

Importance of Bandwidth in PD Measurement in Operating Motors and Generators

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ABSTRACT

It is well known that partial discharge (PD) events produce electromagnetic radiation with frequencies from dc to sometimes hundreds of megahertz. In addition, in complex structures such as stator windings, the initial pulses are significantly distorted and attenuated as they propagate through a winding. The detection of the PD pulses needs to account for these effects. In particular, the bandwidth of the detection system will influence the sensitivity of the PD measurement, as well as to what portions of the winding PD can be detected. This paper summarizes over 20 years of research into these effects in stator windings, and discusses the implications for off-line and on-line PD testing, and the calibration of the PD quantities into apparent charge.

1 INTRODUCTION

PARTIAL discharge testing has been used for nearly half a century to evaluate the quality and condition of the electrical insulation in HV motor and generator stator windings. As a quality control test, partial discharge (PD) testing of both coils and complete windings, detects manufacturing problems such as poor impregnation by epoxy or polyester bonding materials. PD is also a symptom of many aging mechanisms such as overheating, load cycling and coil vibration in both air-cooled and hydrogen-cooled machines, although PD activity is less in a high-pressure hydrogen environment. Thus on-line PD testing is now used routinely in ~3500 motors and generators to help plan maintenance requirements.

The widespread application of PD testing, both as a quality control tool and a maintenance planning tool, requires the understanding of what the PD test is measuring, and the significance of the measured signals. Specifically, used as a control test by users who desire to establish a level above which PD is unacceptable, it enables users to reject poorly made windings or coils. In maintenance planning, users want a level of PD above which maintenance is required, but below which the machine can continue to operate safely. It is not likely that these desires can be fulfilled easily, at least for testing on complete windings. This is because complete windings are not lumped capacitive elements, but are complex transmission lines with significant inductive components. Both ASTM D1868 (in North America) and IEC 60270 (internationally) caution against the calibration of PD quantities into pC in inductive apparatus. Furthermore, the

transmission line aspects of windings yields attenuation and distortion effects which, are highly dependent on frequency. The result is that the PD test on complete windings is at best comparative, and is definitely not absolute.

This paper reviews the research that shows the problems caused by the inductive nature of stator windings, and discusses the implications for on-line and off-line PD testing.

2 PD DETECTION

The pulses detected by PD sensors are affected by many factors. In addition to the size, shape, and any gas in the void within the insulation, the detected pulse is a function of

1. pulse characteristics of the PD at the origin,
2. applied voltage,
3. location of the PD site (slot or end winding),
4. distance of the PD site to the PD sensor.

2.1 PD BANDWIDTH

In the past 25 years the availability of high speed analog and digital oscilloscopes has shown that the majority of individual PD pulses occurring within solid dielectrics have very fast risetime of 500 ps to 5 ns [1-5]. If the current pulse from the PD is carefully measured, the pulse is unipolar, and is essentially non-oscillatory (Figure 1). However, such an impulse in an inductive-capacitive/transmission line network often generates oscillations.

The most common instrument for recording individual PD pulses and oscilloscopes which measure the time domain response. However, a spectrum analyzer records the PD in the frequency domain, i.e. it plots the signal level at each frequency. The frequency domain characteristics of a stream of PD pulses can also be calculated using Fourier transforms [6]. The Fourier transform of a stream of pulses, as does the response from a spectrum analyzer (Figure 2), shows a flat/there is a strong dc (i.e. 0 Hz) component, and then a decrease in signal level, when the frequency increases to infinity.

