STATIC ELECTRIFICATION EFFECTS IN
TRANSFORMER OIL CIRCULATING PUMPS

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ABSTRACT - The work reported herein was aimed at determining whether or not static electrification production mechanisms could be present in the external oil circulating system of a power transformer. Several techniques were utilized. These were: monitoring the leakage current from 1) insulated pipe sections, and 2) conducting probes introduced into the flowing oil. The value of the charge contained in the oil was determined using a recently developed absolute charge sensor. Acoustic emission detection techniques were also used in order to detect any partial discharges resulting from significant charge separation build-up in any one location.

Although doubts exist relative to the quality of some of the data obtained, sufficient evidence was collected to show that under certain conditions the oil circulating pump could be a significant contributor to static electrification levels in operating power transformers.

KEY WORDS
Static Electrification
Circulating Pumps
Power Transformers
Transformer Oil

INTRODUCTION

Recent concern over the possible damaging effects of static electrification in operating power transformers has prompted much investigative work. As the most obvious damaging consequences of this phenomenon is its degrading effect on the internal insulation system, the majority of work has been directed at understanding the static electrification production mechanisms at work within the internal core and coil geometry. Realizing that a significant portion of the oil circulating system is external to the transformer tank, this work was aimed at evaluating whether or not any static electrification production processes were also at work there.

STATIC ELECTRIFICATION, CIRCULATING PUMPS

Experimental Approach

In order to detect the existence of charge separation in the external oil stream, several monitoring techniques were utilized. The first was the utilization of isolated pipe sections [1]. In this technique, charge transport within the pipe is monitored by introducing an electrometer into the circuit connecting the pipe section to ground. The current measured by the electrometer is the difference between current leaving the pipe to that entering the pipe. If no charge is separated within the pipe, exiting current will be less than entering current due to leakage currents to the wall from ohmic conduction or charge migration driven by the space charge self/field. On the other hand, even if there is no charge entering the pipe section, there can be charge leaving if charge is separated from the pipe wall. Thus, from measurement of the wall current alone, it is impossible to decide if the current is due to upstream generated charge, such as from a pump, or from charge separated within the pipe and then entrained in the flow.

The second technique also utilized the ground leakage current monitoring approach. However, in this case, a conducting probe (Fig. 1) was introduced directly into the oil itself.

Fig. 1 Conducting probe.

By this means it was hoped to detect charge stratification in the oil stream. However, interpretation of this measurement is also ambiguous as it is impossible to tell if measured current is due to upstream generated charge impacting onto the conductor or if charge is being stripped off the conductor itself.


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The third technique was partial discharge detection. This was done in an attempt to detect any partial discharges produced if the charge separation in the oil achieves a sufficient magnitude. As there was no external electrical stress applied to the system, conventional partial discharge (PD) detection techniques such as radio interference voltage or apparent charge detection was not applicable. Consequently, an acoustic emission detection technique developed under previous EPRI sponsorship [2] was utilized. The charge density values from flow electrification are not high enough to cause partial discharges. To cause those, electrification charge must accumulate on insulating or isolated surfaces to high enough levels to raise the surface potential above the breakdown strength of the oil.

Despite some ambiguity in measurement interpretation, using these techniques, it was hoped that charge separation in the oil would be detected. Charge build-up on the isolated pipe sections would be detected by leakage current technique and partial discharges detected, and their approximate location determined by means of the acoustic emission technique.

To obtain better understanding of electrification phenomena and to remove ambiguity in measurements, utilization was made of an absolute charge sensor (ACS) developed at MIT under EPRI sponsorship [3]. The electrical and mechanical schematics are shown in Fig. 2, while the detailed construction is shown in Fig. 3.

