ELECTROHYDRODYNAMIC PUMPING OF CABLE OIL WITH SINGLE PHASE EXCITATION

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Abstract - Cable oil is pumped by a single phase voltage supply acting through phase shifting networks which generate a travelling electric field. The field is produced by electrodes which also induce a space charge in the oil as a result of thermal gradients caused by external heating. The electric field acts on the charge to pull the oil in the same direction as the field.

The velocity of the resulting flow is predicted by an approximate theory based on symmetrical components and 3 phase EHD pumping. Occasional erratic behaviors of the pump have not yet been explained.

I. INTRODUCTION

Electrohydrodynamic (EHD) induction pumps[1] offer an attractive alternative to mechanical pumps in several applications because they act directly on the fluid and have no moving parts. One possible area of application is the circulation of cooling oil in underground power cable pipes(2). The length of cable which can be cooled by a mechanical pump is often limited by the pressure head at the inlet which is needed to move the oil throughout the pipe. Since an EHD pump acts directly on the oil, the pressure rise can be eliminated, and the cooled length extended.

In all EHD pumps described to date, however, the electrical input consists of at least three phases, with attendant wires and connections. These three phases are required to produce the travelling wave which is needed for an induction pump, but the complex wiring arrangement is a drawback for practical implementation. The present paper describes the first attempt to operate an EHD induction pump from a single phase source.

The fluid in the experiments is cable insulating oil contained in a re-entrant channel between hot and cold baths. The active section consists of three electrodes extending over one seventh of the circumference of the channel, so that the velocity of the oil can be observed in the relatively smooth flow away from the electric fields.

When voltage is applied to the electrodes a small leakage current flows through the oil. The conductivity of the oil is higher in the hotter regions, and the electric field is correspondingly weaker there. The variation of electric field implies the presence within the oil of free charge supplied by the leakage current. When the externally applied voltage moves along the electrode, the free charge follows it, and in turn drags the oil.

The three voltage phases which are required for a travelling wave are generated inside the pump by combinations of resistive and capacitive elements. Although the eventual design of such a pump envisions a distributed arrangement of these elements, the version described here uses discrete resistors and capacitors connected to electrodes adjacent to the fluid. When driven by a single phase square wave, these circuit elements produce output voltage with varying amounts of phase shift. As is customary in machine theory, these voltages can be represented in terms of symmetrical component waves. By proper choice of elements and frequency, either the forward or the backward wave can be made dominant, thus pumping the fluid in the desired direction as in the usual EHD induction pump.

II Apparatus

The pump was built in a closed loop of rectangular cross section, as shown in Figure 1.

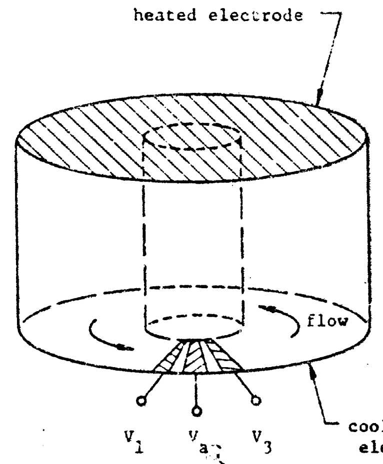

Figure 1. Insulating oil is driven around a closed channel by the electric fields produced by the three electrodes.

The upper electrode was grounded, as was most of the lower electrode, so that the electric field was confined to a short section of the channel, where three externally driven electrodes were located below the oil.

The temperature gradient which creates the conductivity gradient was established by a hot water bath on top of the oil and flow of cooled oil under the pumping electrode. A constant temperature heater element in the hot water bath provided a temperature of about 72°C at upper surface of the oil. Chilled oil at 12°C was supplied by simple heat exchanger in an ice bath and established a temperature of about 30°C at the interface between the oil and the pumping electrode. The temperature gradient established at the normally used 3 cm oil depth was 14°C/cm. These static temperatures (no pumping present) were determined using six thermocouples placed every vertical 1/2 cm and recorded with a Fluke Datalogger. Two hours were allowed for the system to come to steady-state before temperture measurements were taken.

