

APPLICATION OF PULSE WIDTH ANALYSIS TO PARTIAL DISCHARGE DETECTION

S.R. Campbell
IRIS Power Engineering
Mississauga, Canada

G. C. Stone
IRIS Power Engineering
Mississauga, Canada

H.G. Sedding
Ontario Hydro
Toronto, Canada

ABSTRACT: An on-line partial discharge (PD) test for large steam turbine generators has been developed where partial discharges and noise are distinguished on the basis of pulse width. The pulse signals are detected by stator slot couplers (SSCs) which are permanently installed within the generator. Experiments have shown that partial discharge pulses, as detected by an SSC, have a pulse duration of only a few nanoseconds, where all types of electrical noise have a pulse width of greater than 20 ns. An instrument called the TGA has been constructed which performs a pulse width analysis with a resolution of 2 ns. This instrument permits the rejection of noise on a pulse by pulse basis, and the subsequent pulse height and pulse phase analysis of the partial discharge pulses. The SSC/TGA test allows non-specialized personnel to perform a partial discharge test on generators in nuclear and fossil stations, without requiring a generator outage.

INTRODUCTION

For four decades partial discharge testing has been used both as a quality control test for new high voltage apparatus, as well as a diagnostic test for determining the condition of the electrical insulation in operating equipment. Partial discharge testing has been especially useful in evaluating the condition of the stator winding insulation in hydrogenerators and steam turbine generators in nuclear and fossil stations [1]. Utilities have been able to use the results of partial discharge tests to plan generator maintenance and drastically reduce the probability of in-service winding failures [2].

Until recently, the main result from a partial discharge test was the peak partial discharge pulse magnitude determined by observing an oscilloscope screen, or from a peak detection circuit. About 20 years ago, Bartnikas [3] and Kelen [4] introduced the concepts of pulse height analysis (PHA) and pulse phase analysis (PFA), respectively, to extract more quantitative information from all detected partial discharge pulses, and not just the highest pulses. In particular, in a PHA, an electronic instrument sorts all the partial discharge pulses into several magnitude windows, and the number of pulses in each magnitude window is counted. Typically there are from 16 to 1024 magnitude windows. In PFA, the partial discharge pulses above a selected threshold are sorted according to where the discharges occur with respect to the power frequency phase. The ac phase is split into phase windows, with from 2 to 256 phase windows covering 360 degrees.

Pulse height and pulse phase analysis provides an easy means of permanently displaying all detected pulses. Such analysis has also permitted researchers to characterize different kinds of partial discharge sources (eg void discharge, corona, surface discharge) on the basis of their magnitude and phase distributions. Thus from observation of the PHA and PFA patterns, the likely types of discharges occurring in high voltage equipment could be ascertained without dissection of the insulation. PHA has been widely adopted to distinguish between hydrogenerator stator winding problems such as slot discharge, thermally-induced delamination and pollution [2]. In the past several years, easily accessible computer programs have enabled PHA and PFA to be combined to yield three dimensional plots of the number of pulses versus magnitude versus phase [5,6]. Although such plots are more difficult for the casual observer to interpret, an experienced researcher can extract considerable insight into the cause of the partial discharges, and even visually eliminate certain types of noise [7,8].

Recent advances in sensor technology, together with improvements in oscilloscopes and electronic instrumentation, have made another method of analyzing partial discharges pulses possible. Pulse width analysis (PWA), that is the measurement of the distribution of pulse widths, may provide further means of distinguishing between different types of discharges, as well as permitting partial discharges to be reliably extracted from noise, providing the sensor bandwidth is comparable with the signal. This paper outlines the motivation for implementing pulse width analysis, and describes a prototype instrument which performs PWA, as well as PHA

and PFA. The practical application of PWA to the on-line detection of partial discharges in large steam and gas turbine generators is also presented.

ULTRA WIDE BAND PARTIAL DISCHARGE DETECTION

A partial discharge in a small void is fundamentally an extremely rapid event. The electron transit time across the void is less than 1 ns, which can result in a pulse current which lasts less than 1 ns [9]. Partial discharges in larger voids, or within a delamination between an electrode and the insulation can result in pulses which may be a few tens of nanoseconds wide [10]. To distinguish between these various current pulse widths requires a partial discharge sensor which can detect signals with frequency contents up to 1000 MHz [9]. Although such detectors are not trivial to create, at least three methods have been developed to date which can faithfully detect such rapid current pulses.

Series Impedance

Ultra wide band detection with a series impedance is an evolutionary modification of the conventional RLC detector [11]. Usually the detection impedance is a 50 ohm resistor or the 50 ohm characteristic impedance of a coaxial cable in series with a small insulation specimen. Such detection is only practical when the stray capacitance to ground is minute.