In operation, fluid is pumped in and out of a metal bellows chamber driven by a linear actuator so that the bellows volume periodically changes with time. The metal bellows is connected to an electrometer so that the measured short-circuit current or open-circuit voltage is directly proportional to the fluid charge density. The small entrance pipe to the bellows volume is at the end of a shielded pipe, so that streaming currents generated from flow electrification on the outer surface of the probe are not measured. The Faraday cage volume includes the inner probe and the metal bellows volume. Charge brought into the inner probe immediately induces an opposite charge on the interior wall of the Faraday cage surface. Thus, without actually being transported to the wall, the net charge induced onto the inner wall is equal but of opposite polarity to that in the fluid. In addition to the image charge there are two other currents. One is the conduction current associated with relaxation and migration of the charged fluid. The other is a current due to flow induced electrification processes on the inner surface of the Faraday cage. The external current or voltage measured by the electrometer during the filling cycle is independent of processes that occur inside the Faraday cage volume, whether they are due to imaging, charge relaxation, charge migration, or electrification. This is because the total charge within the Faraday cage volume and surface remains unchanged. Thus, as soon as charge enters the ACS sampling probe, it is immediately recorded by the electrometer, whether it remains entrained in the fluid or is conducted to the wall.
EXPERIMENTAL SET UP

Arrangements were made to carry out the investigation at the facilities of a manufacturer and refurbisher of transformer oil circulating pumps. Consequently, a test facility was already in existence. This was basically a 1500 gallon tank with the appropriate piping and fittings, as well as the necessary instrumentation for pump performance monitoring. The system was further modified to enable a nitrogen gas blanket to be applied to the oil, and an auxiliary header tank was added so that the system could also be set up to simulate an oil conservator system. The test setup is shown schematically in Fig. 4. Two probes were placed into the oil stream as shown in Fig. 5. One was mounted at the flange just upstream of the pump inlet, and the second at the flange just downstream of the transformer valve outlet. In each case, the conducting tip was introduced approximately 2 cm into the oil stream. Preliminary ACS measurements were also conducted with the ACS mounted just downstream of the transformer valve outlet.

The intent being to simulate transformer oil circulating systems currently in use in the field, pumps and valves produced by several manufacturers were utilized. Initially, only the same manufacturers' pump and valve combinations were used, however, later in the series tests were run with no valve in the system and its place taken by either a plain or corrugated pipe section.

The oil used for the test was a new batch of Shell Diala A transformer oil.

The system was first set up to simulate a conservator arrangement, and filled with "wet" (18 ppm moisture) oil. Each manufacturer's pump and valve combination was set up to deliver the nameplate flow rate, while working into the appropriate back pressure, etc. The oil temperature for this and all subsequent tests was maintained at 40°C ± 5°C.

The tests were then repeated with the tank setup simulating a nitrogen blanketed transformer arrangement.

The oil was then dried to a moisture level of 6 ppm and the tests repeated utilizing the conservator simulating setup.

For each of the previously described tests, the pump was allowed to run for approximately 15 minutes so that all parameters could equilibrate before data was acquired. Also, by manipulating the pump back pressure, each pump/valve combination was made to produce oil flow rates both higher and lower than their nameplate ratings. It should be noted that these flow variations were obtained with the pump motors running at constant speed, the flow rate being modified simply by manipulating the back pressure into which the pumps were working. One of the pumps was also modified by substituting a smaller diameter impeller. In this case, no back pressure modification was required to achieve a lower flow rate.

The pumps used were as follows:

A. Westinghouse/Ingersol-Rand rated at 800 gpm with bronze bearings.
B. Westinghouse/Ingersol-Rand rated at 650 gpm with bronze bearings.
C. Westinghouse/Cardinal rated at 800 gpm with bronze bearings.
D. Westinghouse/Cardinal rated at 650 gpm with bronze bearings.
E. Westinghouse/Cardinal rated at 800 gpm with polymeric bearings.
F. Westinghouse/Cardinal rated at 650 gpm with polymeric bearings.
H. General Electric mixed flow rated at 650 gpm with ball bearings.

