EXPERIENCE WITH COMPACT EPOXY-MICA CAPACITORS FOR ROTATING MACHINE PARTIAL DISCHARGE DETECTION

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Abstract - Partial discharge pulses in operating motors and generators are often detected by either RF current transformers or high-voltage capacitors. Since the mid-1970's, an 80 pF capacitor has become popular for detecting partial discharges in hydrogenerators and, more recently, in motors. The 80 pF capacitor is made from XLPE power cable, resulting in an inexpensive, yet bulky, capacitor. A reliable 80 pF capacitor has now been developed using a mica and epoxy dielectric. The epoxy-mica capacitor is much more compact making it significantly easier to install. In fact, the installation time for the epoxy-mica capacitor is typically half the time needed to install the cable-type capacitor. More than 600 capacitors have now been installed on hydrogenerators, motors, and small turbine generators. This article discusses the design of the new capacitor, presents its electrical characteristics, and provides some examples of its installation.

INTRODUCTION

Partial discharge (PD) testing of the condition of the stator winding insulation on operating motors and generators has been a practical technology since the early 1950's [1,2]. By measuring the level of PD, the overall condition of the high-voltage insulation can be assessed. As well it is often possible to determine the main cause of any deterioration (for example, overheating, loose coils, load cycling, etc. [1-3]). Motor and generator users prefer on-line tests since they do not require machine shutdown and can be performed as frequently as needed (typically every six months).

This paper briefly reviews some of the lumped electrical sensors that have been used for on-line partial discharge detection in motors and generators, and describes a new capacitive sensor that has proven reliable and cost-effective.

TYPES OF PARTIAL DISCHARGE SENSORS

Partial discharges are initially voltage or current pulses with a duration of a few nanoseconds [3,4]. As the pulses propagate through the stator winding, the pulse usually becomes very oscillatory and essentially manifests all frequencies below several hundred megahertz. Thus sensors must be sensitive to these high-frequency electrical pulses, yet be insensitive to high 60 Hz voltages and currents in the stator winding. Since the original development of the on-line partial discharge test by Johnson [1], two main types of electrical sensors have been used to detect the PD: the radio frequency current transformer and the high-voltage capacitor.

Radio Frequency Current Transformers

A radio frequency current transformer (RFCT) was perhaps the first sensor used to detect PD on operating machines [1]. The RFCT is installed on the (low-voltage) cable which usually connects the neutral point of a wye-connected stator winding to a ground fault detection system (normally a neutral grounding transformer). Any partial discharges will create high-frequency current pulses that travel through the winding, with some of the pulse current reaching the neutral grounding transformer. The RFCT detects this current, and the output signals can be displayed on an oscilloscope, spectrum analyzer, or pulse height analyzer. Users of the RFCT often refer to this type of PD test as RF Monitoring or EMI monitoring [5].

The RFCT usually has a split ferrite core and a 3 cm opening for the cable to pass through. No high-voltage insulation is needed since the neutral grounding cable is normally at ground potential. (Some provision is usually made for the high-voltage impulse voltages that may occur during a fault.) When compared to other types of CTs, the RFCT output is relatively large PD because of the ferrite

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core. The bandwidth is typically about 30 MHz. However, the actual pulse currents at the neutral are relatively small since considerable pulse energy gets diverted to ground as the pulse travels from the high-voltage part of the winding (where the PD occurs) to the neutral. Furthermore, since the RFCT is at the neutral point of the winding, it is not possible to determine on which phase the PD activity is occurring.

High-voltage Capacitors

The latter disadvantages lead some users to temporarily or permanently install high-voltage capacitors on the motor or generator terminals to detect the PD [2,6]. Capacitors behave like a short circuit to the high-frequency PD pulses, yet block the power frequency voltage. Since the voltage on the terminals of a machine can vary from 2.3 kV (for a 4 kV motor) to about 18 kV (for a 26 kV turbine generator), the PD capacitor must be able to withstand the high 60 Hz voltage without failure. Capacitances of 80 pF to 10,000 pF have been used for PD detection. The disadvantage of using capacitors is that care must be taken to ensure that the capacitors can withstand 60 Hz high-voltages, and the capacitors must be designed to have low inductance ensuring a good high-frequency response. These two properties typically make the capacitors more expensive than RFCTs. The advantage of using capacitors connected to the high-voltage terminals is that the pulse signals are usually much larger, since they are close to the parts of the winding where PD occurs. Furthermore, the PD activity in each phase can be determined.

