Investigations Into the Use of Temperature Detectors as Stator Winding Partial Discharge Detectors

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Abstract: This paper presents results from tests on eight stators as well as a laboratory model on the characteristics of partial discharge (PD) pulses detected by resistance temperature detectors (RTDs). It is clear from these experiments that the RTD leads – rather than the RTD element itself, primarily detects the PD signals. In addition, if the RTD lead is shielded, the detected signal is extremely small. Thus PD measurements should only be attempted with unshielded RTD leads. Unfortunately whether leads are shielded or unshielded is often unknown. The data also shows that even with unshielded RTD leads, the detected signals are usually uncorrelated with the PD measurement using conventional sensors, and thus the known condition of the stator winding. Although RTD leads may detect PD, interpretation of the results cannot be based on magnitude, polarity or phase position. Thus interpretation is extremely subjective – even by an experienced expert.

I. Introduction

The vast majority of motor and generator on-line partial discharge (PD) measurements are made with high voltage capacitors mounted on the stator winding terminals [1,2]. Researchers have recently explored using RTD-type and thermocouple-type temperature detectors as PD sensors [3,4]. RTDs are typically installed in one or more slots per phase between the top and bottom coils in motor and generator stator windings in machines rated 3.3 kV and above. The RTD, thermocouple, and/or its lead, is considered to be an antenna that can detect the electromagnetic radiation created by individual PD events. The desire to use temperature sensors as PD sensors is high, since these are often already installed in many modem stators, and thus there is no need to retrofit capacitive sensors specifically for PD sensing.

Various organizations have expressed concern about the usefulness of RTDs as PD sensors [5,6]. To study this matter, over the past 6 years, a number of experiments were done on 8 motor and generator stator windings to clarify how RTDs detect the PD pulse signals, and to compare their sensitivity to conventional capacitive couplers. In a few cases, the use of thermocouples was also explored. This paper presents and discusses some off-line and on-line PD tests done on stator windings where conventional capacitive couplers are compared with RTDs and thermocouples, as well as low voltage pulse propagation and coupling efficiency tests on some of stators and a stator model.

II. Measuring PD Using RTDs

RTDs are a three or four terminal device where current is passed through a resistive element (usually a metal film with a serpentine path) and the voltage is measured across the element, to determine the resistance, and hence temperature. In machine windings, RTDs may be from a few centimeters to tens of centimeters long. The three or four leads from the RTD are twisted together. With higher quality RTDs, such as those used on larger machines, the leads are sometimes contained within a grounded metal shield to reduce electrical interference, and hence the risk of poor temperature readings. The lead lengths from the sensors to the terminal panel can vary significantly from RTD to RTD, even in the same stator. In motors the RTD leads may be only a meter in length, whereas in large generators they may be 10 to 15 m in length.

Usually only a few RTDs are installed in a stator. In motors, there may be from 3 to 6 RTDs mounted within the stator winding. Even very large generators typically have only about 12 RTDs. Most, but not all machine manufacturers tend to install the RTDs in slots containing coils that are not operating at high voltage if the coils do not have a grounded semiconductive shield on the surface of the groundwall insulation. Where there is no semiconductive coating (most machines rated 4.1 kV or less), the RTDs will be exposed to high electric fields, if either the top or bottom coil in the slot is connected near to the phase terminal. Most machine OEMs consider it prudent not to install a quasi-grounded device such as an RTD in such locations.

In our experiments, the high frequency signals from the RTDs were measured in two ways. For RTDs connected to the temperature measurement electronics, the RTDs were measured with a split core high frequency current transformer (HFCT) with a bandwidth of 30 MHz, and terminated in 50 ohms. This is similar to HFCTs used for monitoring PD currents at stator neutrals or in surge capacitor grounds [1,2]. For RTDs not connected to temperature measuring electronics,

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the open circuit voltage from the joined three leads was measured with a high input impedance oscilloscope probe. In some cases the three leads were connected to ground via a 50-ohm resistor, and the voltage measured across the resistor with a probe. In general, the HFCT produced a signal about 4 times smaller than the probe measurements.