Transmission Line Couplers

For practical equipment such as gas insulated switchgear, electromagnetic couplers mounted within the switchgear have been shown to have bandwidths of several hundreds of MHz [12,13]. Such couplers sample the electromagnetic wave initiated by a partial discharge which propagates along the coaxial bus duct.

Stator Slot Coupler (SSC)

The stator slot coupler is an electromagnetic coupler which is designed specifically to detect partial discharges (and noise) in the stator windings of large gas and steam turbine generators [14]. The SSC is a two-port stripline antenna which is about 50 cm long, 2 mm thick, and is customized to be the same width as the generator stator slot (Figure 1). The SSCs are installed in the stator slots, underneath the wedges which hold the stator winding within the slot. There is no galvanic connection between the SSC and the high voltage stator winding. The substrate of the SSC is an epoxy-glass laminate onto which thin copper electrodes are deposited. All copper electrodes are covered by a thin layer of epoxy-glass laminate, so that no copper is exposed. Each end of the SSC is connected to a micro-coaxial cable. Each SSC has two coaxial cable outputs exiting from one end of the device, which are ultimately routed to connectors outside the generator. The SSC has a relatively flat frequency response in the range 30 MHz to greater than 1 GHz [14], due to its 50 ohm characteristic impedance and the 50 ohm coaxial output cables. Therefore the SSC can detect the true pulse shape of any high frequency signal propagating along the stator slot, since the stator bar in the slot does create a well-defined high frequency transmission line.

Any one of the above partial discharge detection methods will have sufficient bandwidth to detect the true temporal response of the pulse current, thus making PWA possible.

APPLICATION OF PWA TO ON-LINE GENERATOR TESTING

An application of PWA is in the measurement of partial discharges in large steam turbine generators. The signals are detected by SSCs permanently installed in the turbine generator. PWA permits both the elimination of electrical interference, as well as the categorization of different types of deterioration based on different partial discharge pulse widths. The latter will require further research, but noise elimination is critical to the practical application of on-line partial discharge testing of turbine generators. By eliminating electrical noise such as created by arcing from shaft grounding brushes, it is possible to implement a partial discharge test which can be performed by non-specialized generating station personnel during normal operation of the generator.

Noise Elimination

The temporal shape of current pulses detected with SSCs in operating turbine generators has been studied with 1 GHz analog oscilloscopes (Tektronix 7104) and 350 MHz bandwidth, 1 GHz sampling rate, dual channel, digital oscilloscopes (HP54111D). Figure 2 shows a partial

discharge pulse obtained from a 500 MW, 22 kV steam turbine generator operating at full power. The pulse has a width of only a few nanoseconds, that is the partial discharge yields a very fast pulse response from the SSC. The very short duration is remarkably similar to the pulse shapes recorded in small-scale laboratory measurements [9], indicating the capability of the SSC to respond to the true partial discharge signal. The trace marked "1" in Figure 2 is the output from the end of the SSC closest to the end of the stator slot. Trace "2" in Figure 2 is the output of the other end of the SSC which is located 45 cm further into the slot. Because trace "1" has been detected first, the response is due to a PD pulse propagating into the slot from the immediately adjacent endwinding. Pulses similar to those in Figure 2 were also detected when the stator winding was separately energized, and thus electrical interference from noise was not present. In addition, SSCs installed in slots containing neutral-end stator bars, where the probability of partial discharge is very low, had no signals similar to the PD in Figure 2.

There are three major electrical, pulse-like noise sources associated with the turbine generator environment:

- arcing and corona occurring on the isolated phase bus (IPB) connecting the generator to the step-up transformer
- arcing from the turbine generator shaft grounding brushes
- field excitation thyristor transients and slip ring brush arcing.

The response of the SSC to each of these noise sources has been studied in several turbine generators. Figure 3 shows the response of the SSC due to arcing on the generator output bus. The noise pulse detected at the SSC is very oscillatory and has a duration of more than 20 ns.

In all the pulse shape studies in the 17 machines equipped to date with SSCs, the partial discharge pulses tend to be non-oscillatory, and have a pulse duration of less than 5 ns. In contrast, the electrical noise pulses are oscillatory, and have a duration of 10 ns to microseconds, depending on the source of the noise. With PWA, this clear distinction in pulse shape can be used to distinguish between noise and partial discharge. The partial discharge pulses are short because the SSC can detect something close to the true pulse current and a stator bar in a slot constitutes a distortionless (although lossy) RF transmission line. Noise pulses have a longer, more oscillatory shape because the noise signals must first propagate through the connection rings and endwindings of the stator, which is actually an inductance, rather than a well-defined transmission line. Noise from the rotor is also waveshaped, since the rotor is not a good high frequency antenna.