Each pump was run in conjunction with its matching valve.
The McGraw-Edison and Westinghouse valves were similar in design, both being "flap" valves. The principal difference being that the McGraw-Edison flap was a plain steel disc while the Westinghouse disc had a polymeric coating. In contrast, the General Electric version was quite different in that it was a "gate" valve design.

In order to determine the effect (if any) of the valve, pump (E) was also run with either a plain pipe or flexible section substituted for its valve.

RESULTS

McGraw-Edison Company

The charging tendency of the wet oil was checked using a mini-static charge density tester and found to be 25 microcoulombs per-cubic meter. This was considerably lower than had been anticipated so a sample was sent to another laboratory for corroboration. Within a reasonable experimental area, the results were confirmed. When using this wet oil, no combination of test setup or pump/valve combination produced any significant charge separation detectable with our instrumentation. No ACS measurements were conducted at this time because the instrument was not then available. At a later date the oil was dried to a moisture content of 6 ppm at which time the charging tendency was found to be 121 microcoulombs per-cubic meter. Repeating the tests with the oil in this condition produced significant results. The current measured both by the probes in the oil stream and the surface contacted insulated flanges produced the results shown in Table 1.

It can be seen there that higher flow rates always produced higher currents. It should also be noted that the polarity of the leakage current detected from the insulated flanges depended on the type of material used in the bearings. Those values denoted as being unusable resulted from the simultaneous evaluation of other instrumentation which interfered with the performance of these instruments.

Partial discharges were detected by the acoustic emission system any time the flow rate exceeded approximately 700-gallons-per-minute with any test setup. A typical example of a PD burst is shown in Fig. 6.

![Fig. 6 Typical acoustic emission burst from partial discharges.](image)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Flow Rate</th>
<th>Pump A (GPM)</th>
<th>Pump B (GPM)</th>
<th>Pump C (GPM)</th>
<th>Pump D (GPM)</th>
<th>Pump E (GPM)</th>
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Table 1: Results from Oil Probes and Insulated Flange Sections

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Note: X = Unusable/Erratic Values
Fig. 7 Output from conductive probe and acoustic emission monitors.

Whenever PDs were detected, their locations were found to be close to the pump outlet and the valve inlet. When the valve was removed and substituted with a plain pipe section, no discharges were detected at that location and furthermore, fewer discharges were detected near the pump outlet. With a corrugated pipe section in the same position, again no PDs were detected at that location, however the activity at the pump outlet was now intermediate between that produced when a valve and smooth pipe was used.

Little or no difference was found when the tank test setup was configured either as a conservator or nitrogen blanketed transformer. However, as the nitrogen was introduced into the head space only shortly before testing commenced, there is some doubt as to the degree of saturation of nitrogen in the oil at that time.

Little difference was found in the results of modifying the oil flow by either varying back pressure or changing the impeller diameter. In either case, higher flow rates produced higher leakage currents and more discharges.

The ACS was connected to a flange just after the discharge side of a 6 HP Westinghouse/Cardinal Clean Flow Pump with polymeric bearings. This was the only pump testing with the ACS. With the pump off so that the oil was stationary, no charge was detected by the ACS. With the pump turned on, the measured average charge density in the oil for flow rates of 600 to 1030 gpm decreased from 10.6 to 5.0 microcoulomb per cubic meter. The streaming current generated by the pump, given by the product of charge density and flow rate, remained roughly constant for these measurements. The charge density decrease with increasing flow rate was probably because the flow was decreased by closing a downstream valve keeping the pump impeller tip speed constant. For a constant impeller speed, the hydrodynamic diffusion sub layer thickness near the pump and impeller surfaces remains constant. Analysis [4] shows that when the oil residence time within the pump is much shorter than the dielectric relaxation time and diffusion time for charge to diffuse across the hydrodynamic sub layer, the streaming current reaches a saturation value independent of the flow rate. The charge density is then given by the saturation current divided by the volume rate of flow.

