The scalar potential developed by a spinning current-carrying solenoid

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Abstract. A current-carrying solenoid was spun about its winding axis and the resultant scalar potential was measured between its metal container and a surrounding metal enclosure. The two metal enclosures were separated by polystyrene stand-off insulators. The coil, spinning at 17.3 revolutions per second and carrying 1.13 A, was found to develop $-0.96 \pm 0.2$ mV between the two enclosures when the current flowed in the direction of coil rotation. This voltage difference is equal to the voltage that would be developed by a charge of $-4.8 \times 10^{-14}$ C inside the inner enclosure.

1. Introduction

The electric and magnetic effects of a current-carrying solenoid spinning about its winding axis have been studied by a number of investigators. A circular winding carrying an alternating current was spun about its axis by Nichols and Franklin (1889) to see if the rotation would unbalance the average magnetic field. Using a magnetic needle to detect average magnetic field they found the rotation had no effect.

O’Rahilly (1938) conducted a theoretical analysis of the electric field about a spinning current-carrying coil. He conducted two analyses, one based on equations developed by Lorentz and the other on equations developed by Ritz. Both studies showed that currents in the spinning coil would generate electric fields which produced forces on stationary charges. The two theories were in disagreement on the value of electric field.

There is no experimental evidence that a DC electromotive force can be induced around a stationary closed loop. Thus if a spinning current-carrying solenoid does set up an electric field in surrounding space that field must be the gradient of a scalar potential. This paper describes an experiment in which the scalar potential developed by a spinning current-carrying solenoid was directly measured.

2. Experimental set-up

A solenoid was enclosed in a sheet-iron box. A current was applied to the solenoid through slip rings, and the solenoid was rotated about its cylindrical axis by a DC electric motor. The metal box with enclosed solenoid, battery, motor, and slip rings was mounted on polystyrene stand-off insulators inside a larger metal enclosure. The outer dimensions of the inner box were $6 \times 6 \frac{1}{2} \times 18 \frac{1}{2}$ in$^3$; the inner dimensions of the outer metal enclosure were $15 \times 15 \times 24 \frac{1}{2}$ in$^3$. A schematic of the experimental set-up is shown in figure 1.
The current through the rotating solenoid was turned on and off at a two-second period by an internally mounted thermal interrupter. The change of potential between the two metal boxes due to the solenoid current was detected with a balanced cathode follower electrometer. A Hewlett-Packard 412-A millivoltmeter connected between the balanced cathodes measured potential change. The solenoid data are listed in table 1.

Table 1. Solenoid data

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius of coil</td>
<td>$7.93 \times 10^{-3}$ m</td>
<td>$N$:</td>
<td>5600 turns</td>
</tr>
<tr>
<td>Outer radius of coil</td>
<td>$49.7 \times 10^{-3}$ m</td>
<td>Wire size:</td>
<td>18 AWG</td>
</tr>
<tr>
<td>Length of coil</td>
<td>0.173 m</td>
<td>Current at 24 V:</td>
<td>1.13 A</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>17.3 revolutions/second</td>
<td>Resistance at 20°C:</td>
<td>21.2 Ω</td>
</tr>
</tbody>
</table>

The balanced cathode follower was made up of two 5886 vacuum tubes each having 15 000 Ω resistors from cathode to ground. A separate 1.5 V dry cell furnished heater power for each cathode, and a 12 V storage battery furnished power to screen and plate which were tied together. One grid was connected to the inner box whose potential was to be measured. A $2 \times 10^8$ MΩ resistor was connected from this grid to the outer enclosure, which served as ground potential for the cathode-follower circuit. The other grid was connected to the variable tap on a resistor to provide an adjustable DC voltage source. By varying the resistor tap the two cathode voltages were balanced and their difference could be measured on a millivoltmeter scale. A Hewlett-Packard 412-A millivoltmeter was connected between the two cathodes. Then the difference in voltage level between cathodes was measured when the rotating solenoid current was turned on and when the current was turned off. The difference between the two readings is a measure of the potential due to rotating coil current.

The cathode-follower gain measured from grid to cathode was found to be 0.52.
The capacitance between the inner and outer metal enclosure was measured by the substitution method using a General Radio precision variable capacitor and a General Radio impedance bridge. The capacitance between the two enclosures was measured as \( K = 50 \times 10^{-12} \, \text{F} \).

3. Results

The coil was rotated at 17.3 revolutions per second. A current of 1.13 A flowing in the direction of coil rotation was turned on and off over a 2 s period. The potential of the inner metal box with respect to the outer enclosure went negative by \( 0.96 \pm 0.2 \, \text{mV} \) when the current was turned on. When the current was turned off the potential went up to its former value. With the coil stationary no potential change was observed when the current was turned on and off.

With \( 50 \times 10^{-12} \, \text{F} \) capacitance between the enclosures a \( -0.96 \times 10^{-8} \, \text{V} \) potential change is equivalent to \( Q = -4.8 \times 10^{-14} \, \text{C} \) inside the inner enclosure.

When the current in the rotating coil was turned on a change of \( -0.5 \pm 0.1 \, \text{mV} \) was observed on the millivoltmeter. With a voltage gain of 0.52 for the cathode-follower electrometer this represents \( -0.96 \pm 0.2 \, \text{mV} \) between the two metal enclosures.

The absolute meter accuracy was specified as 1% of full scale. The measurement accuracy was limited by small drifts in the cathode voltage and by 0.1–0.2 mV noise at the meter terminals. This noise was due to piezoelectric effects generated by small vibrations in the polystyrene insulating spacers between inner and outer enclosures. In the presence of noise, measurement precision was 0.1 mV at the meter terminals.

The noise, which was observed as random fluctuations on the indicating meter, was not present when the coil was stationary. With the coil rotating noise was independent of whether the current was on or off. Since noise was small compared with the signal, a change in potential level could be clearly observed when the coil current changed.

A study of the spinning-coil time-constant shows that the observed signal does not result from induced EMF. The coil inductance, calculated from equations for multi-layer solenoids, was found to be 1.3 H. This inductance, with 21.2 Ω resistance, results in a coil time constant of 0.062 s.

The inductive EMF, which is generated by switching a battery across a coil, is a maximum at the time of initial switch contact. With a time constant of 0.062 s the EMF drops to a negligibly small value after several tenths of a second. The voltmeter signal gave no indication of an initial EMF surge. After the battery had been switched on, the meter indicator reached a constant level within several tenths of a second and then remained substantially constant until the coil current was interrupted. After current interruption, the meter indicator fell to its original level within several tenths of a second and then remained substantially constant until the next current change.

Acknowledgments

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References

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O’Rahilly A 1938 Electromagnetics (New York: Longmans Green & Co.) pp 584–8