TGA Instrument

The oscilloscope studies described above indicated that there are clear pulse width differences between partial discharge and noise, when such pulses are detected by the SSC. Unfortunately, oscilloscopes can trigger and display only one pulse at a time at fast sweep speeds. An instrument called the TGA has been developed which measures the width of all pulses detected by the SSCs, thus permitting the discrimination between partial discharges and noise on the basis of pulse width. Noise pulses can then be discarded pulse by pulse. The remaining (short) pulses are then classified as partial discharge and are subjected to conventional PWA and PFA. The specifications of the TGA are:

- a pulse width analysis with a nominal resolution of 2 ns. There are 9 width windows which can be adjusted as desired in hardware. The prototype has the following width windows: 0-2, 2-4, 4-6, 6-8, 8-16, 16-24, 24-32, 32-40, and >40 ns. Until further experience is gained with partial discharge and noise in turbine generators, pulse widths greater than 16 ns will be classified as noise.
- a pulse height analysis responding simultaneously to both polarities. There are 32 magnitude channels. The PHA is accomplished sequentially with a dual polarity single window pulse height analyzer. Although this sequential approach is probably not suitable for partial discharge detection in insulation with single voids, it is effective for turbine generator windings where there are thousands of discharges per second in thousands of sites, and the generator is operating in steady state.
- a pulse phase analysis with a resolution of 3.6° , i.e. 100 phase windows.

Figure 4 shows the block diagram of the TGA. The front end electronics which perform the PWA and PHA are fabricated from ECL components operating at a design speed of 800 MHz. The prototype was directly constructed on a printed circuit card using surface mount

components. Such construction techniques were required to achieve 2 ns resolution. The TGA contains an embedded 386-type computer to control the sequential PHA and sort the pulse data according to phase position. The computer also processes the data to display simple pulse height, pulse width and pulse phase plots. An RS232 port permits control of the TGA by an external personal computer, and downloading of data for more sophisticated analysis. The external computer is not required to perform a partial discharge test or for simple data display. Figure 5 shows the TGA with an external monitor for data display.

Preliminary Testing

The ability of the TGA to measure partial discharges in operating turbine generators has been demonstrated at Ontario Hydro's Nanticoke G.S. The TGA was connected to the 6 SSCs which were previously installed on Unit 5, a 500 MW coal-fired generator. The partial discharge activity was measured while the generator was operated at about 540 MW. Figure 6 shows the partial discharge activity from this generator. The measurements indicate that the partial discharge activity is high, as also measured by the "portable coupler" test method, which Ontario Hydro has been using for almost 40 years on operating generators [1]. Partial discharges were defined to be any pulses with a width less than 8 ns, while pulses longer than 8 ns were classified as noise. Further testing on a wide range of generators is necessary to determine if this classification is correct.

CONCLUSION

A method has been developed to analyze the width of pulses from ultra wide band partial discharge detectors. By analyzing the width of all the partial discharges from high voltage apparatus, it may be possible to determine the cause of the partial discharges. For the specific application of measuring partial discharges in operating steam turbine generators, an additional advantage is obtained. When combined with a suitable sensor, it has been shown that one can distinguish between partial discharges and noise on the basis of pulse width. An instrument called the TGA has been constructed which performs a pulse width analysis, and can thus be configured to reject noise. The ability of the TGA to discriminate between partial discharge and noise has been demonstrated on operating steam turbine generators. Therefore, by using pulse width analysis techniques, it is now possible for non-specialized personnel to perform a partial discharge test on normally operating nuclear, coal and oil-fired generators.

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Figure 1. An SSC which can be installed under the stator wedges in turbine generators to measure partial discharge.

Figure 2. Response of both SSC outputs to partial discharge occurring just outside of the slot. The generator was operating at 22 kV, 500 MW. The horizontal scale is 5 ns/div. and the vertical scale is 5 mV/div.

Figure 3. Response of both SSC outputs to arcing on the generator output bus. The oscilloscope was externally triggered by the noise on the generator IPB ground [15]. The horizontal is 20 ns/div. and the vertical scale is 20 mV/div.

Figure 4: Block diagram of the TGA instrument which performs a pulse width analysis

Figure 5: Photograph of the prototype TGA with an external monitor

Figure 6: Plot of the partial discharge activity measure by the TGA from an SSC on an operating turbine generator.