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CHARACTERISTICS OF PARTIAL DISCHARGE PULSES FROM OPERATING ROTATING MACHINES

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ABSTRACT - *The recent introduction of 2 GHz multi-channel digital oscilloscopes has made it possible to more accurately measure the waveform characteristics of partial discharge and electrical noise pulses. Waveform measurements were made on several operating hydrogenerators equipped with 80 pF "PDA" capacitive couplers. In many cases the oscilloscope was triggered on pulses which had been categorized by a PDA-type instrument as due to partial discharge or noise. A wide variety of partial discharge waveforms were encountered. Some pulses had risetimes as short as 3 ns, while others had risetimes as long as 10 ns. Even on the same generator, some discharge pulses were very oscillatory, while others were not. Often, the oscillatory discharge pulses had waveforms where the second "ring" in the pulse had an amplitude which was significantly higher than the first ring. Noise pulses generally had a longer risetime than partial discharge pulses, and were very oscillatory. These waveform characteristics have important implications for the design of instrumentation which classifies pulses as noise or partial discharge, and for determining the correct magnitude of the pulses.*

INTRODUCTION

For over 4 decades partial discharge tests have been used to assess the condition of the stator winding insulation in operating generators and motors [1]. Since the mid 1970's there has been a realization that partial discharge (PD) signals consisted of steep-fronted, oscillatory pulses with risetimes in the nanosecond range[2]. Although in many applications the very fast nature of the PD pulse does not have a major effect on measuring PD, the nanosecond duration of PD pulses did enable the creation of on-line PD tests which could be performed by non-specialists. A test which can be performed by non-specialists requires a reliable method of reducing the influence of electrical interference or noise. In the PDA test for hydrogenerators, the difference of arrival times of pulses at two sensors enabled discrimination between noise and PD [3,4]. Similarly the on-line TGA test for turbine generators distinguishes between noise and PD based on the width of the detected pulse [5].

When the PDA test for hydrogenerators was developed, the only instrumentation available for measuring the waveform characteristics were 100 MHz analog storage oscilloscopes such as the Tektronix 466. Such oscilloscopes, although responding to 4 ns risetime pulses, could only measure the response on one channel at a time, and had primitive sweep triggering facilities. Thus it was often impossible to measure the initial part of the waveform, and the signal from only one PDA coupler at a time could be measured. The result was that only a general understanding of the nature of the partial discharge and noise pulse waveforms was possible with such oscilloscopes.

In the past few years, multi-channel digital oscilloscopes have become available (and affordable). In particular 2 GHz sampling rate digital oscilloscopes can faithfully record the PD and noise pulse waveforms with risetimes as short as 2 ns or so [6]. Since the characteristics of the PD and noise pulse waveforms can have a large influence in defining the specifications for instrumentation for separating PD pulses from noise, as well as accurately determining the magnitude of the PD pulses, measurements of the pulse characteristics have been recently remade with modern digital oscilloscopes. The measurements were performed during normal hydrogenerator operation on stators equipped with 80 pF coupling capacitors.

This paper reviews the PDA approach for distinguishing between noise and PD, outlines the measurement apparatus and method for recording the true waveforms, and describes the results of measurements on several operating hydrogenerators in different generating stations.

PDA TEST FOR HYDROGENERATORS

The partial discharge analyzer (PDA) test was developed in 1976 for the express purpose of allowing non-specialists to measure the partial discharge activity in hydrogenerators during normal generator operation. The key reason non-specialists could perform the test was that special efforts were taken to reduce the influence of electrical noise (from output bus arcing, transformer PD, power tool operation, etc.). The noise was reduced on a pulse-by-pulse basis by electronic hardware, rather than by software-based signal recognition techniques which have difficulty in eliminating unexpected types of electrical interference.

In the PDA method of eliminating noise, a minimum of two 80 pF high voltage capacitors per generator phase are installed on the circuit ring bus [4]. The capacitors are usually installed at the ends of the circuit ring bus (Figure 1).

