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Improving generator stator rewind quality and reliability through end-winding impact testing and analysis

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SUMMARY

Rewinding a large utility generator stator is a very complex, time consuming, and costly exercise and so it is no surprise that end-users demand the highest level of quality and reliability. Similarly, both original equipment manufacturers and third-party service providers are expected to stand by their product and workmanship through inspection, testing, and analysis. Therefore, a series of acceptance criteria at various stages of the project must be satisfied prior to re-commissioning. The majority of these will be electrical in nature, evaluating the windings themselves and their insulating systems, namely insulation resistance, hipot, dissipation factor, and partial discharge measurements. However, mechanical evaluation in the form of end-winding impact testing and modal analysis is also increasingly common, which provides an opportunity to validate the end-winding basket support structure design as well as its fabrication and assembly. A significant amount of ongoing work has been performed on the subject of impact testing in recent years, greatly improving guidance and conformity for the testing. However, there continues to be a lack of standardization regarding what constitutes an acceptable result and so details such as allowable limits are typically subject to agreement between the end-user and the service provider.

Performing an impact test requires a fair amount of training and equipment, as well as some experience in vibration analysis. Detailed analysis of the data, on the other hand, should be performed with support from seasoned generator vibration experts as it requires specialized software and knowledge. A rapid turn-around, typically less than twenty-hour hours, from data collection to a preliminary reporting of findings is also required to minimize delays in the rewind process. Additionally, if findings are not deemed to be acceptable, recommendations for remediation should always be made with great care to not have unintended repercussions, which could create other problems and further delays. Even so, modifications may have limited success if there is a fundamental design issue and so what constitutes an acceptable test result may need to be re-evaluated on a case-by-case basis.

The following case study examines a relatively small (75MVA) two-pole turbine driven generator which was initially found to have multiple undesirable characteristics through impact testing and modal analysis. These likely could have resulted in unsatisfactory end-winding vibration in service that may have gone unnoticed for many years as this unit is not currently equipped with online end-winding vibration monitoring. Modifications to the structure were performed which successfully detuned a global mode of concern, as well as greatly decreased the responsiveness of the phase connections within the frequency range of interest (twice line frequency -120 Hz). Ultimately, even

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though the project was delayed slightly because of the need for adjustments, the result was a superior rewind with a significantly improved probability of reliable operation throughout its intended service life.

KEYWORDS

End-winding vibration, turbine generators, impact testing, modal analysis, rewind

INTRODUCTION

The design, fabrication, and maintenance of a large utility electric generator is a unique challenge, particularly for stator end-windings, as these are subjected to complex and powerful electromagnetic forces which are proportional to the stator current squared [1]. Most of the winding is well supported by the grounded core of the generator stator, however the portions that resides outside of the core – the end-windings – present additional difficulties. The support system must both be strong and rigid to contain normal operating forces while simultaneously being compliant to thermal cycling and differential expansion. Additionally, the presence of strong magnetic fields and high voltages limits material selection to good insulators, posing further difficulties.

This is of particular concern in two-pole units which have proportionally the highest percentage of the total winding length dedicated to the end-turns and is of heightened interest in very large units (upwards of 100-300 MVA) due to their high stator currents. Furthermore, additional demand is continuously being placed on both original equipment manufacturers (OEMs) and end-users (utilities) to reduce costs (often by reducing or substituting materials and processes) and provide more flexible operation (more frequent load changes as well as starts and stops). The combination of these pressures has resulted in the recent trend of increasing stator end-winding vibration problems, combined with improvements in early detection [2-7,9].

The subject of this case study is a 75 MVA steam turbine driven generator (Table 1) which was recently rewound onsite. The end-winding vibration data was collected by the rewinder and analyzed remotely by vibration consultants. This working relationship developed from the COVID-19 pandemic as it was determined to be more effective to provide on-line training to the rewind personnel rather than trying to bring vibration specialists to site (and therefore additional potential vectors of contagion).