The oil had a dielectric relaxation time of about 12 seconds. At 1030 gpm (1.065 m/s), the linear oil velocity for a 6 inch diameter pipe is 3.6 m/s. Then the relaxation length is about 43 meters. Because this length is much greater than the flange length of about 4 inches, a current measured to the flange wall is simply equal to the difference in charge densities at flange outlet and inlet multiplied by the flange volume and divided by the dielectric relaxation time. Dividing the current measurements in Table 1 by the flow rate gives the charge density. For the Cardinal high flow pump with plastic bearings at flange 3 where the ACS was placed the charge density is thus 1.3 microcoulombs per cubic meter at 430 gpm and 10.4 microcoulombs per cubic meter at 800 gpm. These values are comparable to the ACS measurements. Note however, that the "probe" measurements cannot give an absolute value of charge density, only the difference in charge densities at inlet and outlet of the test flange.

LABORATORY MODEL

The acoustic emission measurements indicate the presence of partial discharges in the vicinity of the valve at the pump outlet and within the pump itself. Charge generated within the pump could accumulate on the insulating surface of the valve causing the surface to rise in potential. If leakage is slower than the rate of charge accumulation, the potential of this surface will also rise. When the electric field exceeds about 100 kV/cm, spark discharges can occur. Charge may be generated within the pump by stripping positive charge off the rotor. This will leave negative charge behind on the rotor surface and raise the rotor potential. Partial discharges could then result across the insulating oil in the small gap of the bearing. Because this gap is so small, modest voltages could result in an electric field that exceeds the oil breakdown strength.

To better understand such mechanisms the Couette charger (CC) system in Fig. 8 was used in laboratory measurements (4). Notation of the inner cylinder simulates the role of the pump rotor. The ACS is used to measure the charge density in the turbulent core flow.

Fig. 8 Couette charger with electrical terminals connecting inner and outer terminals for measuring open circuit voltage or short circuit current.
The open circuit voltage or short circuit current to the rotor is also measured. In our apparatus at 2000 rpm, the open circuit voltage reaches 20 volts in about 3 minutes (5). If such modest voltages developed across the small lubricating gap in a pump bearing, the resulting large field strengths could cause a discharge. Continuing analysis and modeling is examining voltage rise predictions for dimensions and flow conditions appropriate to a rotor bearing.

CONCLUSIONS AND DISCUSSION

Although this investigation was by no means exhaustive, sufficient evidence was produced to suggest that charge separations can take place in the external oil circulating system of a power transformer. When it occurs, the prime producer appears to be the pump. Its interaction with its neighboring valve apparently playing a secondary role. Although some differences in charge amplitude and polarity could be correlated with variations in pump design or bearing material, the most significant parameters appear to be the oil flow rate and oil moisture content. Both high flow rates and dry oil were necessary to produce significant charge separation. Although some doubts arise regarding the nitrogen gas saturation data, at least superficially it appeared to have little effect.

This investigation addressed only one portion of the transformer external oil circuit. The effects of oil coolers, etc., was not involved. However, if as this work suggests, the circulating pump can under some circumstances produce a significant level of static electrification in the oil, more work needs to be done in order to obtain a better understanding of this phenomena. The pump is normally in very close proximity to the transformer tank wall so that it is possible that statically-charged oil could be introduced into the transformer. Its effects could then be further enhanced by internal charge generating mechanisms.

Continuous EPRI directed research is planned to quantify magnitude and polarity of static charge generation and relaxation within representative forced-oil flow path elements external to the core and coils of large power transformers. Electrification measurements are planned in a test fixture consisting of appropriate pumps, valves, and heat exchangers. In this work it is intended to use multiple ACS monitors to quantify the charge both entering and leaving components. Refinements of the insulated pipe section and oil probe techniques will also be used. It is also intended to study the effect of oil temperature, moisture and gas content as well as the obvious parameters associated with pump operation such as flow rates, etc.

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REFERENCES


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Mr. Lindgren is a member of the Power Engineering Society, Eta Kappa Nu, Sigma Tau and Phi Kappa Phi.