A Study of the Pulse Propagation Behavior in a Large Turbo Generator

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***Abstract* – The experiment described in this paper was performed to gain a better understanding of the partial discharge (PD) pulse propagation behavior in the stator winding of a large turbo generator. The winding insulation was drilled at several locations in the slot section and in the end-winding area. A PD calibrator was used to inject artificial PD pulses at these locations. The pulses were then measured at different sites, including at the line terminal, using both a frequency-selective PD measurement system and a wideband digital oscilloscope. The results are displayed using an attenuation matrix where a normalized measured quantity is plotted as a function of distance from the sensor. Several different frequency bandwidths were used to demonstrate the advantages of the apparent charge measurement in the low frequency range.**

Two main pulse propagation modes are discussed in this paper: a) a slow mode and b) a fast mode. Different examples are used to show the effects of pulse attenuation and cross-coupling between bars in the end-winding area.

In addition, some common industry practices related to PD measurement on stator windings are briefly discussed.

Keywords- partial discharges, PD, rotating electrical machines, turbogenerators, stator windings, insulation, cross-coupling

I. Introduction

Partial discharge (PD) measurements have been performed on stator windings for many decades. Nowadays, it is a widely accepted and recommended tool to assess the insulation condition of rotating electrical machines. PD is a localized discharge that partially bridges the insulation and occurs at imperfections and defect sites of stator windings. When it occurs, a current impulse with a certain energy and a short rising time is generated. These pulses contain a broad frequency spectrum and are subjected to several phenomena (attenuation, reflection, inductive and capacitive coupling) as they travel through the winding. Because PD in stator windings cannot be measured where they take place, the measured pulse characteristics differ from those at the location where PD occurs. As it was previously proven by others [1, 2, 4], the frequency spectrum of PD can be divided in two different pulse propagation behaviors: a) the fast mode – a high frequency (HF) content that is inductively and capacitively coupled through nearby components and that is strongly attenuated when traveling the conductor path; and b) the slow mode – a low frequency (LF) content that is conducted through the winding as a traveling wave. The cut off frequency at which the energy of the pulse is equally shared by the slow and fast mode is determined by the winding geometry and construction [2].

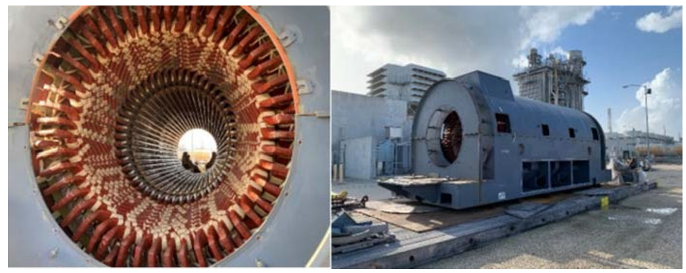

Fig. 1 Pictures of the turbo generator

II. Test Object

The experiment was performed on a 15 kV, 234 MW turbo generator (Fig. 1). The core has 48 slots with each phase having two parallel circuits of 8 turns (16 bars).

The stator core is approximately 4.5 meters long with an inner diameter of 1.25 meters. The overhang area has a length of approx. 1.5 meters.

To be able to inject artificial PD pulses into the stator winding, several holes were drilled in the insulation. Four injection points were created within the slot section of bar T16. Other injection locations were added by drilling in the end winding area of each turn of Phase B. An additional hole was drilled in the middle of the end ring. The stator latter diagram and the winding diagram are shown in Fig. 2 and Fig. 3.

