal in winding phase L3 is mainly cross-coupling. Voltage is all the time steady rated voltage and the time stamp h:min is shown on the horizontal axis.

In addition to the behavior shown here the generator has also shown periods of steadily increasing on-line partial discharge magnitude at steady power level, without any obvious reason. It has also shown periods where the on-line partial discharge magnitude was more or less constant despite of changing power level. It can be said that one of the symptoms is the unstable behavior of the on-line partial discharge magnitude.

However, the most common behavior recorded with continuous on-line PD monitoring system is the type shown in Picture 2, clear positive correlation between PD magnitude and stator current.

Picture 4 shows an on-line PD measurement pattern measured with Iris TGA-B system. This is measured in 2021. Unfortunately no on-line PD measurements were performed before the failure. After the failure the on-line PD magnitude has been high in all measurements, with some variation.

The result is high even at less than half the rated output power. Typical or expected pulse magnitude in machine with normal condition would be less than half of the values shown in picture 4. In Iris comparison tables Qm 95 % = 619 [10].



Phase: B, Sensor(s): B-M2B-S2 Delay Time: 16

Mach.: NQN+1309/-1256, Qm+662/-600 K-scale: 1.00

Picture 4. Result of a single on-line PD measurement 2021 of phase L2 at power level 84 MW + 13 MVAr showing high pulse magnitude. Measured with Iris TGA-B system (frequency range 40-350 MHz).

Also off-line partial discharge measurements have been performed. Significant increase in magnitude can be seen in the results of Table 1, but only during recent years, many years after the first failure in 2014.

Another untypical behavior is that the winding phase capacitance demonstrates significant decrease over the years. In 2009 C = 712 nF and in year 2021 C = 669 nF (- 6 %) in the winding phase showing the biggest decrease. This may be caused by gradual erosion of the slot corona protection electrode in vibrating bars. However there has not been any significant change in the dissipation factor of the winding.

PD nC	Phase L1		Phase L2		Phase L3	
	2018	2021	2018	2021	2018	2021
0,4 x Un	0,3	7	0,3	14	0,4	9
0,6 x Un	0,4	10	0,4	20	0,7	14
0,8 x Un	0,6	40	0,8	45	1,0	29

Table 1. Increase in off-line PD magnitude 2018 – 2021 measured from line-end. Measured with Omicron MPD600 system (frequency range 100-400 kHz).