Rogowski Coils

Some researchers have used "Rogowski" coils (a variant of the RFCT) to measure the PD currents on the machine terminals, enabling the researchers to measure the PD in each phase separately and to be close to the PD sources [7]. This sensor is a coil of usually hundreds of turns formed around a non-ferrous tube, which, in turn, is wrapped around the high-voltage lead from the machine. Since the machine lead is at high voltage, the Rogowski coil tends to have a large diameter (typically 10 to 15 cm) to ensure adequate voltage clearances, especially during lightning or switching surge conditions.

Since it does not have a ferrite core, the Rogowski coil has significantly lower sensitivity than an RFCT. Also, the bandwidth is relatively low (typically less than 100 kHz) due to high turn-to-turn capacitance, making the sensor insensitive to the frequencies containing most of the PD energy. As a result, the Rogowski coil is applied infrequently. Only experts who are knowledgeable about high-voltage clearances and who can separate the PD pulses from other types of high-frequency noise tend to use the Rogowski coil.

Cable-type Capacitors

In the mid-1970's, a variant of the capacitive sensor was developed especially for on-line PD detection in hydrogenerators. Two capacitors are permanently installed per phase to balance out electrical noise, which, if not eliminated, can lead to false indications of stator winding problems [8]. By the mid-1970's, it was apparent that PD pulses have their main energy content in the hundreds of megahertz, so only a small capacitance was needed to detect PD. The capacitance was arbitrarily chosen to be 80 pF. The cable-type capacitors, as they are termed, are usually fabricated from short lengths of 25 kV XLPE-insulated power cable. The center conductor of the cable is the high-voltage "plate" of the capacitor, and the cable shield is the low-voltage plate.

Since the capacitor is formed from 25 kV power cable, it was possible to make a capacitor that had a discharge extinction voltage (DEV, the voltage at which PD stops, as the voltage is lowered) of 35 kV rms or more. Furthermore, it was possible to design the cable-type capacitor to withstand the pollution that can occur in machines by ensuring a long creepage distance (that is the length of insulating surface between the exposed high-voltage conductor and ground). Since, the cable-type capacitors are relatively inexpensive to make and have a good bandwidth, over 6000 such capacitors have been installed in machines over a 15 year period.

The disadvantage of the cable-type capacitor is that it is relatively large with a length of about 1.2 m. This, in turn, makes them difficult to install with adequate electrical clearances, especially on smaller machines. In the early 1980's, the large size led one utility, BC Hydro, to employ a small, commercial, canister-shaped capacitor (made by Cornell-Dubilier Marketing, Inc.) for radio station transmitter applications as a PD sensor. This capacitor had mica splittings in an epoxy molding as the main dielectric.

Although effective, the capacitor was not designed for use on 60 Hz power equipment. Consequently it had a relatively poor DEV and could be subject to electrical tracking if the capacitor was exposed to partly conductive contamination over a long period of time. To overcome these limitations, a new epoxy-mica capacitor (EMC) has been developed for use as a partial discharge detector in motors and generators.

DESIGN OF THE EPOXY-MICA CAPACITOR

The dielectric of the new capacitor is ruby muscovite mica. Over 60 individual 46 µm thick mica wafers are interleaved with tin foils to form an 80 pF series stack of capacitor elements with less than 150 V stress on each section when the capacitor is operating at 8 kVac line-to-ground. Attention to rounding of all edges and vacuum epoxy impregnation of the soldered, stacked assembly assures discharge free voltage typically beyond 25 kVac. This conservative design has about one-tenth the stress of the groundwall insulation of a typical stator coil.

The mica stack is encapsulated in an epoxy using a vacuum casting process. A cycloaliphatic epoxy is used since this type of epoxy has excellent electrical tracking resistance. Cycloaliphatic epoxies are widely used for support insulators in gas-insulated switchgear operating up to 800 kV. The external shape of the capacitor is contoured to increase the creepage distance between the high-voltage and low-voltage electrodes. The creepage distance is 20cm, the typical creepage distance for 15 kV class insulators used in outdoor conditions, where contamination from rain, fog, salt, etc. can occur.

The capacitor is 13 cm high and 9 cm in diameter, considerably smaller than the cable-type capacitor.

ELECTRICAL CHARACTERISTICS

The nominal capacitance of the EMC is 80 pF.

