The Unipolar Generator:

A Demonstration of Special Relativity

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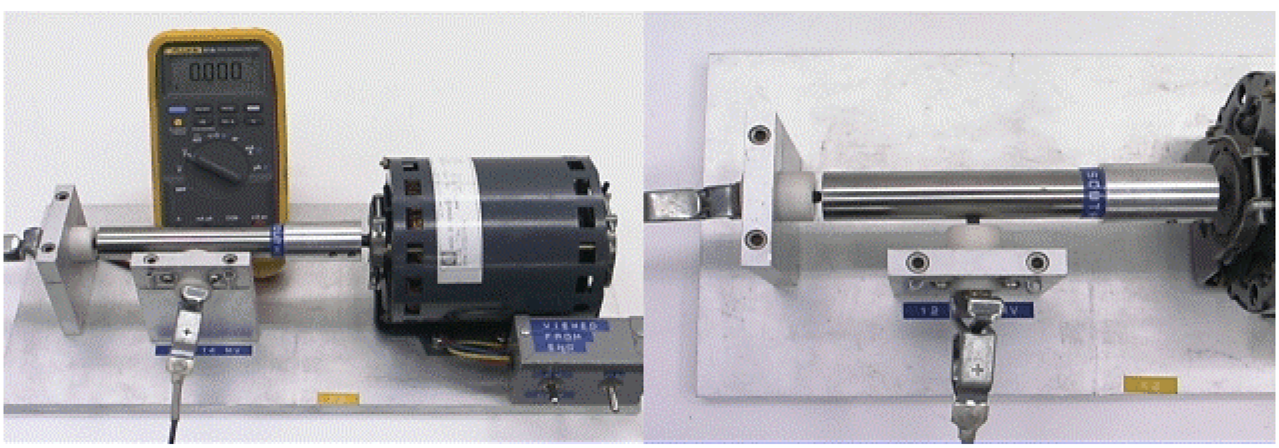
(Edited January, 2005)

This interesting and surprising device, sometimes called the homopolar generator, is one of the more forgotten of the significant experiments in the history of physics. It is perhaps the only table-top demonstration of special relativity.

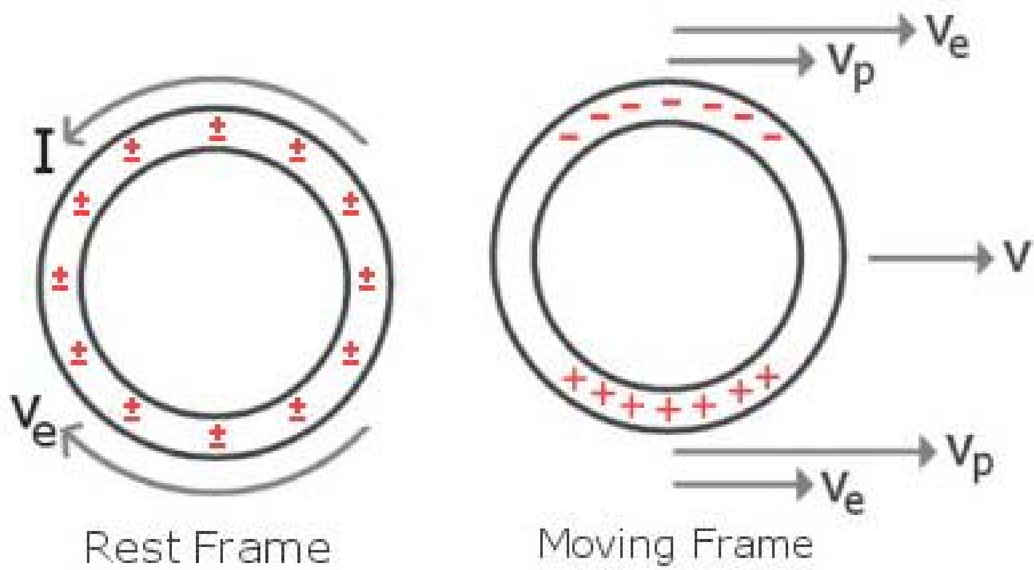
A cylindrical alnico magnet, one inch in diameter and six inches long, having its poles at the ends, with a residual magnetic induction of about one Tesla, is rotated around its axis at 1725 RPM. Brushes are positioned on the axis of rotation at one end and on the "equator" of the cylinder. While the magnet is being rotated a potential between the brushes of about 13 mV is observed. This potential reverses in sign when the direction of magnetic rotation is reversed or when the poles of the magnet are interchanged.