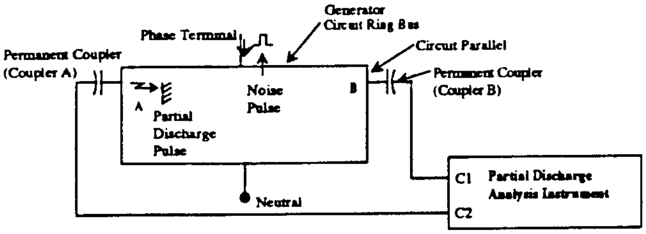

Figure 1: The 80 pF couplers (A, B above) usually are installed at the connection point of the generator circuit ring bus to the coils. C1 and C2 are the input terminals of the PDA instrument.

Assuming the ring busses are the same length to the left and the right of the output terminals in Figure 1, a noise pulse coming from the power system would enter the circuit ring bus and propagate along the bus in both directions, at close to the speed of light (0.3 m/ns). The noise pulse is then detected at the two couplers at the same time. By subtracting the detected pulse at one coupler from the other, ideally no net response would occur. That is the noise is subtracted out.

In contrast, PD pulses produce a net response. Since each partial discharge event is discrete and localized, a PD pulse in a coil in the parallel circuit near coupler A (Figure 1) is first detected by coupler A. The pulse then travels up to the ring bus and may propagate along the ring bus to the coupler at B. Since the circuit ring busses in hydrogenerators are typically 10 m or more in length, the pulse reaches coupler B say 33 ns after it was detected at A. Since PD pulses have a duration of only a few nanoseconds, and if the bandwidth of the subtraction unit is high enough, a net response is detected. There are many engineering details to be overcome with installing the sensors, but experience with more than 1000 installations in many dozen utilities around the world over the past 15 years has indicated that this means of detecting PD pulses is effective, while reducing the impact of noise.

WAVEFORM MEASURING SYSTEM

For all measurements, the PD sensors were the PDA-type 80 pF coupling capacitors which were installed on hydrogenerators in Ontario Hydro's generating stations in the late 1970's. The signals from the capacitive couplers are brought outside of the generator on 50 Ω coaxial cables. As is usual with the PDA system, the lengths of the coaxial cables from the two couplers in a phase were such that any external noise pulse injected into the phase terminal arrived at the oscilloscope within a few nanoseconds of each other. Note that since the coaxial cable lengths were determined using calibration equipment from 15 years ago, the lengths are not as closely matched as they would be with modern calibration techniques.

The output signals from a pair of couplers were fed to a 1 MΩ terminated, dual channel Tektronix TDS 620 digital oscilloscope. This oscilloscope has an analog bandwidth of 500 MHz, and a maximum digitization rate of 2000 million samples per second on each channel. Combined with the 80 pF coupling capacitors, only signals with frequencies above 40 MHz are detected. Since each partial discharge event has a unique magnitude, the oscilloscope was used in the "single-shot" mode. The waveforms were stored on a personal computer and later printed out.

Two methods of triggering the oscilloscope were used. The first involved triggering on the magnitude of the pulses from one coupler, and recording the waveform from that pair of couplers. The second triggering method used a digital signal from a specially modified PDA-IV instrument [7] (Figure 2).

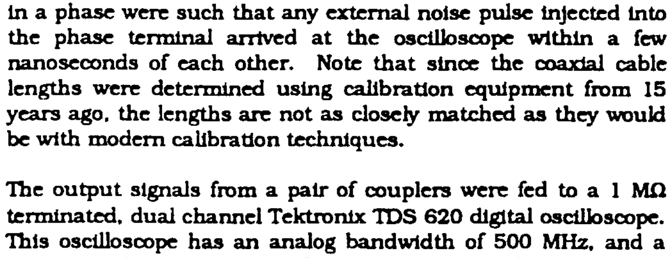

Figure 2: Arrangement for monitoring Pd and noise pulses, when triggered by specified type of pulse by the PDA-IV.