Each of the three electrodes was driven from the same high voltage square wave source through a different phase shifting network. The square wave was generated by connecting two high voltage DC power supplies of opposite polarity to a commutator which was rotated by a variable speed motor. The voltage range possible from the rheostat controlled DC power supply was 0 to 30 kV and the variable speed motor produced frequencies from .3 to 4 HZ.

Initially it was thought that the phase shifting networks could be incorporated immediately into the electrodes, but difficulty with material stability

Proceedings, IEEE/IAS Conf. on Industrial Application, Oct 1979

made it desireable to locate these networks externally, where they could be checked more easily. The circuits used in the experiments, shown in figure 2, were chosen to duplicate the electric relaxation times of the oil and electrodes.

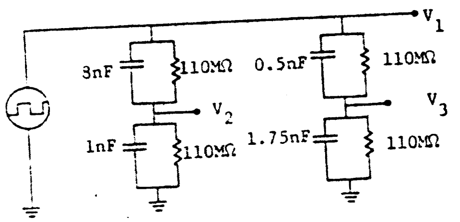

Figure 2. The three voltage phases were produced by RC phase shifting networks.

The impedance levels, however, were approximately 1% of the oil and electrodes, so that the voltages were not greatly affected by changes in the material properties.

II Theory

The voltages at the three electrode surfaces form a highly unbalanced three phase voltage system. These voltages will not usually lead to a pure forward travelling wave at the electrode surface, so some type of analysis must be employed to obtain the magnitude of the forward as well as the backward wave. A common method of analyzing unbalanced three phase systems to obtain the net force produced is the symmetrical components technique(3) used in electrical power systems. This technique was used to determine the magnitudes of the positive (forward) and negative (backward) waves.

To determine the voltage magnitude and phase angles across the insulating oil, the phase shifting networks were analyzed as a series arrangement of two parallel RC circuits, using standard circuit techniques for each electrode voltage. These electrode voltages are used in the symmetrical component equations (1), (2), (3), to calculate the forward, backward, and standing wave magnitudes.

$$|V_{FORWARD}| = \frac{1}{3}\,[V_1 + cV_2 + c^2 V_3] \qquad (1)$$

$$|V_{BACKWARD}| = \frac{1}{3}\,[V_1 + c^2 V_2 + cV_3] \qquad (2)$$

$$|V_{STANDING}| = \frac{1}{3}\,[V_1 + V_2 + V_3] \qquad (3)$$

where $c = 1.0 \angle 120°$ $c^2 = 1.0 \angle 240°$

With the magnitude of the travelling wave determined from symmetrical component analysis and a knowledge of properties and dimensions of the pumping configuration, the electrical shear stress produced can be determined from earlier work[4].

The actual pump contains some continuous temperature gradient (not known exactly causing a gradual change in the oil properties (permittivity, conductivity, and viscosity). This situation can be simplified by modelling the insulating oil as two distinct layers each having their own uniform conductivity, permittivity, and viscosity as shown in figure 3, in which the channel is assumed to extend indefinitely in two dimensions.

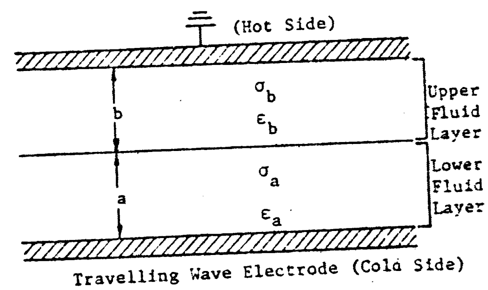

Figure 3. The oil is modelled as two layers at different temperatures

With these assumptions, the shear stress on the liquid can be calculated in terms of the magnitude and frequency of the applied voltage, the repeat length of the electrodes, the conductivity and permittivity of the oil, the geometry of the channel and the velocity of the flow. This result can be used to estimate the force applied by a short pump by multiplying the stress by the active area.