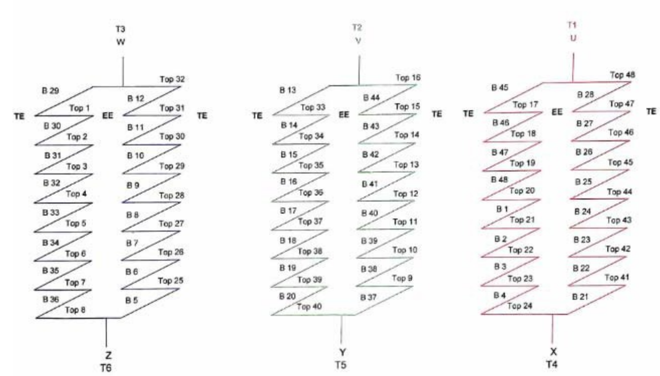

Fig. 2 Stator ladder diagram

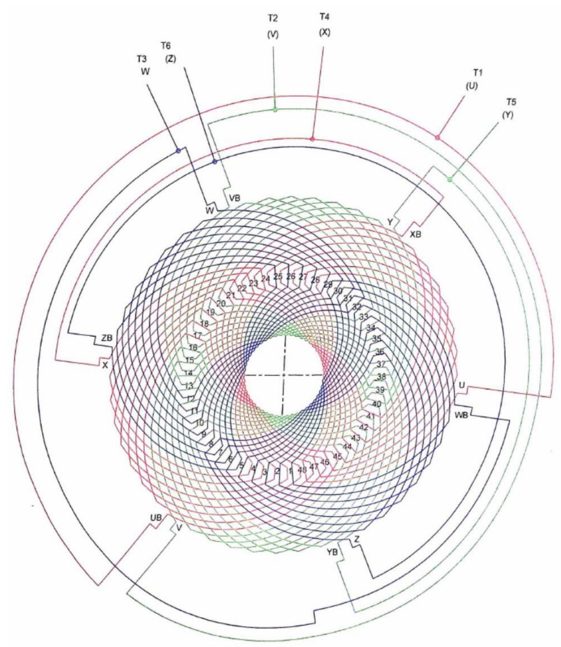

Fig. 3 Stator winding diagram

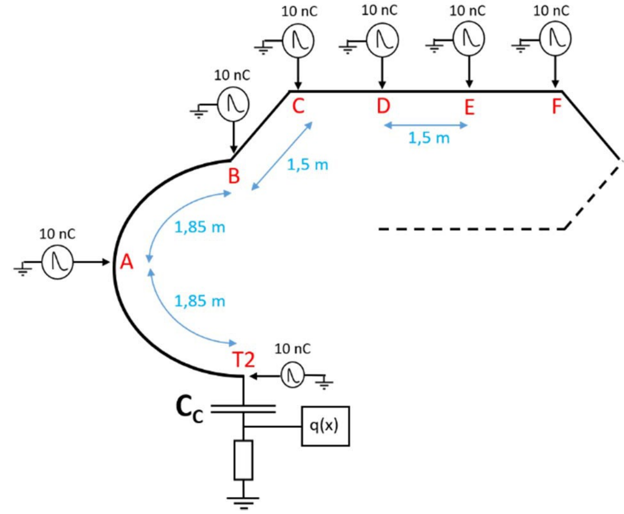

Fig. 4 Schematic of the setup used for the measurements in frequency domain for bar T16

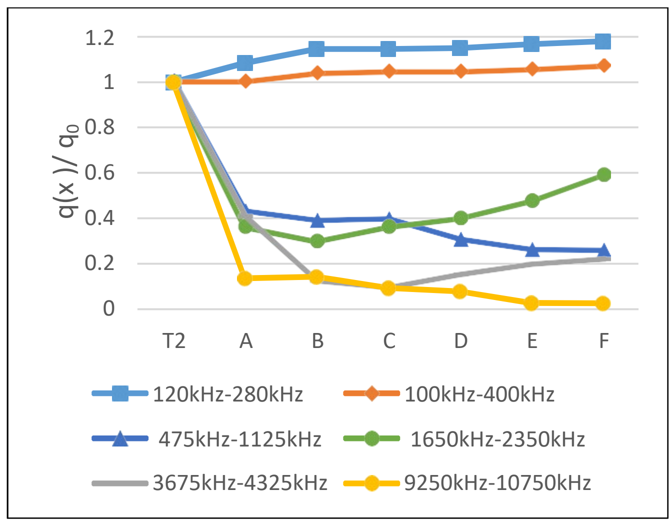

Fig. 5 Attenuation matrix for bar T16 in frequency domain

III. Measurements And Results

A partial discharge calibrator was used to inject artificial PD pulses into the winding. The calibrator is compliant with IEC 60270:2015. The pulses have an apparent charge of 10 nC and a typical rise time of below 10 ns.