The PDA-IV instrument produces an output trigger signal on any user-defined condition such as whether the pulse was defined by the PDA-IV electronics as noise (pulses arriving within 6 ns of one another), PD from coupler C1 (the pulse at the C1 input arriving 6 ns or more before the pulse from C2), or PD from coupler C2 (the pulse from C2 arriving 6 ns or more before the pulse is detected at C1). In addition, the trigger signal could be conditioned by the polarity, magnitude and ac phase position of the pulse.

The measurements were carried out on four 80 MVA hydrogenerators at Ontario Hydro's Sir Adam Beck generating station and three 60 MVA generators at the Saunders generating station. Between the plants, three different stator winding manufacturers were involved.

PARTIAL DISCHARGE PULSE CHARACTERISTICS

As shown in Figures 3 to 8, a variety of PD pulse waveforms were recorded from the different generators while they were delivering full power. Most PD pulses had a risetime of the first peak of the pulse of about 3 ns (Figures 3 to 5). However, in some cases, PD pulse risetimes were as long as about 10 ns (Figures 6 to 8). Different risetimes were sometimes measured on the same generator (Figures 6 and 7). The fastest risetime of 3 ns is probably due to the inherent bandwidth limitation of the 80 pF capacitors which were fabricated from lengths of 25 kV shielded power cable. The longer risetimes may be due to PD which originate two or more coils from the phase end of the winding, rather than from the phase-end coil. Such PD pulses must propagate through more coils and may thus be wave-sloped by the intervening capacitance and inductance.

Most of the PD pulses had an initial peak followed by an oscillatory waveform. However, occasionally, some of the PD pulses only had a single peak, i.e. there was no ringing (Figure 7). Both ringing and non-ringing pulses were detected on the same generator (Figures 6 and 7). It is not readily apparent what the cause of the different waveforms may be, but different PD locations along the coil (i.e. in the slot or in the endwinding) or different PD locations within the coil (i.e. at the groundwall surface or from voids within the groundwall insulation) may be possible explanations. Where ringing occurs, it is not uncommon for the second peak to have a magnitude which is greater than the initial peak (Figures 3, 5, 6). The most likely cause of the second peak being higher is the superposition of incident and reflected pulses (from impedance discontinuities at the slot and endwinding interface) as the PD pulse propagates from the discharge site through the coils to the PDA coupler.

All the pulses in Figures 3 to 8 were classified as PD pulses since the pulse arrived from one coupler in a pair at least 6 ns before a corresponding pulse (referred to as the second pulse) arrived at the other coupler. The actual delay time between the arrival of the pulses from the pair of couplers depends on the length of the circuit ring bus between the coupler pair. In many cases, the second pulse to arrive is discernible (Figures 4 and 6), however, the magnitude of the second pulse may be from 10% to about 100% of the magnitude of the first pulse to arrive. This difference in magnitudes between the pairs of pulses is probably due to the distance between the couplers (along the circuit ring busses), as well as due to attenuation of the transmitted signal along the circuit ring bus as the pulse encounters circuit parallels between the couplers. (These generators had either 4 or 6 circuit parallels per phase.) Note that in Figures 3, 5, and 7, essentially no pulse was detected at the second coupler in a pair. (Since the digital oscilloscope had a long record length, we were able to confirm that the second pulse was not occurring beyond the time interval shown in the figures.) Presumably there can be enough attenuation along the circuit ring bus that a PD pulse originating at point A in Figure 1 will result in no detected signal at point B.

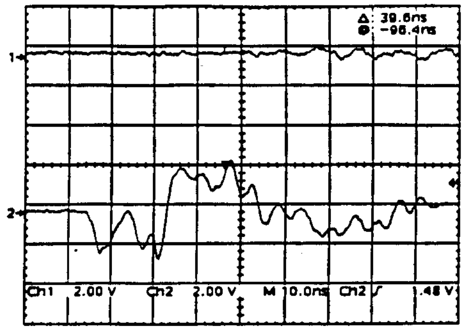

Figure 3: PD pulse Beck Unit 22. The upper trace is the response from coupler C1, the lower trace is the response from C2 to the same PD pulse. The PD pulses orginiated near C2.