III. Pulse Injection Measurements

A. 12 MW Standby Generator

This stator was rated 12 MW, 13.8 kV and 1800 rpm. It was equipped with 6 RTDs, which could be approximately located around the stator by a visual inspection. The leads from the RTDs were unshielded. A hole was drilled through the ground insulation in a coil, just outside of the slot. A 1 ns risetime, 5 ns wide, 2 V pulse (from an HP 8082A pulse generator) was injected between the exposed copper conductor and the grounded stator core near the slot exit, similar to the approach used in [5]. This injected pulse simulated a PD pulse occurring within the groundwall. The voltage pulse injected was measured with a FET input oscilloscope probe. The coil was part of a group of 5 coils in series that was connected to the phase terminal of the stator. The signal was injected one coil down from the phase terminal. One of the RTDs was located within the group of coils (the exact location could not be determined). Measurements were also made on other RTDs located remote from the group of coils where the pulse was injected. The current detected by the RTDs was measured with a 30 MHz HFCT with a 10-turn secondary.

In addition to monitoring signals from the RTDs, an 80 pF, 16 kV capacitor, typical of many used for on-line PD monitoring in machines [1,2], was installed at the machine terminals. Thus the capacitor was one coil away from the injection point.

Fig. 1 shows the signals measured at the injection point (bottom trace, 500 mV per division sensitivity), as well as the signals measured from the capacitor (top trace), and two RTDs. The second trace from the top is from the RTD installed in a slot adjacent to the coil where the pulse is injected. The third trace down is from an RTD installed 180° around the stator from the injection point. All three output signals are recorded at 10 mV per division. Similar results were obtained with different injection points and RTDs.

Clearly the capacitor yielded a signal that was almost 4 times more sensitive tban the signal from the RTD with the highest response, even though the capacitor was a coil away from the injection point. What was even more surprising, the signal from the RTD near the injection point was little different than the signal from an RTD remote from the injection point. This is most likely to occur if it is the RTD leads which detect the electromagnetic signal, rather than the RTD element itself, since the leads are routed throughout the whole stator.

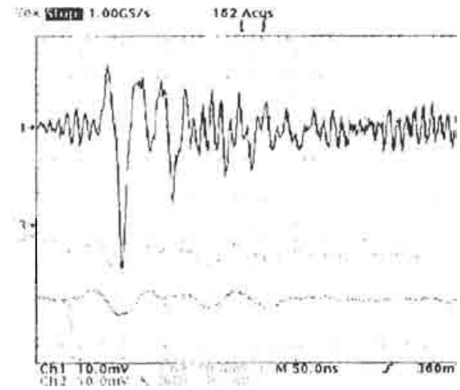


Fig. 1. A 500 mV simulated PD pulses injected into the 12 MW generator stator (bottom trace) with the response of the 80-pF coupler (top trace) and 2 RTDs (middle traces). The horizontal scale is 50 ns/div

B. 2000 HP Motor Stator

Pulse injections tests were also performed on a new 4160 V, 2000 HP 2 pole stator that had 2 parallels per phase and 8 coils per parallel. The stator was equipped with 6 RTDs mounted symmetrically around the core. There was about 5 m of unshielded RTD lead from the point the RTD emerged from the stator core. The stator coils did not have a semiconductive slot coating. Since drilling through the insulation was not permitted, simulated PD pulses as described above were injected via an aluminum foil capacitor plate with an area of about 25 cm^2. The capacitor plate was applied over the coil surface, just outside of the stator core. The pulse voltage was applied between the aluminum foil plate and the stator core. A Tek TDS 644B 2.5 GHz sampling speed digital scope was used to measure the responses from the 6 RTDs and a 80 pF capacitor mounted on the machine terminal.

The pulses were sequentially injected into most of the 8 coils in a B phase circuit parallel. RTD6 was the only RTD in the vicinity of this parallel. Fig. 2 shows the response of RTD6, RTD3 which is 180 degrees from the parallel under test and the 80-pF coupler to a pulse injected at the line end coil. Table 1 shows the response when the pulse is injected deeper into the winding.