There is often confusion that the low signal levels at high frequencies in the spectrum analysis (e.g. >40MHz), are an indication that there are no high frequencies in a PD pulse; this is not true. As displayed in spectrum analysis, the high frequency level appears to be small compared to the 0 Hz (dc) component. In addition, if the PD pulse repetition rate

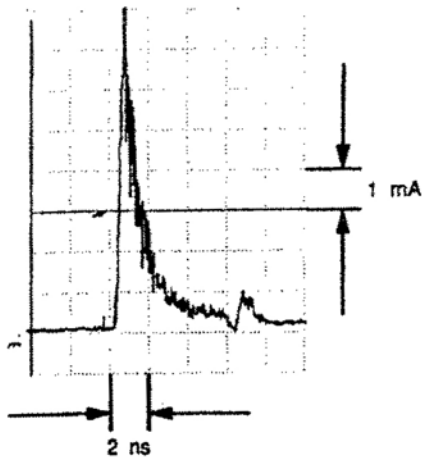


Figure 1. Scope photo of a PD pulse, as published by Baumgartner and Fruth [4].

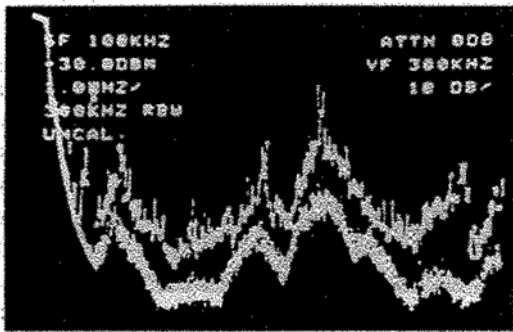


Figure 1. Spectrum analyzer output for a stream of PD pulses occurring in an operating generator, which shows the frequency domain response. Note that at high frequency the signal levels are relatively low. The spectrum covers the range from 100kHz to 35 MHz.

is low, the high frequency content is even easier to lose in the dc component.

The frequency domain characteristics of a pulse stream can be calculated using standard Fourier transforms [6]. Alternatively, several papers [7–9] show how to calculate the spectrum, including the all important upper frequency at which the signal level starts decaying to 0. From these calculations methods, it is clear that pulses, such as those shown in Figure 1 produce frequencies into ~300 MHz. To a first approximation, this can be seen by making the unipolar pulse shown in Figure 1 into the first half cycle of a sinusoid. The unipolar pulse in Figure 1 has a duration of ~3ns. In constructing the sinusoid, there is a period of ~6 ns. Since frequency is the inverse of the period, the pulse in Figure 1 has harmonics at 160 MHz, For shorter duration pulses, frequencies to 350 MHz are present.

The conclusion is that frequencies are produced which are directly related to the risetime (or duration) of a PD pulse. Thus, PD creates very high frequency signals, which has led to the use of ultra-wide band (UWB) detection methods for a variety of apparatus, including switchgear and rotating machines [3,10,11]. However, there is not much energy at

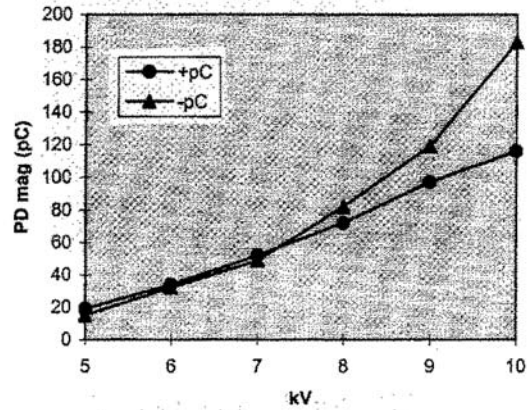


Figure 3. Effect of applied ac voltage on PD magnitude in a 13.8 kV stator coil.

the higher frequencies if the pulse repetition rate is relatively low.

2.2 EFFECT OF VOLTAGE

Another important factor in PD testing of windings is the effect of the coil voltage or the detected PD magnitude, 3n operating motors and generators, the voltage across the insulation in the phase end coil, is the rated line-to-ground voltage (U_n). The voltage drops to zero in the coil connected to the neutral. For a typical winding, there may be 10 coils between line and neutral, Thus the voltage across the coils is $1.0 U_n$ (at the phase terminal), $0.9 U_n$, $0.8 U_n$,... $0.1 U_n$ and 0 in the coil at the neutral. That is, there is a 10% decrease in coil voltage for every coil further into the winding.