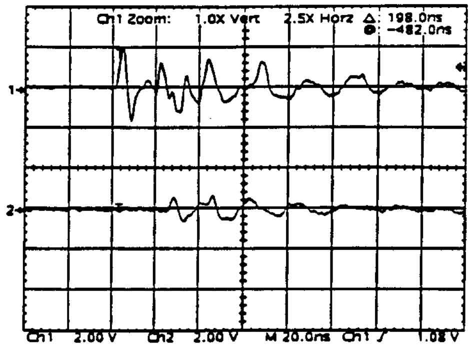

Figure 4: PD from Beck Unit 22. The PD pulse originated near C1, (upper trace), but some response was also detected at C2.

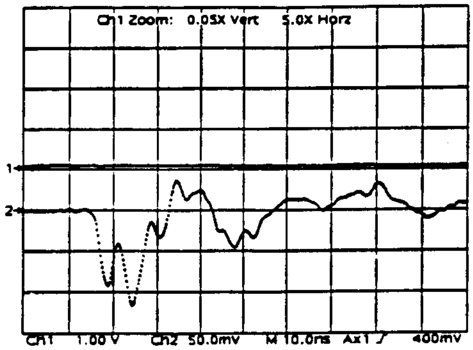

Figure 5: PD pulse near C2 in Saunders Unit 2.

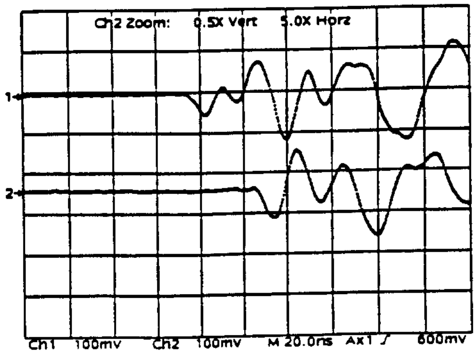

Figure 6: PD pulse near C1 in Saunders Unit 4.

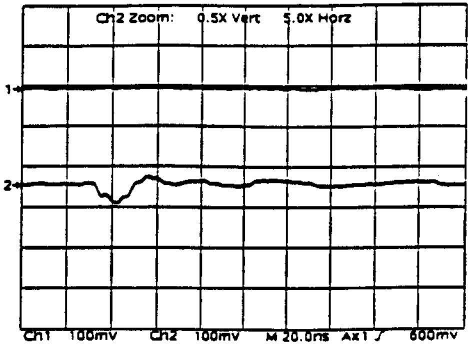

Figure 7: Non-oscillating PD pulse near C2 in Saunders Unit 4.

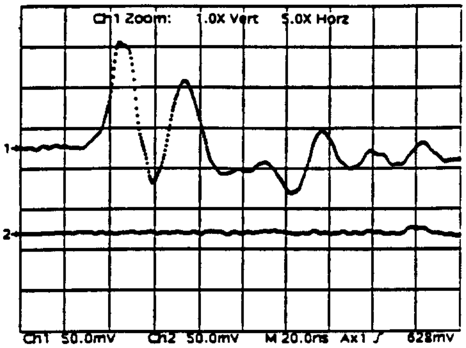

Figure 8: Slow risetime PD pulse near C1, on Saunders Unit 6.

NOISE PULSE CHARACTERISTICS

Figures 9 and 10 show the waveforms of noise pulses which were detected. As mentioned above, noise is defined to have occurred when a pulse of the same polarity above a critical threshold is detected from both couplers in a pair within 6 ns of one another. Unfortunately, noise pulses were detected on only 2 of the 7 generators measured. The risetime of the pulses varied from 5 ns to 10 ns. That is, they had a slightly lower risetime than PD. Observation of both Figures 9 and 10 reveals that the waveshapes are not the same. Thus it is clear that a simple subtraction of the signals from one another, as was done in early PDA instruments, including the PDA-H^{TM}, may not result in complete subtraction. Thus in the few hydrogenerators which experience very high levels of external noise, some portion of the noise may be classed as noise with older instruments. Note also that the difference in time of arrival at the oscilloscope varies by up to 5 ns. All noise pulses recorded had a very oscillatory waveshape.