TABLE I
RESPONSE OF RTD AND 80-PF COUPLER TO PULSE INJECTED INTO VARIOUS LOCATIONS IN A PARALLEL

Injection Location*	Response** (mV)		
	80 pF capacitor	RTD6	RTD3
1	23	2	3
2	20	2	3
3	25	2	3
4	15	2	3
6	15	2	2
8	15	2	1

* No. of coils from phase end,
** as measured from the first detected peak

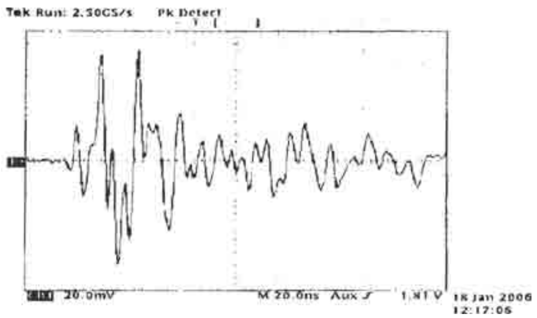


Fig. 2(a). Pulse measured from 80-pF capacitor due to pulse injected one coil from line end (20 mV, 20 nsldiv)

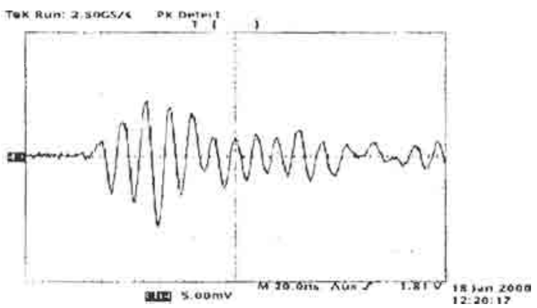


Fig. 2 (b). Same as 2(a), but with the response measured from RTD6, which is located in the same parallel where the signal is injected (5 mV, 20ns/div).

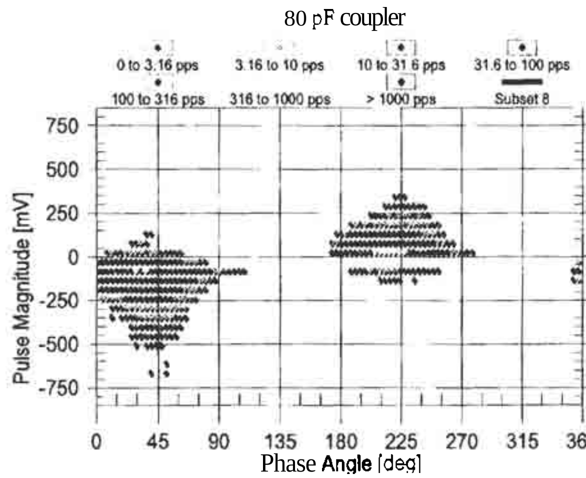
The signal from the capacitor is 10 times larger than the highest RTD signal. The further the pulse originates from the capacitor, the lower is the detected magnitude - although as found in previous similar studies – at some point there is no further attenuation presumably due to capacitive coupling across the endwinding. Note that the PD detected by the RTDs seems to be relatively insensitive to the distance between the sensor and the pulse source, presumably due to the routing of the unshielded RTD-leads around the stator.

IV. High Voltage PD Tests

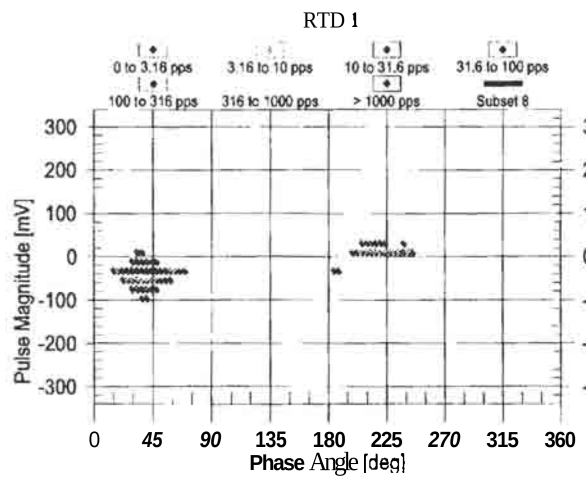
A. 12 MW Standby Generator

PD activity in the stator was created by energizing all or part of the stator winding from a noise-free ac transformer in an off-line test. The PD signals were measured from both the 80 pF capacitor on the phase terminal, and the 6 RTDs around the stator, with either two 4 channel, 1 GHz sampling rate digital oscilloscopes (Tektronix TDS 784C), or a pulse height, pulse phase analyzer (Iris TGA-B). As for the pulse injection tests, the signal from the RTDs was detected by a 30 MHz bandwidth, 10 turn secondary HFCT widely used for PD detection on the neutrals of generators or on surge capacitive grounds.