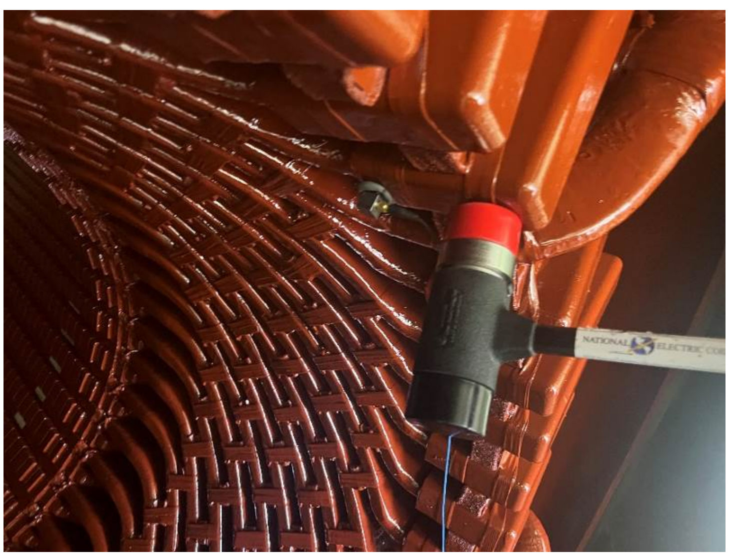


Figure 1: Exciter End – Impact Test Example at Series Connection – Photo courtesy of NEC

Table 1: AC Turbine Generator Nameplate Rating

MVA	75	RPM	3,600	Volts	13,800
KW	60	PF	0.8	Amperes	3138
Phase	3	Hz	60		

OVERVIEW

Impact testing is generally recommended for: new (or rewound) machines, as part of routine inspections at scheduled outages, in response to changes observed from end-winding vibration monitoring systems (and prior to installation thereof for sensor placement), in response to visual inspection findings, post-transient event investigation, as well as before and after major repairs or modifications [2-7]. Testing was performed in accordance with multiple publications and guidelines, namely IEC 60034-32 which offers a solid foundation for end-winding impact data collection and reporting [5], as well as the EPRI bump test guide [6] which helps provide valuable insight on the interpretation and analysis.

The following acceptance criteria were utilized for this example within a 110-140 Hz exclusion band:

- There should be no 2-lobe / 4-node elliptical modes within the exclusion band
    - Typical requirement for 2-pole machines as this mode shape will be readily excited by the electromagnetic force [4-7]
- Warning limit – natural frequencies present within the exclusion band with amplitudes greater than 0.11 [m/s^2]/N in any direction [6]
    - A rather ambitious target, may be conservative for smaller machines
- Alert limit – natural frequencies present with the exclusion band with amplitudes greater than 0.44 [m/s^2]/N in any direction [7,8]
    - A common target for most turbine generators
- Elevated amplitudes may be considered acceptable providing they can be attributed to global modes which can not be excited [6]
    - As this should be addressed in the first criterion above, modes present within the exclusion band will not be of concern

EXPERIMENTAL MODAL ANALYSIS (EMA)

Analysis of the end-winding global "basket" structure identified a mode shape of concern near the primary excitation frequency (120 Hz). That is, a 2-lobe / 4-node elliptical mode was measured at 116 and 115 Hz on the turbine and exciter ends respectively as illustrated in Figure 2.