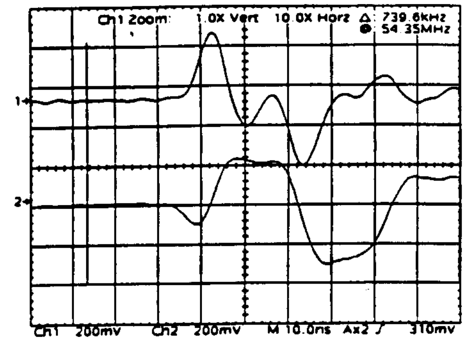

Figure 9: Response at C1 (top trace) and C2 (bottom trace) due to external electrical noise.

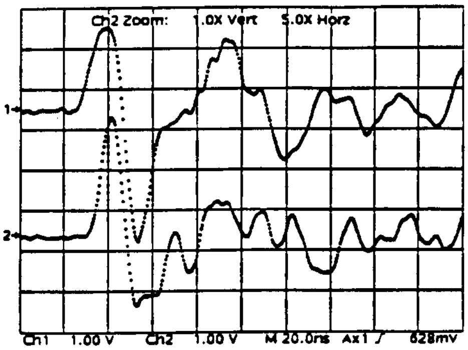

Figure 10: Response at C1 and C2 on Saunders Unit 6 due to external noise, apparently due to operation of an electric arc welder nearby.

IMPLICATIONS FOR PD MEASURING SPECIFICATIONS

Using an oscilloscope to measure the PD activity would be very tedious since an oscilloscope can accurately capture only a few of the thousands of PD pulses per second. Thus since the late 1960's, an instrument called a pulse height analyzer has been used to measure and summarize all the PD activity. This involves determining the number and magnitude of the PD pulses.

A key requirement for any instrument intended for use with PDA couplers is to separate the PD pulses from noise which could lead to false indications that a winding is deteriorating. Since PD pulses from a matched pair of couplers may be separated in time by as little as 6 ns, this has required the pulse height analyzer in all designs of PDA instruments to respond to the fast nature of the PD pulses. Initial instruments, which were limited by the electronics available at the time, had a bandwidth of about 70 MHz, while the more recent PDA-H had a bandwidth of about 100 MHz. By Fourrier analysis, 100 MHz corresponds to a pulse risetime of about 3 ns. Since the measurements described above have shown that the risetime is in fact as short as 3 ns, to properly record the magnitude of the PD pulses requires an overall bandwidth of at least 100 MHz.

The analog bandwidth is also important to ensure that, if the second peak is higher than the first peak (as seen in Figures 3, 5, and 6), the magnitude of the second peak is not recorded by the instrument. If the bandwidth is too low, the first and second peaks tend to become merged (i.e. integrated), which can result in PD pulses being incorrectly identified as having a magnitude which can be significantly higher than reality.

The fact that the same noise pulse rarely has the same shape when detected by the matched pairs of couplers, indicates that some noise could be interpreted as PD if an analog subtraction method is used. Thus it is clear from Figures 9 and 10, that distinguishing between noise and PD based solely on the arrival time (and not the shape of the entire first peak of the pulse) will enhance immunity to noise, and thus false indications of insulation problems.

CONCLUSIONS

1. Measurements with high performance digital oscilloscopes have revealed with more clarity the waveform characteristics of both PD and noise, as detected by matched pairs of 80 pF capacitors installed within hydrogenerators.

2. The PD pulse risetime from 80 pF capacitors installed in hydrogenerators is usually about 3 ns, although pulses with risetimes as long as 10 ns were sometimes measured. Thus any pulse height analysis equipment needs a bandwidth of at least 100 MHz to faithfully determine the magnitude of the PD pulses.

3. Since PD pulses are usually oscillatory, and sometimes the second peak in an oscillating PD pulse is higher than the first peak, careful electronic design and a 100 MHz bandwidth are needed to ensure that the true PD peak magnitude, as represented by the first peak which has not undergone traveling wave reflections, are measured.

4. As has been observed by many investigators over the years, pulse risetime and ring differences could perhaps reveal more about the location or nature of the PD pulses occurring within a stator winding.

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