In the first test, all three phases (and all coils) were energized. The winding had exceptionally high PD, and very low inception and extinction voltages (Table 2). In addition, the insulation was known to be very delaminated. Since the capacitors had a better signal to noise ratio compared to the RTD sensors, it was possible to determine that the inception and extinction voltages were lower with the capacitors. The pulse height analyzer measured a peak PD magnitude (Qm) of 700 mV with the capacitive sensor, and from about 50 to 100 mV with the RTDs, with the stator energized at 3 kV (Fig. 3). Clearly from the classic pattern with, respect to the 60 Hz AC voltage, both types of sensors measured PD. However, the capacitive sensors were from 7 to 14 times more sensitive than the RTDs.



(a)



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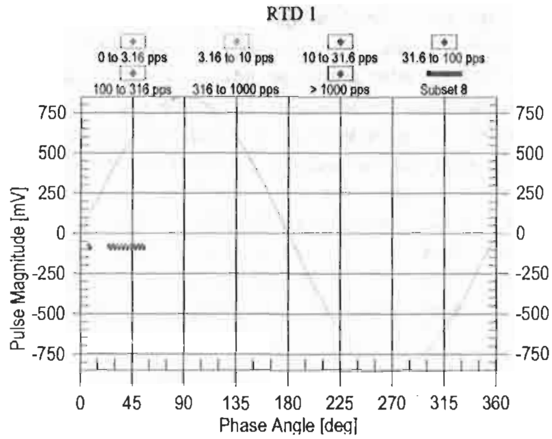

(c)

Fig. 3. Off-line PD pulse phase analysis plots for PD measured on the 12 MW stator with 5 coils energized and measured with the (a) 80 pF coupler and the RTDs measuring the highest (b) and lowest (c) PD at the same time. Note the different magnitude scales.

TABLE II
PD INCEPTION AND EXTINCTION VOLTAGES

	RTD Sensor	80 pF Sensor
PDIV (V)	800	760
PDEV (V)	750	550

Fig. 4 shows the pulses from the capacitor and 3 RTDs as displayed on the multi-channel oscilloscope, when the entire winding is energized. The pulses are recorded on all sensors (all with a sensitivity of 200 mV per division), although the signals from the capacitor (top trace) are about 4 times larger. With the entire winding energized, all the coils may experience PD, and thus it is to be expected that all the RTDs detected PD.

Tests were also done with just a group of 5 coils energized at 3 kV. This simulates the situation in an operating machine where only a few coils are energized to rated voltage, and most operate at considerably lower voltage, and consequently with much lower or no PD activity. Fig. 5 shows the results. The capacitor and RTDs clearly display the clumped PD activity in this off-line test, however the PD activity detected by the capacitor is over 20 times higher than the signal detected by any of the RTDs (note that the capacitor signal has a sensitivity of 500 mV per division, compared to 50 mV per division for the RTDs). When the oscilloscope is triggered by a large PD pulse from the capacitor at a high temporal resolution, the relatively small signals from the RTDs can barely be seen (Fig. 6). The RTD output shown in the second from the top trace is from an RTD in the energized set of coils. Even with an RTD that is in a slot with energized coils, the capacitor is at least 10 times more sensitive.

In this stator, where the RTD leads are not shielded, all RTDs seem to detect signals to some extent, and with only about 2 times difference in magnitude for PD anywhere in the stator. In a normally operating 3 phase stator, determination of where the PD is occurring, and in fact confirmation that the signals are due to PD (where there will now be 6 clumps), will require great skill.

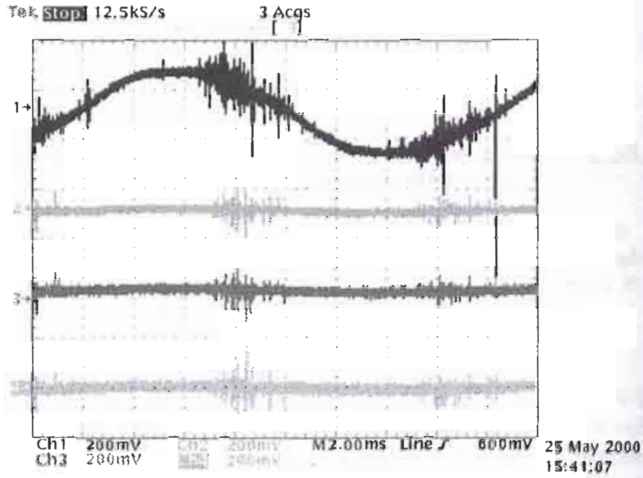

Fig. 4. PD measured with a digital oscilloscope using an 80 pF coupler into 50 ohms (top trace) as well as three RTDs (bottom three traces) with the entire generator stator energized at rated voltage (8 kV, line to ground). Note that the AC voltage from the capacitor is 90 degrees out of phase from the true terminal voltage.