It is well known that voltage has a dramatic effect on the PD magnitude, at least if the insulation is not excessively overstressed. Figure 3 shows the effect of voltage on the PD magnitude of a 13.8 kV epoxy-mica insulated stator coil, A 5% reduction in voltage around 8 kV causes 30% reduction in the PD magnitude. A 10% reduction, 60%. Thus, a small decrease in applied voltage causes an even larger decrease in the detected PD pulse magnitude. In addition, at a given test voltage, the number of pulses per second drops exponentially with pulse magnitude (Figure 1). Hence, there is a significantly lower PD pulse count rate at the lower voltages.

This has a significant implication for on-line PD testing, where the voltage across each coil decreases linearly between the phase terminal and neutral. In a typical machine with 1.0 coils, the coil connected to the phase end will have the highest PD activity (magnitude and number), A coil connected one coil down, will have a PD magnitude that is about half of that in the phase end coil, with the same amount of deterioration. A coil two coils down from the phase end, will have a PD magnitude one quarter of the magnitude in the phase end coil, and even fewer pulses. This analysis, plus many years of visual observation of PD effects in actual machines, shows that only the first few coils in a winding suffer the most from PD. There is no PD at the neutral end.

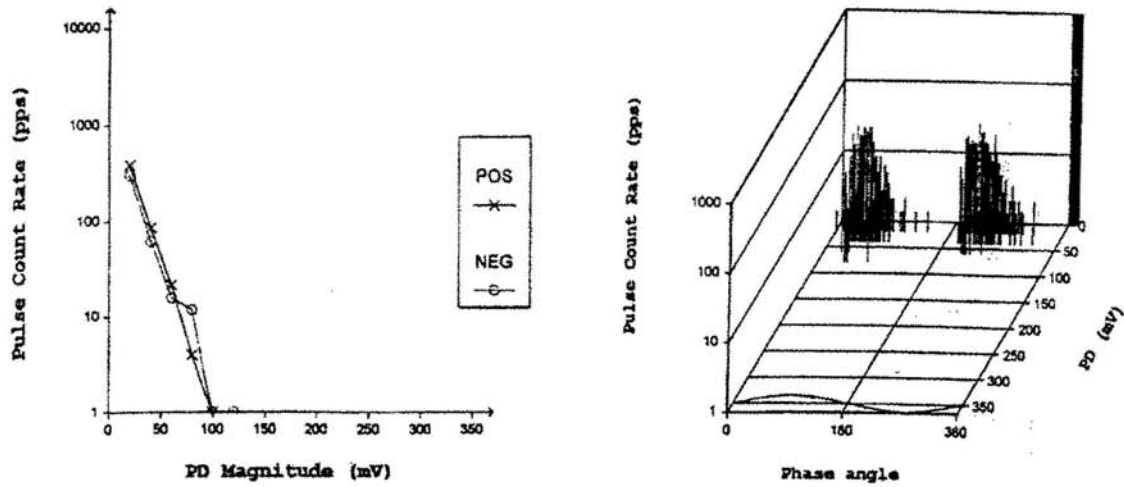


Figure 4. Pulse magnitude and pulse phase analysis of Ehe PD on the stator coil energized to 8 kV in Figure 3.