The apparent charge was measured at different locations (including the line terminal) of the winding and at different frequencies using a quasi-integrating PD measurement system. The signal was decoupled using a 1.2 nF capacitor. In addition, the pulses were also measured in time domain using a wideband 500 MHz digital oscilloscope.

To investigate the change of the pulse shape from its origin to the measurement point, so-called attenuation matrixes are created for the different measurements. Those graphs display the apparent charge measured at terminal T2 as a function of the injection point and the measurement filter settings. Another graph with the same purpose is used for the time domain measurement. The measured quantities were normalized with the value of the impulse at the injection site.

In addition, experiments were performed to show the influence of energy cross-coupling in the end-winding area.

A. Slot Section – Apparent Charge Measurements

Fig. 4 shows the setup for the apparent charge measurements.

Fig. 5 illustrates the dependency of the measured apparent charge on the filter frequencies and injection sites.

B. Slot Section – Time Domain Measurements

Fig. 6 shows the setup for the measurements in time domain. Impulses of known magnitude were injected at different locations and measured at location B, which is the end of bar T16.

Fig. 7 illustrates the dependency of the measured pulse peak value on the distance between the measuring device and the injection site.

Fig. 8 shows the pulses measured at location B using the digital oscilloscope.

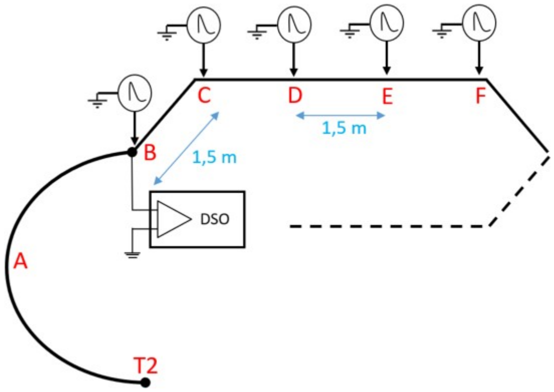

Fig. 6 Schematic of the setup used for the measurements in time domain for bar T16

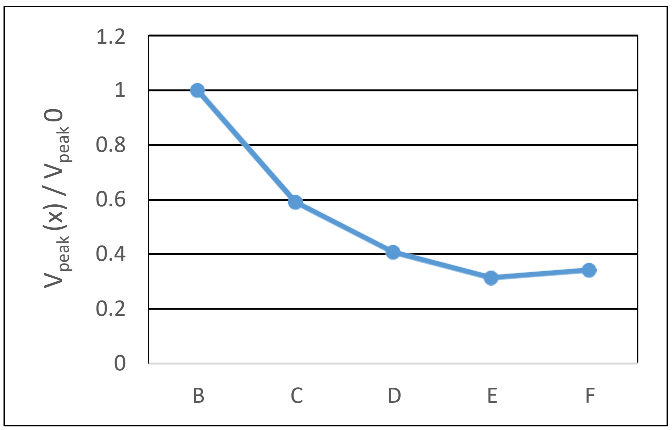

Fig. 1 Attenuation for bar T16 in time domain

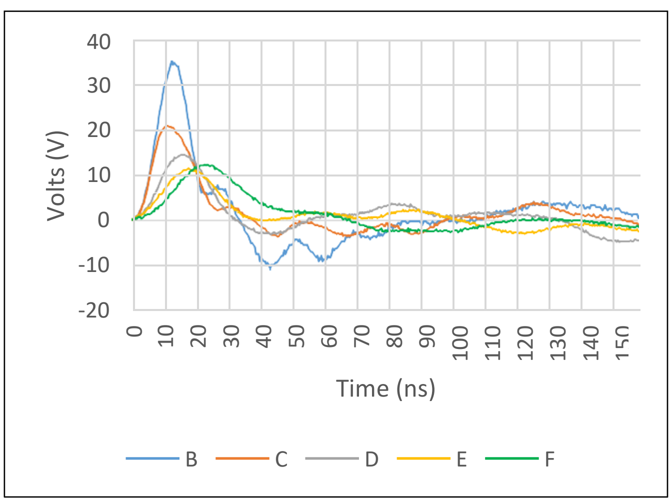

Fig. 8 Measured pulses at location B using the wideband digital oscilloscope

C. *Complete Winding – Apparent Charge Measurements*

Fig. 9 shows the setup for the apparent charge measurements. Similar to the single bar measurement, known impulses with a charge of 10 nC have been injected at different sites along the winding. The measurement of the apparent charge was performed at the terminals as it is done as well during practical measurements.