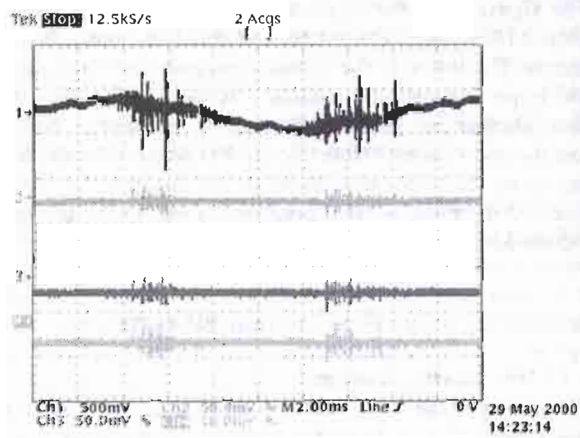

Fig. 5. PD measured on the 12 MW generator, when only 5 coils are energized to 8 kV (and the rest of the stator is floating). The top trace shows the PD from the 80-pF coupler and the bottom traces show the PD measured from the RTDs. The time scale shows one AC cycle (2 ms/div)

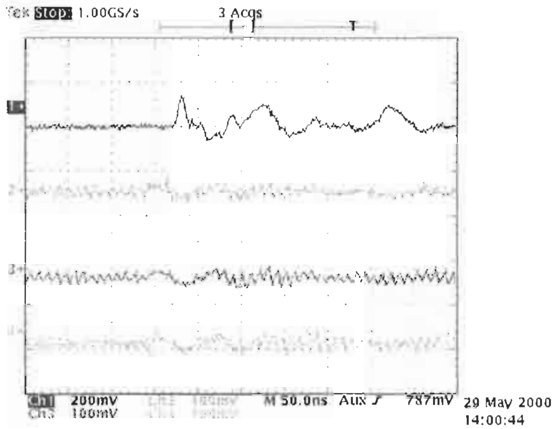

Fig. 6. High-resolution oscilloscope image (50 ns/div) of one PD pulse for the same situation as Fig. 5. The top trace is the PD detected by the 80 pF coupler (200 mV/div), whereas the bottom three traces show the PD measured on the three RTDs with the highest signals (all 100 mV/div).

B. 2000 HP Motor Stator

The 4160 V motor described above for pulse injection tests was also used for comparing the PD results from 80 pF (top trace) and the RTD6 sensor in an off-line PD test. All three phases are tied together and energized to rated line to ground voltage (2400 V). Fig 7 shows an individual PD pulse measured by both the 80-pF capacitor and the RTD. Unlike all the other data discussed in this paper, the PD magnitude was much higher from the RTD (about 4 times higher). The PD was distinctly audible, and it seems that the PD was occurring between the surface of a stator coil, and the RTD lead wire as it came out of the slot. Thus if a higher response is obtained from an RTD, it is likely the source of the PD is the RTD itself. The stator insulation itself has very low PD.

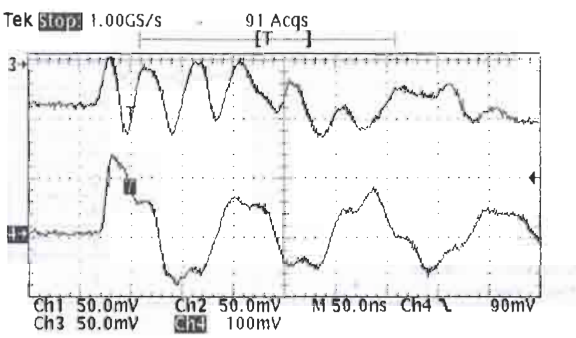

Fig. 7. Response of a capacitive coupler (top trace) and an RTD (bottom trace) to a PD event in a 4160 V motor.

C. Refinery Motors

Three motors rated 3500 HP to 12,000 HP; all at 4.1kV were available for high voltage on-line PD testing. Each stator had one 80-pF coupler per phase in the motor terminal box. Each also had either 4 or 6 RTDs in unknown locations throughout the stator. One motor had RTDs with shielded leads (3301).