The force produced by the pump must balance the viscous drag of the oil, which also depends on flow velocity. For the experiments described here. The fluid Reynolds number is ≈10, so the flow can be considered laminar. Laminar flow solutions in a rectangular channel are well documented and indicate a linear relation between viscous shear stress and mean channel velocity[5].

Once the electric force and viscous drag expressions are obtained, they can be equated to give the velocity of the oil. This was done numerically, due to the complexity of the equations[6]. In these calculations, the following values, corresponding to experimental conditions, were used:

<u>Oil</u>

viscosity	= 6.16 mPa-s
Permittivity	$= \varepsilon_a = \varepsilon_b = 2.5\ \varepsilon_o$
conductivity	$= \sigma_a = 70.4$ pS/m
	$\sigma_b = 31.2$ pS/m

<u>Channel</u>

circumference	= 0.62 m
width	= .05 m
depth	= .03 m
active region length	$= \lambda =$ .09 m

Since the applied voltage was a square wave, only the fundamental component was used to calculate the voltages produced by the phase shifting networks.

IV RESULTS

Using the test apparatus described above, two basic experiments were performed with the pumping electrode. First, the dependence of velocity on the frequency of the applied voltage was studied. Experiments were performed at voltage levels of 5 kilovolts and 8 kilovolts and the frequency was swept from 0.5 Hz to 6.7 Hz. These voltage values were chosen because they gave velocities of large enough magitude to be measured by simple means. Also, at the these voltage levels vertical stirring of the oil in the channel was kept to minimum; at higher voltages large swirling eddies almost covered the active region of the channel, greatly disturbing the temperature gradient. Once the temperature gradient was mixed a definite decrease in flow velocities was noted.

A second type of experiment was performed to find the dependence of velocity on the voltage level of the applied potential wave. Tests were performed at frequencies of 1.0 Hz and 2.25 Hz for a range of voltages between 4.0 kilovolts. At voltages below 4.0 kV, velocites were very small and difficult to measure because most particles would not remain suspended throughout the test region.

In an effort to produce repeatable test conditions, care was taken to keep both the chilled oil and hot water baths at similar temperatures during each test. Also the gradient was applied for two hours before any velocities were measured in an effort to obtain a "steady state" temperature gradient.

The results of these experiments are shown in the following figures, along with the theoretically calculated velocites. Figures 4 and 5 show that both the magnitude and the frequency response of the pump agree with predictions, although the higher voltage (8kV, Figure 5) appears to give more than the predicted flow. Although measurements for lower frequencies (<0.3 Hz) are not shown, the flow stopped when DC was applied, indicating that ion-drag pumping is prabably not responsible for the oil velocity observed here.

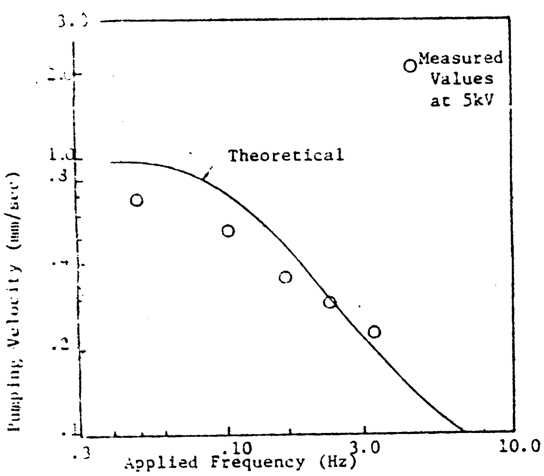

Figure 4. Pump velocity versus frequency at 5.0 kV

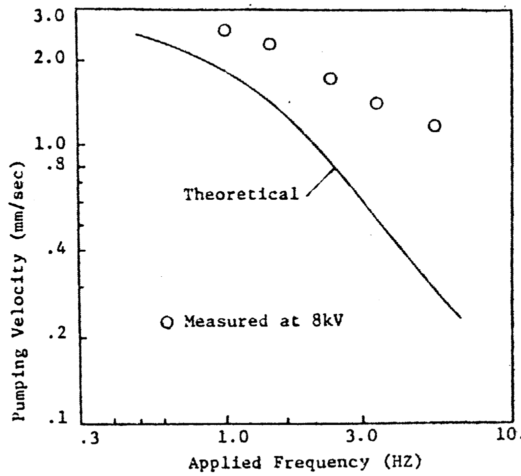

Figure 5. Pump velocity versus frequency at 8.0 kV.