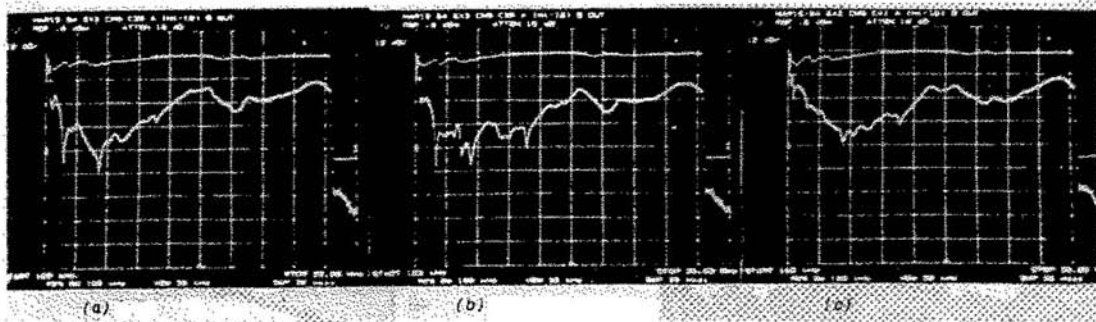


Figure 5. Spectrum analyzer response to a swept sine wave from 100 kHz to 3.5 MHz at different injection points. The vertical scale is 10 dB per division.

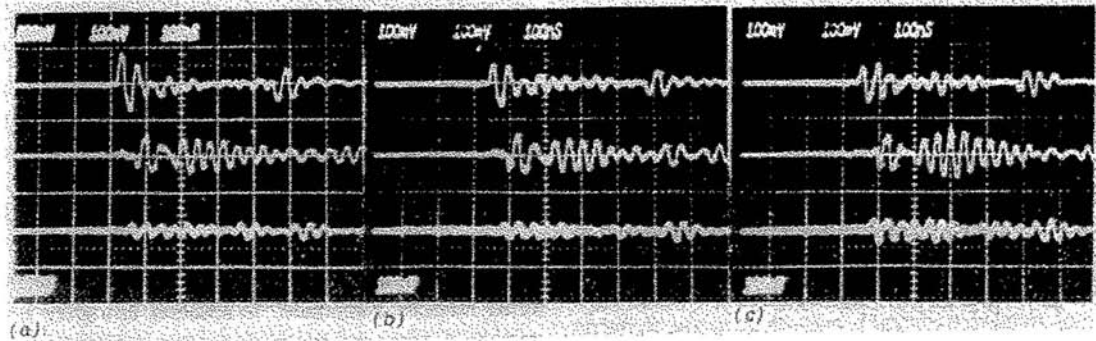


Figure 6. Pulse response at the phase terminal to a stimulated PD injected at various points in A phase. The vertical scale is 100mV per division and the horizontal scale is 3.06 ns per division. (a) Inject at phase end, (b) inject 1 coil down from phase end, (c) inject 3 coils down from phase end.

As noted in ASTM D1868, and IEC 60270, a PD pulse occurring within a stator winding can be changed profoundly by the time it is detected at the phase terminals (or for that matter, at the neutral). Stator windings are complex electrical systems. Within the slot, they have a transmission line character, with a surge impedance of $\sim 30\Omega$, as well as capacitance to ground (typically $\sim 5\text{nF}$). Outside of the slot (end winding), there is no well defined surge impedance, and instead a coil end winding seems to appear as an inductance, with strong mutual capacitance to other coils [12].

A PD pulse occurring with the slot will see a transmission-line structure, and produce the initial high speed unipolar

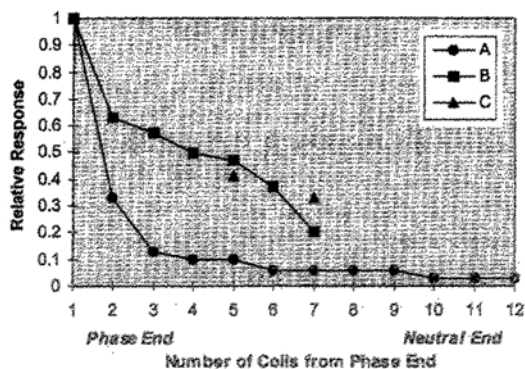
pulse. This is followed by oscillations with frequencies that depend on the slot length and permittivity of the insulation. PD pulses in the end winding will also produce the initial fast unipolar pulse, followed by oscillations that generally will contain different frequencies [13–15]. The result is that a rich variety of frequencies are created by a PD pulse in a winding, with components that reach up to the frequency associated with the pulse risetime.