Table 3 shows the PD as measured with 80 pF couplers on each phase terminal, using the TGA-B analyzer. Regrettably (for this study) the motors had little PD. The highest PD was occurring on Motor 3301 (Fig. 8), with a Qm of +13 mV and –5 mV. In all cases no PD was measured on any of the RTDs. In addition, when the signals were measured with an oscilloscope (Fig. 9), the PD signals measured via the 80 pF capacitor did not correlate with any signal from the RTD. Thus it seems the RTDs in these machines were not at all sensitive to PD. Since motor 3301 had shielded RTD leads – this may account for the lack of any response from the RTD in the motor with the worst PD.

TABLE III
PD RESULTS FROM IN-SERVICE TEST

Motor	Qm from 80 pF sensors and TGA-B (+/-mV)			Max PD from all RTDs (mV)
	A	B	C	
3300	2/0	2/0	0/0	0
3301	13/-5	5/0	7/2	0
3700	0/0	0/0	0/0	0

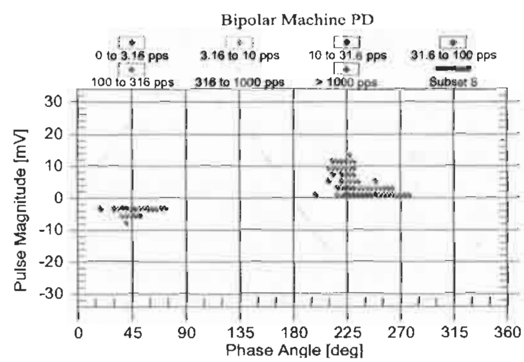

Fig. 8. Classic PD recorded on-line using an 80-pF coupler on A phase. The noise has been automatically separated from the PD.

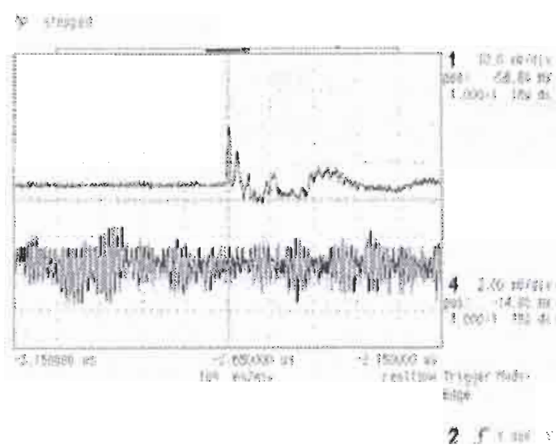

Fig. 9. Triggering from a large PD pulse via an 80-pF coupler (top trace) while viewing the output of the RTD with shielded leads (bottom trace). In hundreds of triggers on 6 RTDs, no corresponding PD pulse from any RTD was noted. The RTD scale is 5 times more sensitive.

D. Hydrogenerator Stators

On-line PD measurements were made on two 60 MW, 13.8 kV hydrogenerators. Instead of RTDs, these machines were equipped with 6 thermocouples. It was not known if the thermocouple leads were shielded or not. Using the 80 pF couplers, Unit G1 had the lowest PD of the two machines with a Qm of 106 mV, compared to 137 mV for G5. The signals from the thermocouples were heavily corrupted with static excitation system interference. However, when this was discounted, the signals from G1 thermocouples were 7 times bigger than those from G5. That is, using the thermocouples, one would infer that the wrong winding is the most deteriorated.

V. Coupling Of PD Signals Into As RTD

The above results in stators with real windings do not permit controlled studies of the effect of RTD lead length or the type of RTD lead shielding to be easily investigated. As a result, a laboratory test was made to determine the effect of RTD lead shield and to investigate exactly how the RTD detects the PD.

A simulated slot was made from a 2.5 m long aluminum channel, and a 2.5 cm diameter copper tube was suspended in the slot to represent the HV conductor of a coil with an air dielectric. The copper tube/slot combination was terminated at each end in its characteristic impedance to prevent reflections. A commercial platinum 100 ohm RTD with a 25 cm long element and a 3 m long unshielded triplexed wire was inserted at various locations in the slot. The RTD lead was sequentially placed in three locations:

- inside the slot from the RTD to one end of the slot;
- outside of the slot – but with the lead run on the outer surface of the channel;
- and with the lead outside of the slot and perpendicular to its slot length.