The low frequencies at which peak force is generaged are characteristic of EHD induction pumps designed for fluids that must be good insulators at 60Hz. The relaxation frequency of such liquids is always far below 60Hz, and since pumping is most effective when the applied frequency is near the relaxation frequency, the pumps are usually designed to operate at sub-Hertz frequencies.

The results for velocity as a function of applied voltage (Figure 6 and 7) show similar agreement with theory.

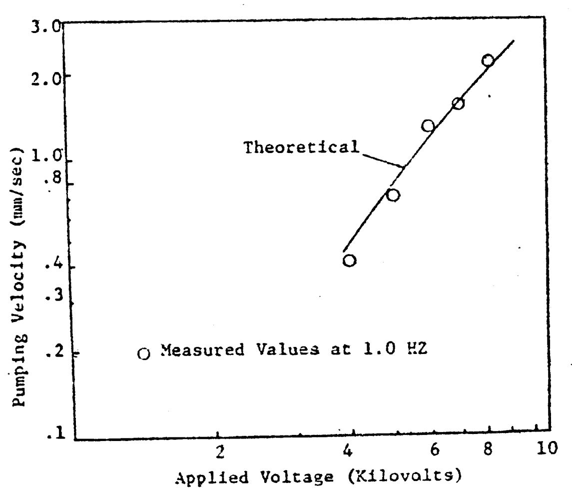

Figure 6. Pumping Velocity vs. Voltage at 1.0 HZ

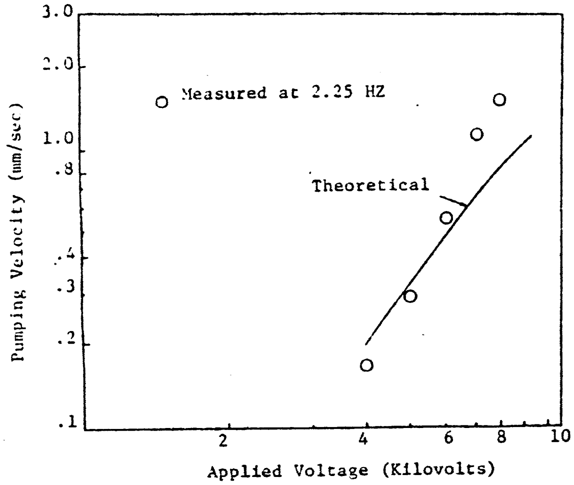

Figure 7. Pump velocity versus Voltage at 2.25 Hz

Above 8kV, electroconvection of the oil set in, so that the thermal gradient could not be determined, and no measurements were taken, although motion could still be observed.

These results were all obtained when the pump was operating "normally", i.e. as predicted by the theory. On several occasions, however, the pump behaved erratically, for reasons which are not entirely clear. For example, the pump might refuse to start, or after running for some time, it would slow down and stop. Often, reversing the phase sequence would not reverse the direction of flow, as expected, although it would change the speed significantly. Since this erratic behavior would not be acceptable in undeground power cable pipes, its causes are being sought in further research.

V CONCLUSION

From the results of the experiments, it seems clear that an EHD induction pump can be successfully operated from a single phase supply by using RC phase shifters. This type of circuit, although easy to build, can only give a total phase diffence of 90°, compared to the 240° in an ordinary 3 phase circuit. Nonetheless, this reduced difference is sufficient to generate a travelling wave capable of pumping cable oil, at a flow rate which can be estimated by a straightforward application of existing theory. Further work must still be done, however, before the pump is reliable enough for unattended operation.

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ACKNOWLEDGEMENT

This work was supported by the Electric Power Research Institute under Contract No. RP 7853-1-B, and is based in part on an M.S. thesis submitted by one of us (M.F.O.) to the Department of Mechanical Engineering of the University of Illinois.