The results using different filter frequencies of the measurement instrument are summarized using the attenuation matrix in Fig. 10.

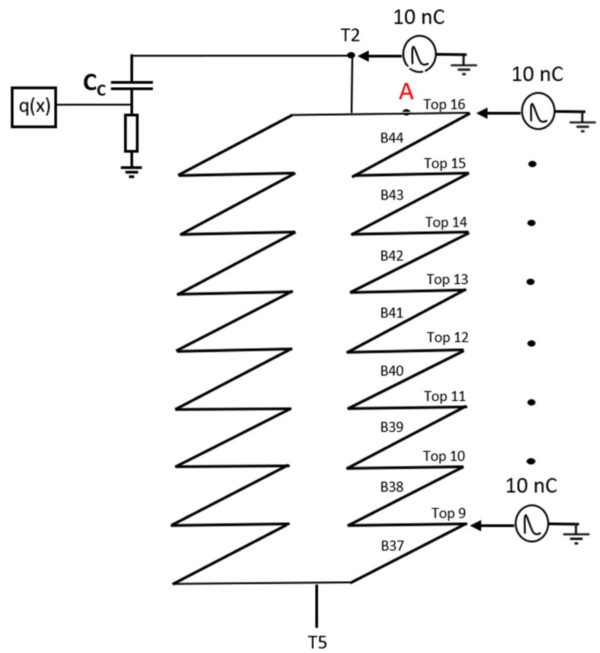

Fig. 9 Schematic of the setup for the complete winding in the frequency domain

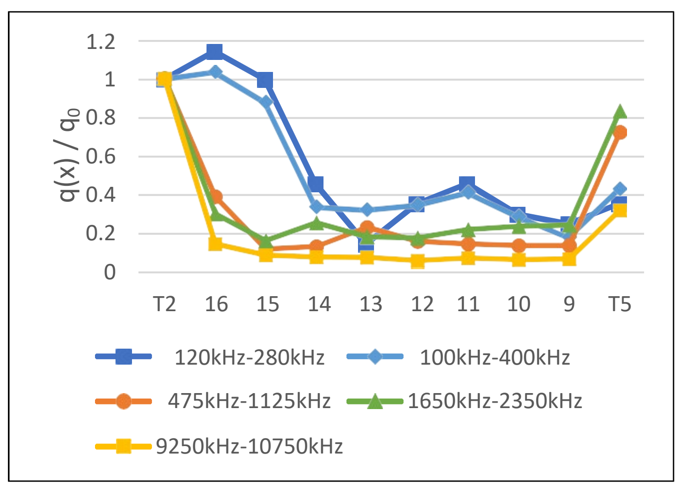

Fig. 10 Attenuation matrix for the complete winding in frequency domain

D. *Complete Winding – Time Domain Measurements*

The same setup was used to measure the pulses in time domain. An oscilloscope was used instead of the PD system to measure the shape of the impulses at the measurement sites. Fig. 11 and Fig. 12 explain the setup.