This burst of frequencies travels through the winding to be detected at the phase terminals. Again, the inductive and transmission line nature of a winding has a profound effect. Figure 5 shows the detected signal of a broadband PD

detector at the phase terminal of a 500 MW turbine generator stator to a swept sinusoid, from 100 kHz to 35 MHz [15]. The measuring instrument is a HP 8568A spectrum analyzer. It is clear that the winding can attenuate the signal from 0x to 100x, depending on the frequency and the location of the source.

Therefore a detector operating at one frequency will detect a large signal, but another detector operating at a different frequency may detect almost nothing above the noise. Although not shown in Figure .5, the attenuation at frequencies above 35 MHz is much stronger. Kemp [14] has shown that, in general, the lower frequency components seem to be less attenuated than the high frequency components. The cause of this frequency dependent response is the L-C nature of a stator winding.

The effect of the winding modifying the PD pulses can also be observed in the time domain. Figure 6 shows the detected pulse due to simulated PD pulses injected at different locations in a 500 MW stator winding, which has 7 coils (each coil consisting of 2 'half turn' Roebel bars) between the phase terminal and neutral. The initial pulse' peak of the detected transient is more strongly attenuated, the further the pulse has to travel in the winding. The initial pulse peak that is detected from a simulated PD that is injected one coil down (i.e. at the $0.86U_n$ point) from the phase end terminal, is 50% lower than occurs in the first coil. The pulse is ~20% of original if it is injected 3 coils down ($0.58U_n$). Figure 7 shows the initial pulse attenuation results from 3 different stator windings. There are large variations from machine to machine, depending on the stator design. Note from Figure 6 that the oscillations after the initial peak are not as attenuated, since they are at lower frequencies.



3 OFF-LINE PD TESTING

The above characteristics of PD and stator windings have several implications for off-line PD testing. In an off-line test all the coils are energized to the same voltage. Thus PD can occur in any coil, even neutral-end coils. Generally PD can only be electrically detected by sensors placed at the phase or neutral terminals. Since there can be a large number of coils between a particular PD site and the location of the PD sensor, significant pulse attenuation may occur, reducing the apparent sensitivity to PD located remote from the sensor.

Since, in general, the attenuation is less at lower measurement bandwidths, it is often desirable to use a r'D detection system which operates at relatively low frequencies. Thus, off-line PD testing is best done with PD detectors operating in the 100 kHz to 1 MHz range in order to be as sensitive as possible to all the PD that is occurring. Note that this assumes that the electrical interference is relatively low, as is generally the case in off-line tests performed with a power supply that is PD free, and connected to the power system via isolation transformers.

4 ON-LINE PD TESTING

There are two very critical differences that distinguish on-line PD tests from off-line tests. In the on-line situation

1. most of the coils are not operating at full voltage. This greatly reduces the PD activity in most coils.
2. the stator winding PD is superimposed on the electrical interference that comes from the power system, to which the stator winding is connected.

The first effect implies that significant PD will only occur on phase-end coils. From the data described above, it is clear that the coil voltage has a much higher impact on the PD magnitude than the winding attenuation effect. The result is that one can choose whatever bandwidth one desires for PD measurements in operating stators; if the PD sensor is located at the phase terminals, it is near the only coils likely to be subject to high PD activity. Therefore, one can detect the PD at either low frequency or high frequency, since pulse attenuation at higher frequencies is relatively small, because the most active I'D sites are close to the PD sensor.

Electrical interference is a factor which can have an influence on the measurement bandwidth. The electrical noise can be as much as 1000x (60 dB) larger than the PD signals from an operating motor or generator, especially if the stator winding is cooled by high pressure hydrogen gas [16]. The interference comes from harmless corona on HV buses and transformer bushings, sparking occurring from slip rings, electrostatic precipitators, power tool operation, power-line carrier communication, radio stations, and switch-mode computer power supplies. This noise can be especially intense at frequencies <1 MHz.