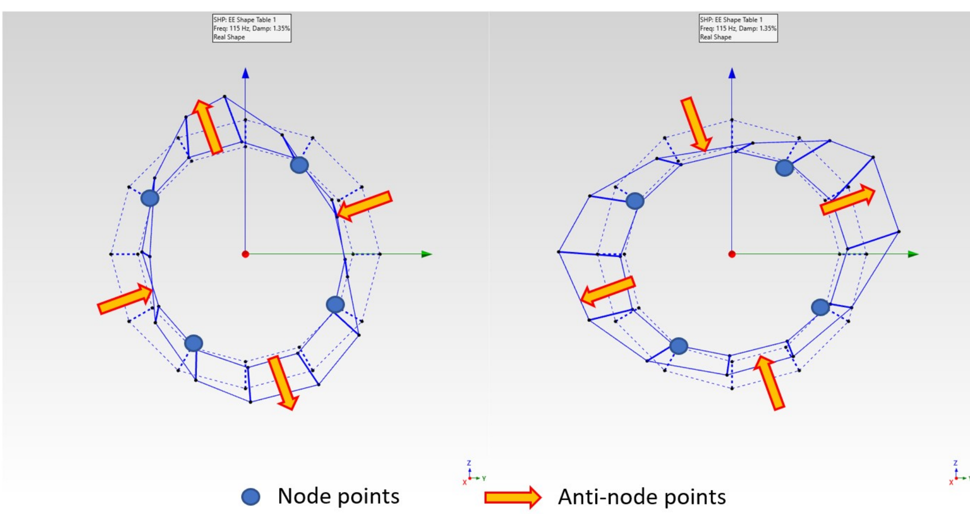


Figure 2: Exciter End "As Found" Elliptical Mode Shape at 115 Hz

It should be noted that the natural frequencies measured at ambient temperature will decrease in service due to higher operating temperatures reducing material stiffnesses [2,4,5]. Therefore, even a relatively small decrease in the natural frequencies of these undesirable modes would provide further separation from excitation (low tuning) reducing the potential for a resonant condition. Investigation of the mode shape provides further insight. Notice the anti-node points at roughly 2, 5, 8, and 11 o'clock positions, these locations of high deflection are good candidates for targeted changes in stiffness and/or mass. Figure 3 below shows the modifications made based on these findings, namely removing the tangential spacer blocks between series-connection end-caps to decrease tangential stiffness at the 5 and 11 o'clock positions on both ends of the winding (highlighted with blue circles).

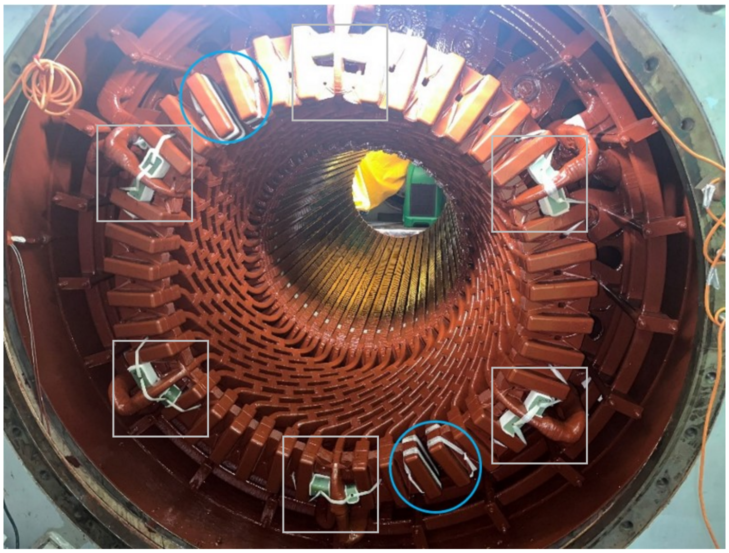


Figure 3: Exciter End – Modifications to Detune the End-winding – Photo courtesy of NEC

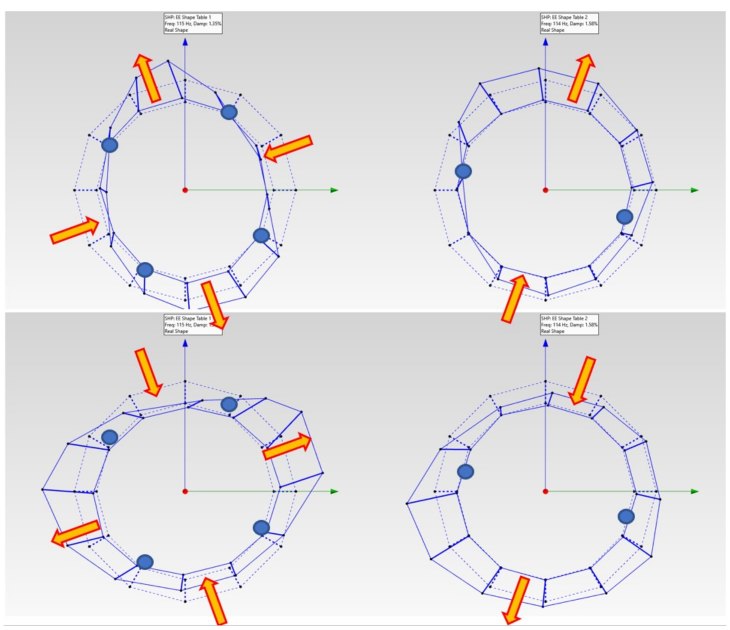


Figure 4: Exciter End Mode Shape Comparison 115 Hz "as found" (LEFT) versus 114 Hz "as left" (RIGHT)

Interestingly, and perhaps counter-intuitively, the follow-up testing indicated that the measured natural frequencies had only decreased slightly to 114 Hz, but it was the mode shape which had changed to a lower order – more resembling a 1-lobe / 2-node lateral mode – as shown in Figure 4 above. By adding asymmetry to the structure at the appropriate locations, the modes of concern are no longer readily excitable by the forces of the rotating magnetic field. A reminder, it is typically recommended to address global modes before moving on to local modes as the former could affect the latter (but the reverse is much less likely) [6].