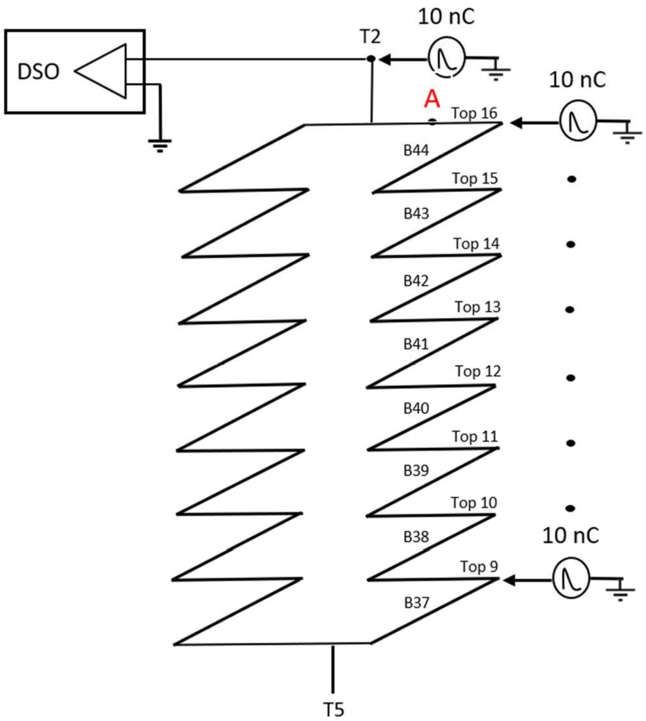

Fig. 11 Schematic of the setup for the complete winding in time domain

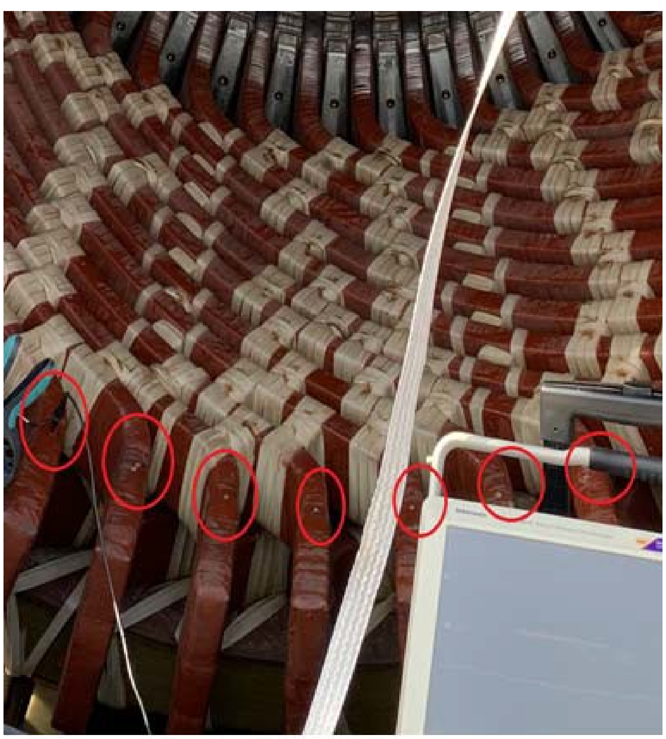

Fig. 12 Picture of the impulse injection sites in the end winding area.

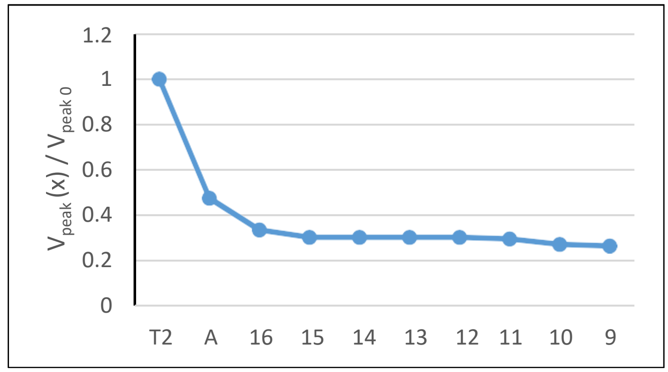

Fig. 13 Attenuation for the complete winding in time domain

The impulses were recorded in mV as a function over time with a resolution of 500 MHz. The high impedance oscilloscope measured the injected impulse as well as the impulse shape at the line terminal. The setup is similar to the frequency domain measurement detailed in the previous section.

The peak value of each signal was analyzed and normalized to the injected one. Fig. 13 shows the results, where on the Y-axis the normalized values are displayed, and the X-axis shows the different injection points along the winding.

E. *Complete Winding – Cross-Coupling in the End winding Area*

To investigate the cross-coupling, a pulse was injected in the end winding area of bar T15. The pulse was then measured in the two adjacent bars: T14 and T16. The end winding of bar T16 was afterward wrapped with grounded aluminum foil in an attempt to limit the phenomenon. Fig. 14 shows a picture of the setup and Fig. 15 shows the measured pulses.