The question to be asked when trying to detect PD in an operating motor-or generator is not-how large is the PD signal, but how large is the PD signal in comparison to the 'noise', i.e. the signal-to-noise ratio (SNR). Boggs [17] shows that if the noise has a broadband (white noise) characteristic, cotam-iftucation theory indicates that the optimum (i.e. highest SNR) frequency band for PD detection, assuming there is little attenuation, occurs at ~250 MHz. This is because the power in broadband (white or electronic) noise increases with the square root of the bandwidth of the measuring system; whereas, the power in the PD signal

increases proportionately, with bandwidth, up to the upper limit set by the PD pulse risetime. The result is that the SNR increases with the square root of the bandwidth. A higher SNR reduces the risk of false indications of stator winding problems caused by noise. This is why UWB (i.e. ~100 MHz) PD detectors have become dominant for on-line PD deflection in switchgear [10,11] and rotating machines [5,16].

Much of the noise encountered in operating machines is not of the white sort, but is pulse-like, for example: corona on HV buses, switching noise, etc. Traditional filtering can not completely remove such pulse-like noise, since, as described above, such signals will contain frequency components at all frequencies, especially if the noise pulse risetime is fast. Hence, any filtering of the noise pulses will also filter the PD, resulting in no net gain in SNR.

It is apparent that alternative methods to filtering are needed to eliminate pulse-like noise. Several methods have been developed based on time-of-pulse arrival from a pair of sensors, or on more complex differentiation of pulse shapes in the time domain [5,16]. Such pulse discriminations are now widely used, and the required specialized sensors are installed in ~3500 machines. The discrimination techniques require the measurement of PD at high frequencies (>40 MHz), since the fast risetime pulse characteristic of PD needs to be preserved so that it can be used as a precise timing signal. Of course, human experts observing data displayed on oscilloscope screens and spectrum analyzers, are also capable of separating the stator PD from the noise.

5 CALIBRATION IN pC

There are two basic problems with using the PD magnitude (whether in pC, mV, mA, etc.) as an indicator of the severity of insulation defects in HV stator windings. The first problem is that PD is often not a cause of failure, but a symptom. The second is caused by the fact mentioned above: complete stator windings are not 'lumped' capacitors. These two aspects are treated separately.

5.1 PD AS A SYMPTOM

In stator windings, the main insulation is now made of mica paper, impregnated with epoxy or polyester. Although the organic epoxy and polyester materials are easily degraded by PD, mica is essentially impervious to moderate levels of PD. Thus the insulation system can withstand the PD (if it is moderate) for many decades. As a result of the presence of mica, the PD in itself does not necessarily lead to failure of the winding. In fact, most stator windings rated 6 kV or more have PD occurring during normal operation; without any adverse consequence.

The PD can be a symptom of the thermal or mechanical deterioration of a winding. PD occurs because these

mechanisms create air pockets. Usually, the more the deterioration, the larger the air pockets, and thus the larger is the PD. However, the actual rate of deterioration is determined mainly by the thermal, or mechanical stresses, and not the PD. Since the PD is not the direct cause of deterioration (although it certainly can have a second order effect), the time to failure is not related to the PD itself causing the insulation deterioration.

For example, if thermal deterioration is occurring, the bonding between the mica tape layers is lost, allowing air gaps to occur, and thus PD. PD is a symptom of the presence of thermal deterioration. However, the magnitude of the PD can still be small, if only small gaps have developed, even though, the insulation has become very brittle and could crack easily. If the PD is increasing over time, the gaps are getting larger indicating more thermal deterioration. Thus an increase in PD over time indicates that more thermal deterioration has occurred. However, the actual magnitude of the PD is unrelated to how long it will take the insulation to fail, since the PD is not the main agent causing the deterioration. Similarly if coils are loose in the slot, the main cause of deterioration is the abrasion of the insulation as the coil vibrates against the laminated stator core. The wearing away of the insulation causes an air gap, and thus PD, but the root cause of the mechanism is the movement, not the PD; again, PD is just a symptom. However, as the mechanism progresses, the PD intensity can become large enough to, in itself, speed the deterioration of the insulation. If the PD increases over time; then more insulation, will be abraded (leaving larger air gaps and thus creating larger PD).