In addition, this set of locations was repeated with the entire RTD lead covered in a woven copper braid to simulate a shielded lead. The RTD element was always unshielded. The PD was detected at the remote end from the RTD element by an HFCT over the RTD lead that was then grounded to the simulated slot.

Fig. 10 shows the response to an injected 12 ns wide, 8 V simulated PD pulse. The pulse detected by the RTD was 60 mV for an unshielded RTD lead, while exactly the same RTD in the same position yielded a 4 mV signal when the RTD lead was shielded with copper braid. Table 4 shows the results with the RTD and its lead in other positions. The less of the lead in close proximity to the copper conductor- the lower the signal. Thus it seems that the PD signals are primarily detected by the RTD lead, and whether the lead is shielded or not has a tremendous impact on the magnitude detected.

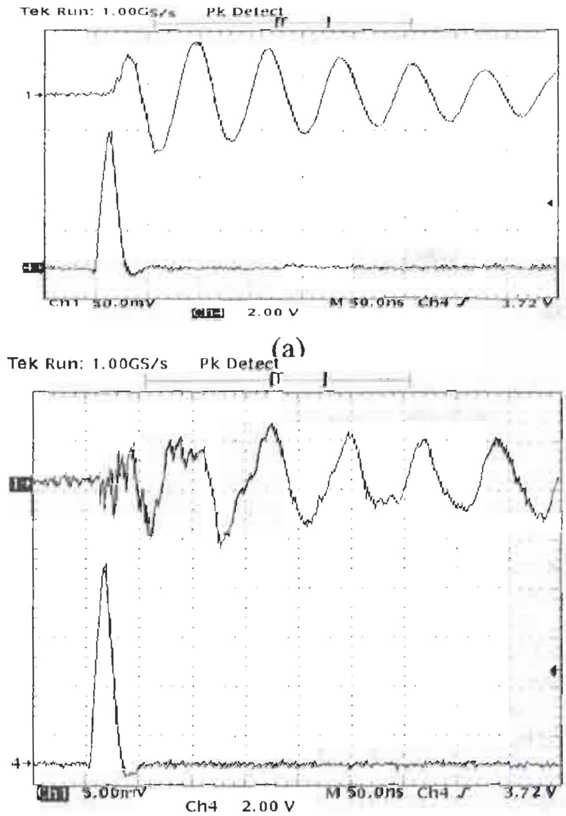

Fig. 10. Reponses to an injected pulse into a simulated slot (lower trace) with unshielded (a) and shielded (b) RTD lead run along the slot. Note the different vertical scales.

TABLE IV
Measured Magnitude Form RTDs

RTD Lead Position	Response (mV)	
	Unshielded Lead	Shielded Lead
Lead along entire slot	60	4
Lead along ½ of slot	20	3
Lead just at entrance to slot	18	3
Lead in adjacent slot	7	3
Lead outside of slot and perpendicular to it	12	5

CONCLUSIONS

Experiments have been conducted to determine the ability of RTDs in stator windings to detect PD. Tests were done on operating and off-line stators from motors, hydrogenerators and a turbine generator, as well as more controlled simulated coils in slots. It is clear that in most circumstances PD can be detected by the RTDs. However, rather than the RTD itself detecting the PD, it is the lead (or wires) from the RTD that detect the PD signal. Since the length of the lead wire, its proximity to high voltage stator coils, as well as whether the lead is shielded or not are all usually unknown– it is very difficult to interpret the severity of any PD from the magnitude of the detected signals.

This is verified by the on-line and off-line PD tests on 8 stators where the magnitude of the detected signals from the RTDs had no correlation to either the detected PD using conventional sensors, nor the known condition of the insulation.

These results also reveal other difficulties with interpreting PD results using RTD sensors. Since it is the lead that detects the PD, and since in most motors the RTD leads take a circuitous path from the slot around the stator – the lead is likely to detect PD from all three phases. Thus one does not normally see just two 'clumps' of pulses per cycle (often indicative of PD), but 6 clumps that often merge into a mass of pulses across the AC cycle, which makes separating noise from actual stator PD very difficult even for an expert. In addition, the actual position of the pulses with respect to the AC phase position is always unknown, and the pulse polarity information is lost when combined RTD/HFCT sensors are used.

The conclusion of these investigations is that while PD may be detected by RTD leads, even an expert with decades of experience will have a great deal of difficulty making useful, accurate conclusions on the condition of the stator winding insulation.

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