Fig. 14 Picture of the setup with the end winding part of bar T16 shielded

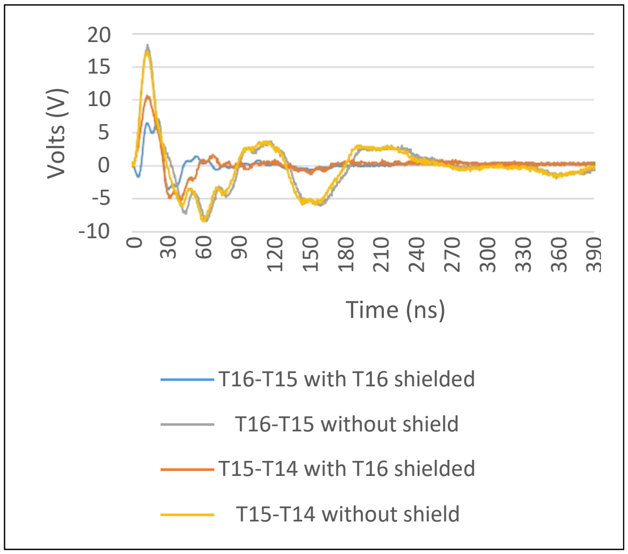

Fig. 15 Measured pulses at bars T14, T15 & T16 using the wideband digital oscilloscope

IV. Interpretation And Discussion

A. Measurements in the Frequency Domain

The results in Fig. 10 show that the coverage zone of a PD system is greatly affected by its measuring frequencies.

When measuring at low frequencies, the injected apparent charge can be detected from the first two bars without significant attenuation. Furthermore, the whole winding can be covered with a measured apparent charge of at least 35 percent of the injected value.

The coverage zone is greatly diminished as soon as the frequencies are increased. At higher frequencies, most of the attenuation occurs between locations T2 and 16, which is the end ring section connecting the first end turn to the line terminal. It has a total length of approximately 3.7 meters.

The experiments show that measuring the apparent charge is more beneficial when it is done in the low frequency range. This can be challenging when dealing with high-level disturbances, such as it is often the case for online measurements. However, advancement in digital filtering techniques has greatly enhanced the capability of online low frequency measurements [9].

An increase in the measured apparent charge at location 11 can be noticed in Fig. 10 for the 120 kHz to 280 kHz filter settings. A possible explanation for this phenomenon might be a superposition of the forward and reflected backward pulses. There are several machine-specific parameters that will influence this phenomenon and therefore, an in-depth investigation would have been needed to confirm the assumption. This was also reported by others [3, 7-8].

The characteristics of the PD pulses are modified within the device under test as they travel through the winding. The PD quantity measured at the line terminals is only similar to the initial value if the discharge occurs near the sensor. This statement is true regardless of whether the apparent charge (pC) or the peak value (mV) is measured. Nevertheless, the measured quantity comes significantly closer to its original value over a large portion of the winding when a low frequency filter is selected.

The experiments also demonstrated the advantages of a frequency-selective PD system. The coverage zone of the winding can be adjusted to the operator needs. If an anomaly is detected during a low frequency measurement, the filter settings can be increased where only the PD pulses close to the sensors would be measured. This way, during offline measurements, PD occurring near the line terminal and the neutral terminal can be separated if sensors are used at both ends of a winding. This provides the engineer with another method to separate sources from each other.

B. Time-Domain Measurements

The results in Fig. 7 show that the pulse peak values are strongly affected by the length of the conductive propagation path. After only one bar (half turn), the measured peak value is approximately 35% of the initial value. As it can be seen on Fig. 8, the high frequency components are rapidly attenuated as they traveled through the bar. The rise time is increased, and the peak value is decreased. The resultant pulse is highly distorted compared to its initial shape. The setup illustrated on Fig. 6 shows that the end ring was excluded from this experiment. It is therefore difficult to draw a qualitative comparison with the measurements in the frequency domain. However, when compared with the results of Fig. 5 and Fig. 10, it is obvious that a better coverage is achieved when measuring the apparent charge at low frequencies.

The stator bar T16 represents 6.25 percent of the total winding length. As mentioned before, when the pulse reaches the other end of that bar, its peak value has already dropped to 35 percent of its initial value. For this reason, no actual limits should be used as the main diagnostic criteria to assess the insulation system of a complete rotating machine winding. This practice could lead to either underestimating or to overestimating the severity of a defect. This is true regardless of whether the measuring quantity is the apparent charge (pC) or the peak value (mV).