4 CASE 2

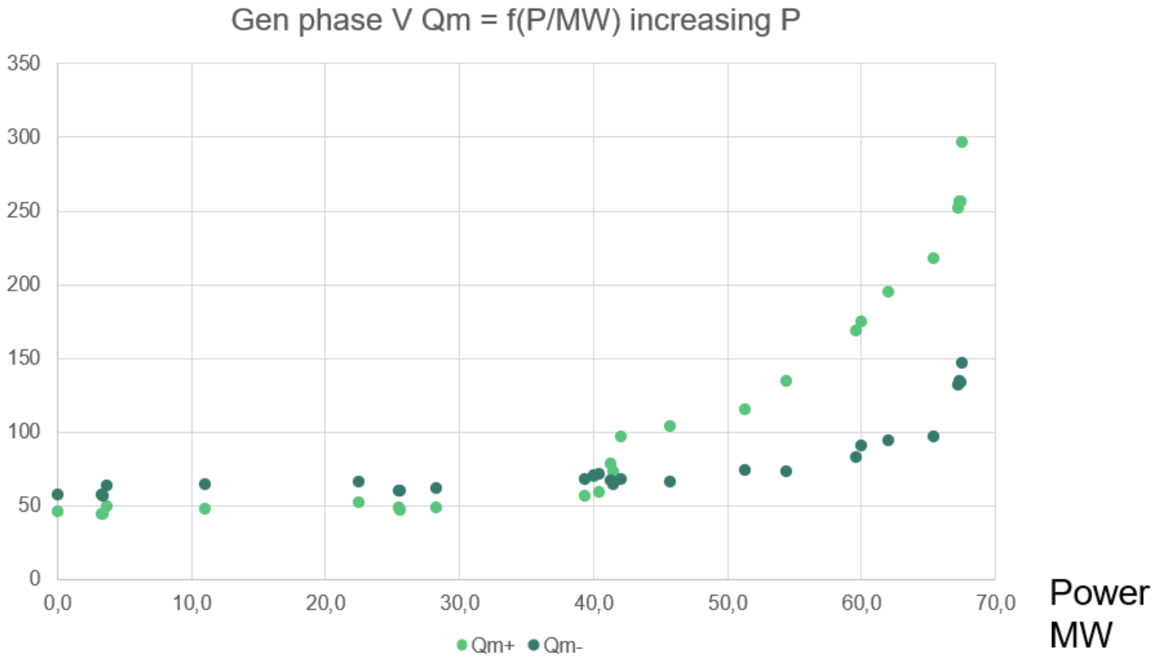
4.1 Introduction and failure

The generator of Case 2 is a 85 MVA air cooled turbo generator with rated voltage 10,5 kV manufactured in 1991. The generator experienced a stator winding failure in 2021, which was confirmed to be caused by puncture of the main insulation of a vibrated stator winding bar. It was repaired by replacing the failed top bar and returned in operation.

Picture 5. Failed bar of Case 2. Bottom of the top bar was punctured (lower picture). The line in the middle of the bottom is caused by the structure of the filler strip between top and bottom bar and is not a feature of the insulation system. No clear signs of sparking (slot discharges or vibration sparking), the erosion appears to be mechanical.

4.2 Symptoms

On-line partial discharge measurement was performed also during start-up of the generator. The result is show in picture 6 and it shows a clear activation threshold of strong discharges, likely caused by bar vibration, with increased stator current. This can be explained by the fact that the forces on the winding bars causing vibration are proportional to the square of current.

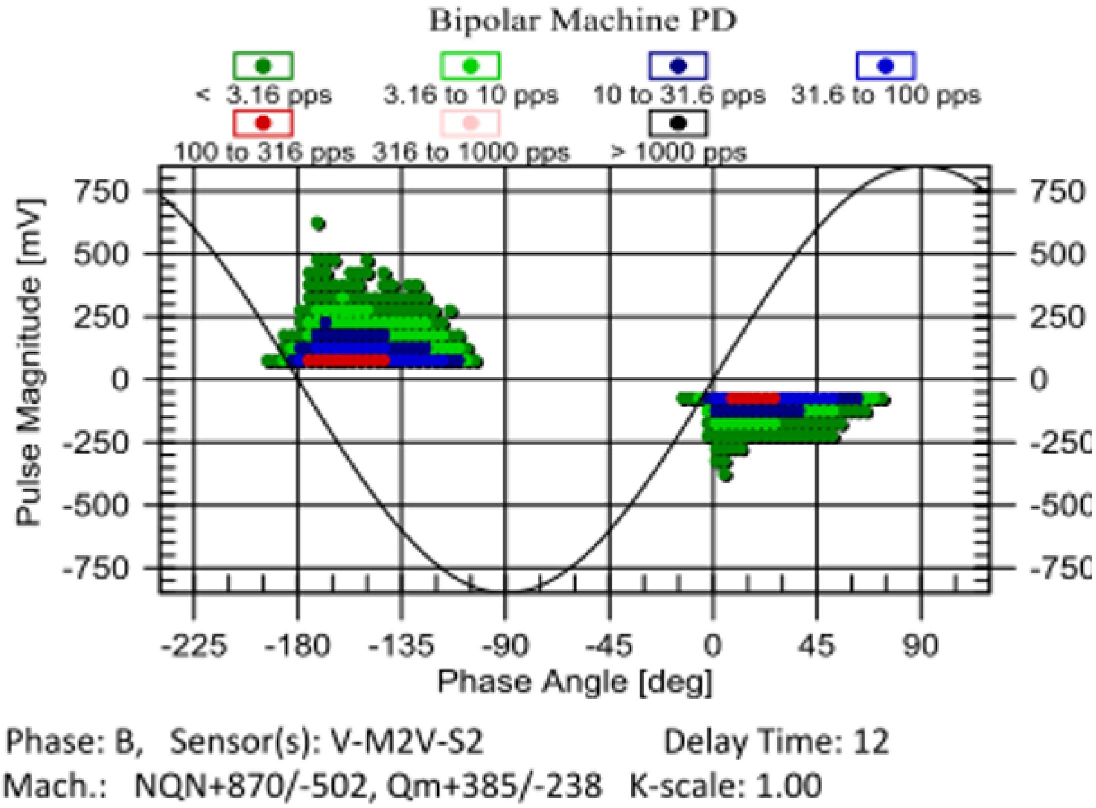


Picture 6. Results on-line PD measurements in 2021 after the repair showing the activation threshold of strong on-line partial discharges during normal start-up of the generator with increasing stator current. Measured with Iris TGA-B system (frequency range 40-350 MHz). Voltage is all the time steady rated voltage. Vertical axis shows the absolute value of parameter Qm.