There are a few failure mechanisms that can occur in stator windings in which PD is the main cause of deterioration. These include PD occurring in large voids next to the copper conductors, caused by poor impregnation of epoxy or polyester during manufacture. PD occurs in the voids, and if the voids are large enough, the PD pulses will be large enough to gradually eat through a few layers of mica paper tape turn insulation, leading to a turn insulation fault (multi-turn coils). The larger the voids, the larger the PD pulses, and the faster the failure.

Therefore the PD magnitude is an indicator of the time to failure. Similarly if the end turns of a stator winding are polluted and electrical tracking is occurring, the insulation will track quicker if the discharges are larger. Hence, with the contamination failure mechanism, the PD magnitudes are a good indicator of how fast a winding will fail.

Summarizing, since the failure mechanisms the PD is merely a symptom of a mechanical or thermal failure process, a single measurement of the PD magnitude cannot be taken as an absolute indicator of the condition of insulation. Effective interpretation involves measuring the PD magnitude over time, to see if the aging is continuing, or comparing the measurements on one machine with another similar machine (similar in manufacturer, design, materials,

and ratings) measured with the same PD measurement system.

5.2 EFFECT OF WINDING CHARACTERISTICS ON PD MAGNITUDE

If the test object is a lumped capacitance, then various standards show how to convert mA, mV, etc. into pC. Thus calibration can easily take into account the capacitance of the test object, independent of the characteristics (i.e. the frequency response) of the PD measurement system, if the test object has inductance as well as capacitance (for example, a stator winding), then the PD impulse will create an oscillating response as discussed above. Since most commercial PD detectors work in a rather limited frequency range, the magnitude of the detected response depends on whether or not a resonant frequency is excited in the frequency band measured by the detector. If there is no resonant frequency, then the detector detects little PD. If there is a resonant frequency, then the detector detects large PD activity,

This calibration difficulty is complicated by the fact that the calibration process is done at the winding terminals, yet the actual PD pulses are occurring within the winding. A PD pulse originating two coils into the winding from the line end, excites local resonant frequencies, and the pulse current (or voltage) has to propagate to the winding terminals to be detected. During the propagation process through the winding, the pulses are attenuated and modified in frequency content by the intervening LC ladder network (or transmission line). Thus a calibration process at the stator terminals does not represent the load that the actual PD pulse sees within the winding.

The effect of resonance and transmission line phenomena on the calibration process has been studied extensively in stator windings [14,18]. In one experiment on a 6.6 kV motor stator winding, three different commercial PD detectors were calibrated according to IEC 60270. Using these three detectors (all of the wideband type), the PD on a motor was measured. The PD measured in pC ranged from ~60 to 1000 pC. This clearly indicates that the calibration process in pC cannot be considered as absolute for stator windings. That is, depending on how the measurement is performed, answers can differ as much as 20 to 1.

6 CONCLUSIONS

1. Off-line PD testing is best performed with PD detectors operating in the 1 MHz range, to ensure that PD can be detected in all the coils in a stator winding with the minimum amount of attenuation.
2. On-line PD tests are best performed at higher frequencies since this optimizes the signal to noise ratio, as well as enabling the separation of noise from PD based on time-of-

pulse arrivals. The result is a PD signal free of interference, and thus a reduced risk of false alarms. Although more pulse attenuation will occur at the higher measurement bandwidth needed to separate out the noise, this attenuation is relatively minor, since in an operating stator the sensor can be placed very close to the few coils experiencing the HV.

3. Results show that it is not feasible to 'calibrate' complete stator winding PD measurements in pC. PD measurements reported in terms of pC are very misleading, and may indicate to unsuspecting users that the PD magnitudes are absolute, when they are not. The only way to interpret PD measurements on complete windings is to acknowledge that the measurement units are arbitrary; thus readings are only meaningful when averaged over time, or similar machines are compared, using the same measurement method.

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