DRIVING POINT ANALYSIS (DPA)

Several phase jumper connections were found to have moderately elevated levels within the frequency exclusion band, often above the warning limit and occasionally slightly above the alert limit. This was generally on the top bars, in the tangential direction, and several at frequencies which are not attributed to global modes. Local stiffening was applied at all parallel connections to shift natural frequencies above the excitation at twice line frequency (high tuning). See Figure 3 above (highlighted with grey squares) and Figure 5 below (close-up of P4 position) for pictures of the modifications as well as Figure 6 for a summary of the findings and a Frequency Response Function (FRF) plot comparison before and after modifications.

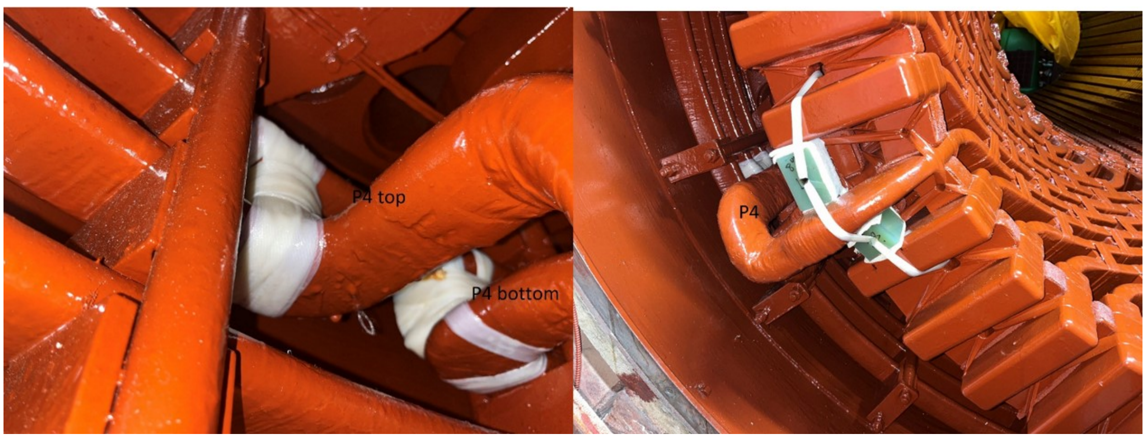
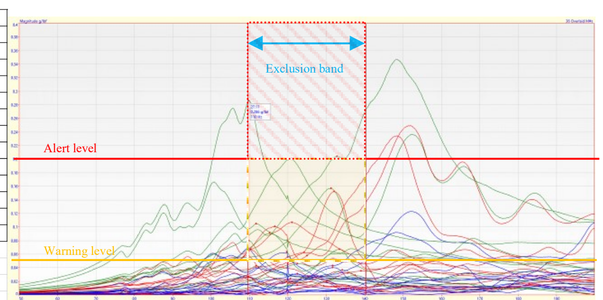


Figure 5: Phase Leads –Examples of Modifications at Position P4 – Photos courtesy of NEC

	Phase Leads - Maximum measured local end turn responses between 110 and 140 Hz			
Position	Magnitude [(m/s2)/N	Frequency [Hz]	Direction	Global/Local
P1 Top	0.6292	110	T resp : T impact	Local
P1 Bot	0.2442	136	A resp : A impact	Local
P2 Top	0.2310	112	T resp : T impact	Local
P2 Bot	0.2838	135	A resp : A impact	Local
P3 Top	0.4488	133	T resp : T impact	Local
P3 Bot	0.1054	120	R resp : R impact	Local
P4 Top	0.4422	121	T resp : T impact	Local
P4 Bot	0.1610	135	A resp : A impact	Local
P5 Top	0.3454	131	T resp : T impact	Local
P5 Bot	0.4400	127	A resp : A impact	Global
P6 Top	0.2222	117	A resp : T impact	Global
P6 Bot	0.0781	139	A resp : T impact	Global
Maximum	0.6292			
Average	0.3026			
STDEV	0.1632			
AVG + 3xSTDEV	0.7922			