Table 1

Coupler Number	Temp (ºC)	Capacitance (pF)	Dissipation Factor @1MHz
#1	23	79.234	0.00630
	85	79.248	0.00689
#2	23	79.060	0.00624
	85	79.106	0.00689

Table 1 shows the measured capacitances and dissipation factors for two capacitors, both at room temperature and at 85ºC, a typical operating temperature. There is very little change in dielectric properties with temperature.

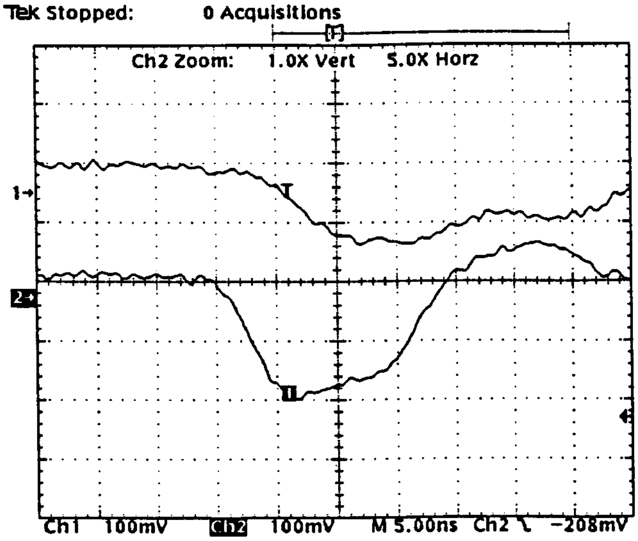

Figure 1: Oscilloscope photo of the response of the cable-type capacitor (top trace) and epoxy-mica capacitor (bottom trace) to a PD pulse from an energized stator coil.

The DEV of the capacitors is typically in excess of 25 kV rms, measured according to ASTM D1868, with a sensitivity of 5 pC. This sensitivity is somewhat lower than can be obtained with a cable-type capacitor (DEVs of 35 kV are typical). However, a DEV of 25 kV for the epoxy-mica capacitor is still more than three times the normal working voltage. In comparison, most 13.8 kV stator windings, using a similar dielectric as the epoxy-mica capacitor, have a DEV of only 6 or 7 kV rms.

Four capacitors were randomly selected for destructive over-voltage testing. Two were exposed to 70 kV rms (the limit of our test supply) for five minutes without puncture. The other two capacitors were subjected to a voltage endurance test at 30kV rms for more than 500 hours without failure. Because none of the four epoxy-mica capacitors failed, they have been rated for application on motors and generators rated 15 kV class or less. The voltage endurance tests continue today.

Since the epoxy-mica capacitors are more compact than the cable-type capacitor and there is less inductance in the epoxy-mica capacitor, it was hypothesized that the epoxy-mica capacitor would respond to PD pulses with greater fidelity. A 13.8 kV stator coil with known discharges from deteriorated semiconductive coatings was subjected to 8 kV. Both a cable-type capacitor and an epoxy-mica capacitor were connected to the coil at the same time.

The lead lengths to the coil were similar to what would occur in a typical installation in a hydrogenerator. Similarly, the shield of the output coaxial leads was not grounded directly at the capacitors, but rather indirectly grounded through the capacitance of the coaxial cable PVC jacket. The pulse response to the same PD pulse is shown in Figure 1.

The pulse response was measured with a 2 channel, 2 GHz single-shot sampling rate digital oscilloscope. The risetime of the pulse from the cable-type coupler was about 7 ns, whereas the risetime from the epoxy-mica capacitor was 5 ns. In accordance with the hypothesis, the pulse response is faster with the epoxy-mica capacitor. This faster response enables the pulse magnitudes to be captured with more fidelity [9]. The difference between the two types of capacitors would be greater if the PD source used produced even faster PD pulses.