No continuous on-line PD measurement has been arranged for the generator of Case 2 but positive correlation between partial discharge magnitude and the power or stator current of the generator can be seen when comparing the individual measurements made at different power levels.

Picture 7 shows an on-line PD measurement pattern measured with Iris TGA-B system. This is measured in 2021 after the repair at appr. 90 % power level. The result is high; typical or expected pulse magnitude of a machine in normal condition would be less than half of the values shown in picture 7. In Iris comparison tables Qm 75 % = 196 and Qm 90 % = 415 [10].

The magnitude was clearly lower at least a year before the failure.



Picture 7. Result of a single on-line PD measurement of phase V at 90 % power level showing high pulse magnitude. Measured with Iris TGA-B system (frequency range 40-350 MHz).

5 COMPARISON OF CASES 1 AND 2

5.1 Common factors

Both Case 1 and Case 2 are made with global VPI technology, however quite differently.

In both cases it was possible to replace the damaged top bar relatively easily, because it had vibrated itself totally free (it was not glued in place any more).

No side packing in the slot or ripple springs under the slot wedges was used in either of the two cases.

In both cases the failed bar was a top bar in a slot where also the bottom bar belongs to the same winding phase.

Prevention of bar vibration in global VPI machines relies at least partially on the gluing of the bars on the slot walls by the (epoxy) impregnation resin. This is because generally the GVPI stators can’t be rewedged and thus retightened (there are exceptions) and wedging made before GVPI process may not be as tight as the traditional and renewable ”dry wedging”.

However bar vibration problems are not limited to GVPI machines; we have seen them also in machines made with traditional resin rich technology.

5.2 Case 1 specifics

Case 1 failed the first time some 5 years after commissioning. Therefore it is obvious that poor design or poor manufacturing quality was a significant factor.

It is likely that the vibration started already soon after commissioning and aging of the insulation system did not play any significant role.

The failed bar location was 40 % from the line-end with some 5,5 kV voltage stress → possibly both traditional PD and some vibration sparking. The surface of the failed bar looked eroded by both mechanical wear and discharges.

The vertical fit in the slot seemed to be quite loose, which may have been a contributing factor preventing proper gluing effect of the stator bars in GVPI process.

According to the information given by the manufacturer there is also a separation layer wrapped around the bars, therefore prevention of proper gluing effect may have been also intentional.

After the failure on-line PD measurements from the star point with HFCT were also made, but the results were inconclusive showing mainly excitation peaks.

5.3 Case 2 specifics

Case 2 served well some 30 years after commissioning before the failure. The failure took place soon after approximately 10 % power increase (causing increasing forces on bars), however within the original rating of the generator. The power increase did not cause the failure but it may have accelerated the damaging of the later failed bar.

It is obvious that the bar vibration did not start immediately or soon after commissioning, but aging of the insulation system played a significant role in the failure by separating the bar from the slot wall and enabling vibration.

The on-line PD magnitude did not increase significantly before the first failure, but did show an increasing trend during the first year after the repair and recommissioning.

The failed bar location was 57 % from the line-end with only some 3 kV voltage stress → likely no traditional PD but possibly some vibration sparking. The surface of the failed bar looked eroded mainly by mechanical wear; no crater-like appearance typical for heavy discharges.

6 CONCLUSIONS

It may not be possible to detect dangerous bar vibration early with on-line PD measurements alone without the possibility to compare results obtained at different power levels. This is well achieved with continuous monitoring.

Measurement during start-up at increasing power level (or during shut-down at decreasing power level) may help revealing the bar vibration by showing sudden strong increase in PD magnitude at certain power level, i.e. activation threshold.

If the vibrating bar(s) are far from the line-end, PD measurement may not give any warning at all.

The situation can be further studied in major overhauls e.g. by checking the slot wedge tightness and by looking for direct evidence on bar vibration, e.g. dust accumulation. Off-line PD measurements should be performed both from line-end and star point end of the winding.

Puncture of the main insulation of the stator winding bar is caused by 1) mechanical wear possibly combined with 2) strong classic PD caused by the damaged slot corona protection (if the voltage stress of the bar is high enough) and/or 3) vibration sparking erosion (may take place in any bar independent of the voltage stress).

Both Cases 1 and 2 show that there is no reason to believe that there would be only one vibrating bar in the winding. If there is one, there likely are or will be more; after all the bars are supposed to be identical and they are subject to the same stresses.

Both GVPI windings and those made with traditional methods (resin rich, local VPI) may fail on bar vibration.

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