	Phase Leads - Maximum measured local end turn responses between 110 and 140 Hz			
Position	Magnitude [(m/s2)/N	Frequency [Hz]	Direction	Global/Local
P1 Top	0.0942	110	T resp : T impact	Global
P1 Bot	0.1197	139	A resp : T impact	Global
P2 Top	0.1797	139	T resp : T impact	Global
P2 Bot	0.1441	131	T resp : T impact	Local
P3 Top	0.1835	137	T resp : T impact	Global
P3 Bot	0.0906	138	T resp : T impact	Local
P4 Top	0.0889	136	T resp : T impact	Global
P4 Bot	0.0891	136	A resp : A impact	Global
P5 Top	0.0627	120	T resp : T impact	Local
P5 Bot	0.1045	131	A resp : A impact	Local
P6 Top	0.0686	135	A resp : A impact	Global
P6 Bot	0.1166	131	T resp : T impact	Local
Maximum	0.1835			
Average	0.1119			
STDEV	0.0393			
AVG + 3xSTDEV	0.2298			

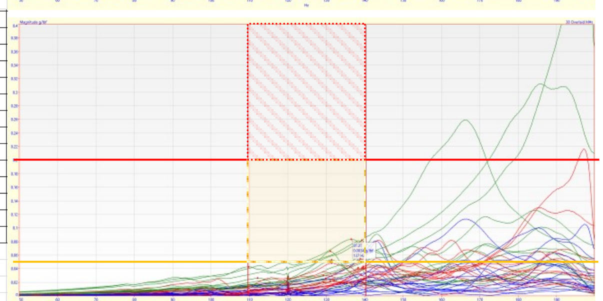


Figure 6: Phase Leads – Summary Table and FRF Comparison
As Found (TOP), As Left (BOTTOM) – Blue = Radial, Green = Tangential, Red = Axial

One challenge to consider with any type of detuning method is that the change of stiffness (and/or mass) should be applied at the appropriate location and in the correct direction to be most effective. Moreover, in the case of a generator end-winding, modifications should not interfere with axial slip planes for thermal expansion. Understanding these limitations is particularly important when examining parallel phase connections which can be difficult to brace due to their relatively longer unsupported spans [6]. It is also important to note that only summarizing "as found" and "as left" conditions, is deceiving. Even with the best equipment and modeling software, an iterative approach is generally required which may take numerous attempts at testing and retesting to achieve satisfactory detuning results as was the case in this example.

Finally, an important disadvantage of the high tuning method to consider is that the materials used in an end-winding support structure will tend to have decreasing stiffness properties over time due to ageing [9]. Additionally, based on experience, most end-winding faults tend to occur due to local resonance problems (point failures due to fatigue). These factors emphasize the importance of both baseline and routine testing as well as robust analysis and data interpretation techniques.

CONCLUSIONS

Examples of both global and local detuning efforts – low tuning and high tuning respectively – were provided using EMA and DPA impact testing methods on the stator end-winding of a rewound 75 MVA generator. Although the unit in question was relatively small by utility standards, and therefore generally less susceptible to end-winding problems than larger units, it is similarly unlikely to be a candidate for continuous end-winding vibration monitoring. Consequently, by investing the time to investigate and address these deficiencies immediately after rewind, rather than waiting for indications at the next inspection opportunity in perhaps years, significant contributions to long-term healthy winding operation were made and a potential issue was remedied prior to inception.

Although there is currently no consensus on what constitutes acceptable impact test results, by combining multiple sources and guidelines it is possible to develop and refine effective procedures and internal standards based upon discussion and agreement between various OEMs, service provides, and end-users. Although large strides have been made in recent decades to improve generator testing and monitoring techniques, namely on the stator end-windings, the development is still ongoing as the cycle of continuous improvement persists. Quality and reliability are improved by setting ambitious – but achievable – targets, adding substantial value to the project. Moreover, this servers as the baseline data set for future reference and trending which will continue to provide ongoing value.

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