Fig. 13 shows that the peak value is quickly attenuated as it travels in the end ring section of the winding. Similar behavior was measured as well when it travels in the straight part in Fig. 7. As it was previously mentioned, the peak value of a PD impulse strongly relies on the high frequencies which are quickly attenuated when traveling along the conductor path. In the end winding area, the pulse magnitude measured at T2 stays constant at 30 percent, regardless of the injection site. This could be related to the cross-coupling taking place between nearby bars in the end winding of the generator.

C. Cross-Coupling Between Bars

A high frequency pulse traveling in the winding of rotating machines is not only traveling through the wire, but is coupled as well into adjacent conductors due to inductive and capacitive coupling. Such phenomenon can occur in the slot sections of stator windings, where usually two bars are installed in the same slot and in the end winding area, where multiple bars are near and run parallel from each other.

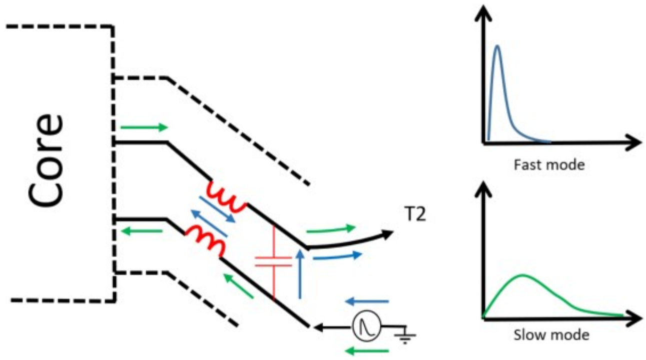

Fig. 16 Simplified schematic of the pulse propagation behavior when injected in the end winding area

The cross-coupling can take place between bars of the same phase and between phases. This phenomenon has been previously studied by different authors [3-6].

Fig. 16 shows a simplified schematic of the assumed path of the high frequency (fast mode) and of the slow frequency (slow mode) components when a pulse is injected in the end winding.

The results of Fig. 15 shows the effects of shielding the end winding part of T16 to reduce the cross-coupling effect in this area. The measured shielded peak value was 33 percent of the unshielded value. This confirms the cross-coupling between bars of the same phase.

The importance of cross-coupling in the end winding area is different for every generator construction. The location where the pulse is injected (where the PD occur) will also significantly influence the phenomenon. Cross-coupling between phases can significantly affect PD measurements especially if performed at high frequencies. A cross-coupling ratio of >1 was recorded in the past by others [5]. This means that the highest recorded value at the line terminals does not come from the same phase, but rather from a discharge that occurs in one of the other two phases.

V. Conclusion

The experiments described in this paper expose some of the major influencing factors of pulse propagation behavior in a large turbo generator. It has been shown that the measurement of apparent charge using a low frequency filter offers a better coverage than when measuring the pulse peak values. If the measuring frequencies are increased, then the measurement of apparent charge and pulse peak values could offer a similar coverage.

The investigations described above illustrate the changes of PD pulses during propagation from the source, through the winding to the measuring point. In the time domain, the pulse is "stretched and shrinks" and hence, strong attenuation of the higher frequency pulse components is observed after a short winding portion. A distinction was made between the slow mode and the fast mode, which represents, respectively, the low frequency content and the high frequency content of a PD pulse. An introduction to the cross-coupling phenomenon was also presented. Its effects were discussed, and explanations have been given for certain behaviors in the studied stator winding.

The reader was warned about the use of limits for measured quantities when performing PD measurements on stator windings. This practice could lead to either underestimating or overestimating the severity of a defect.

The value of using different frequency filters to perform PD measurements on stator winding was also introduced. Measuring the apparent charge at low frequencies offers an extended coverage across a wide portion of the winding while measuring at higher frequencies can be selected to focus on the area near the sensors. This enables the possibility to distinguish between different sources.

It is important to mention that the results in this publication are only valid for the studied machine. Yet, the phenomena and pulse behaviors described are applicable to some extent to a variety of stator windings as it was demonstrated by others [1, 3-6].

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