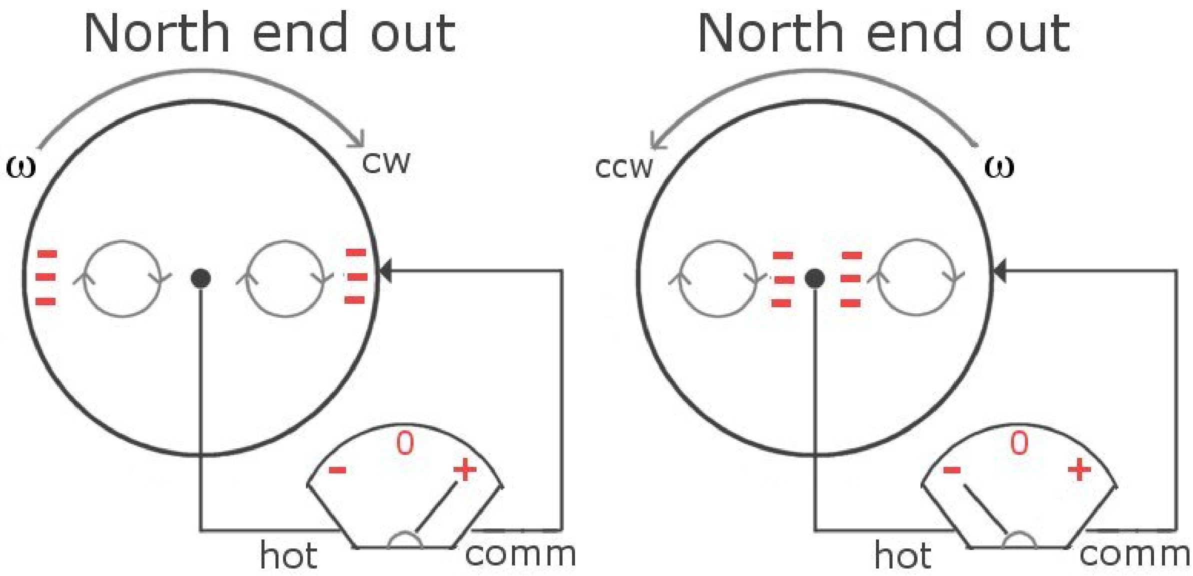
Large generators using unipolar induction were well known in the late nineteenth century, and were used as dynamos to generate DC power during the period when arguments were still raging about whether the best technique for supplying electric power to consumers was by AC or by DC.[1]

Notice that this is not a conventional generator. No net magnetic flux lines are being cut, and the generator produces DC, which would imply a continuously increasing magnetic field. Further, this effect cannot be explained in terms of the classical Faraday disc experiment,[2] which involves the force on a charge moving in a magnetic field. Therefore the generation of an electrical potential by this technique is inexplicable in classical terms. The existence of unipolar induction was likely one of the motivating pieces of experimental evidence leading Einstein to propose the special theory of relativity.

A physically intuitive way of viewing this problem can be developed by first looking at an electrically neutral metallic ring, in which an electron current is flowing clockwise (conventional positive current flowing counterclockwise), and which is moving to the right at a large speed.[3] In the rest frame of the ring no net charge density will exist at any point. As we view the moving ring, the electrons will be moving faster to the right at the top of the ring, while the positive charge will be moving faster to the right at the bottom. Therefore in our frame the length of the electron cloud on top and of the positive cloud on the bottom will be relativistically shortened, leading to a negative charge density on top of the ring and an equal positive charge density on the bottom.



An analogous way of viewing the rotating magnet is to look at the equivalent electron current around any one of the magnetic domains of which the magnet is composed. If in this case the end of the magnet facing us is North, and the magnet is rotating clockwise as viewed from that end back toward the motor, we observe that the velocity of the electron cloud and the velocity of the rotating magnet add on the outside and subtract on the inside of each loop. This means that the electron cloud will have a greater velocity on the outside, so that in the fixed external frame of reference we will observe a length contraction of that side of the electron cloud. Because the electron cloud density in the magnet frame is uniform, we will then view the electron cloud as having a greater negative charge density on the outside, leading to a negative potential of the outside of the magnet relative to that of the center. Similarly, the potential should be positive when the magnet is rotated counterclockwise with the North end out. This analysis gives the correct sign for the observed potential with all four combinations of magnet end orientations and rotation directions.



When Faraday originally performed this experiment he observed no induced EMF when the circuit was rotated with the magnet, demonstrating that the EMF indeed arises from the transformation of the reference frames.

We can approach this problem analytically using the relativistic transformation equation for the electric field observed in a fixed (primed) coordinate system arising from a moving magnetic field:[4]

$$\mathbf{E'} = \gamma\, (\, \mathbf{E} - \mathbf{v} \times \mathbf{B}\,)$$

where the prime refers to our fixed reference frame and the unprimed system is the rotating (moving) frame. For this case there is no electric field in the moving system (the magnet) and the velocity **v** of any point on the magnet due to the rotation of the magnet is always perpendicular to the residual magnetic induction. Therefore the electric field observed in the fixed frame as the magnet rotates, for small velocities (gamma ~1) reduces to

$$\mathbf{E'} = \mathbf{v}\, \mathbf{B}$$

at all points within the magnet, and is in the radial direction.

The total electric potential developed is then determined by integrating this electric field along a radius from the center of the magnet (r = 0) to the outside radius R of the magnet:

$$\mathbf{E'} = \int_{r=0}^{R} \mathbf{v}\, \mathbf{B}\, d\mathbf{r} = \frac{\omega\, \mathbf{B}\, \mathbf{R}^2}{2}\ ,$$

where ω is the angular velocity of the magnet, and the linear velocity of a point in the magnet is:

$$\mathbf{v} = \boldsymbol{\omega} \times \mathbf{r}.$$

For our case the residual magnetic induction is about 1 Tesla, the radius is about 0.0125 m, and the magnet rotates at 28.75 turns per second, so:

$$\mathbf{E'=(28.75x2\pi\ rad/s)(1T)(0.0125m)^2/2 = 0.014\ V = 14\ mV,}$$

in approximate agreement with our experimental results.

Below is a table containing the voltages produced with each pole of the magnet extending out from the rotator and with the magnet rotating in each direction, including the voltage picked up from the rotating aluminum rod.

Pole out →	**North**	**South**	**Aluminum**
CW Rotation	+11.7 mV	-14.2 mV	-0.2 mV
CCW Rotation	-13.5 mV	+11.9 mV	-0.1 mV

Sauter has given an analysis that is strictly correct for rotating coordinate systems. When any individual magnetic moment is either translated or rotated, a polarization charge develops across that region which again is only explainable by special relativity. If the integral of this polarization charge is then taken along a radius from the center to the outside of the rotating magnet, the potential observed across the two brushes can be determined. This integral is similar to the one evaluated above, so that the potential calculated above is approximately correct relativistically.

References:

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