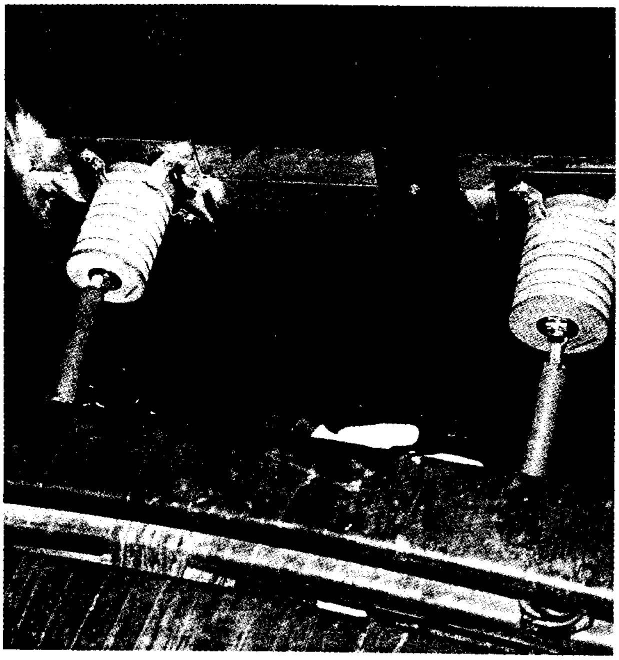

Figure 2: Photograph of the installation of 2 epoxy-mica capacitors on the circuit ring busses of a 14.7 kV, 141 MVA pumped-storage hydrogenerator. The capacitors have a post-insulator shape. The photo shows the high-voltage lead from the capacitor to the ring bus, prior to insulating the connection.

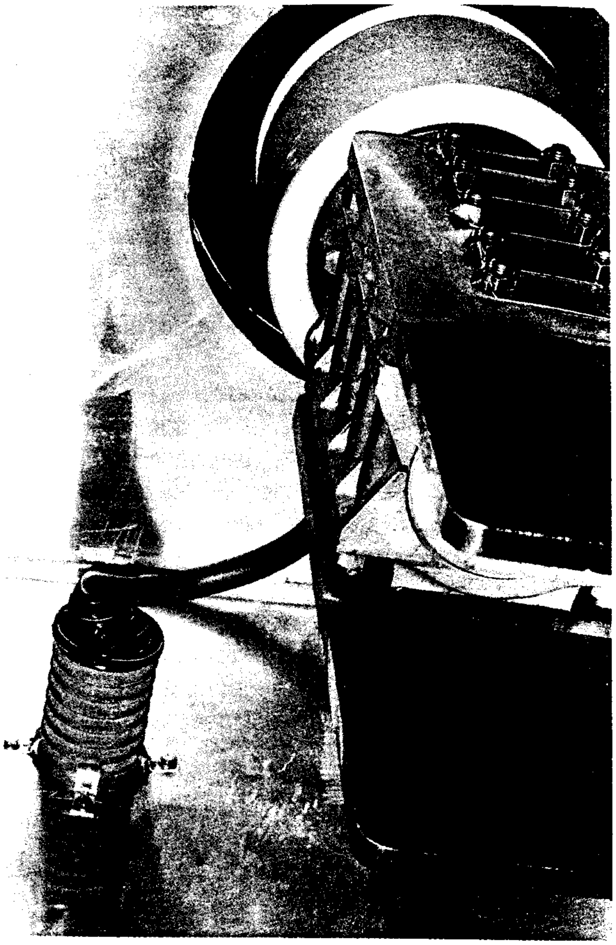

Figure 3: Photograph of the installation of an epoxy-mica capacitor on the terminal of a 13.8 kV, 188 MVA fossil-fired turbine generator. The output coaxial cable is visible from the base of the capacitor, as is the insulated high-voltage lead which is bolted to the generator terminal.

INSTALLATION

Since early 1994, about 600 epoxy-mica capacitors have been installed on hydrogenerators, turbine generators and motors rated 15 kV or less (see Figures 2 and 3 for some typical installations). In virtually all cases, the capacitors are mounted on the grounded metal structure of the generator (in the case of hydrogenerators), or against the grounded metal enclosure of the machine terminal box or switchgear cubicle (motors and small turbine generators). The capacitor is mounted by means of 4 clips which fasten the base of the capacitor.

The high-voltage terminal is connected to the hydrogenerator circuit ring bus or machine terminals by a 15 kV insulated but unshielded lead. To ensure good high-frequency response, the lead is usually less than 30 cm in length. The high-voltage terminal is then insulated with either a thixotropic epoxy or self-amalgamating putty and tapes. In the latter case, a silicon rubber tape or a plastic boot covers the self-amalgamating tapes to protect them from contamination.

CONCLUSIONS

An improved 80 pF capacitor has been developed that is suitable for detecting partial discharges on operating motor and generator stator windings. The capacitor is intended for installation on any hydrogenerator rated about 15 kV or below, turbine generators rated less than about 15 kV and 100 MVA, and all motors.

Experience indicates that it takes about half the time to install the epoxy-mica capacitor than it does to install the cable-type capacitor. Special efforts have been made to make the capacitor compact while maintaining the dielectric integrity necessary to ensure reliable operation.

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