Explaining the Unipolar Induction Problem through a Two-Pole Spherical Magnet Experiment

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Abstract

Analysis indicates that insufficient attention has been paid to the fully symmetric distribution of magnetic field lines relative to the rotation axis in unipolar induction magnets, which constitutes the fundamental cause of the emergence and persistence of the unipolar induction problem. A verification scheme for the unipolar induction problem using a bipolar spherical magnet is proposed. The scheme is straightforward to implement. By selecting an appropriate orientation for the rotation axis, the same magnet can be used to conduct both the classic unipolar induction experiment and the bipolar induction verification experiment that aims to resolve the unipolar induction problem. The two experimental procedures can be performed correspondingly, allowing for comparative analysis of the results. Unlike the case where both viewpoints can offer reasonable explanations for all unipolar induction experimental results, in the bipolar induction verification experiment, the distribution of the magnet' s magnetic field lines relative to the rotation axis is no longer fully symmetric. Consequently, the differences in the reasonable explanations that the two viewpoints can provide for the verification results become pronounced, making the correct and incorrect positions evident. The verification conclusion is that the magnet' s magnetic field lines move with the magnet.

Full Text

Explaining the Unipolar Induction Problem Through Experiments with Bipolar Spherical Magnets

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Fig. 1 [Figure 1: see original paper] Unipolar induction experiment with a cylindrical magnet
Fig. 2 [Figure 2: see original paper] The section view of the magnetic field line distribution around the cylindrical magnet (cut open along the rotation axis)

Figure 2 presents a schematic diagram of the distribution of the main magnetic field lines around a cylindrical magnet cut along its rotation axis (leakage flux, which has negligible effect on electromagnetic induction, is ignored). From Figures 2 and 1, it is evident that the closed magnetic field lines form magnetic field line planes. Within each magnetic field line plane, concentric closed magnetic field lines extend outward from the magnet surface in loops within loops. These magnetic field line planes lie in the same plane as the rotation axis and are uniformly and symmetrically distributed around it, a configuration that remains unchanged during magnet rotation. This distribution is hereafter referred to as a *fully symmetric distribution.* If we assume the magnet in Figure 1 is stationary, and the two contacts a and b on the magnet together with the measurement wire L circle the magnet once along their respective latitude lines (equivalent to the magnet rotating one revolution in the m-viewpoint), let n be the net number of magnetic field lines cut by line segment L (referring to effective cuts that produce EMF; cuts of equal number but opposite direction cancel out and are thus ineffective). Due to the fully symmetric distribution of the magnet’ s magnetic field lines and the fact that these lines are closed, the magnitude of n depends only on the latitudinal positions of contacts a and b on the magnet, and is independent of the length of L or its proximity to the magnet (i.e., the relative position between L and the magnet). Therefore, in unipolar induction experiments, once the positions of sliding contacts a and b on the magnet surface are fixed, the net number of magnetic field lines between them is determined. When the magnet rotates at a constant angular velocity, both the s-viewpoint and m-viewpoint yield the same net number of magnetic field lines cut per unit time, or equivalently, the same induced EMF in the measurement circuit, regardless of the length of L or its distance from the magnet. (Changes in the position of L relative to the magnet during the experiment do not affect the induced EMF, so the galvanometer reading remains unchanged.) Both viewpoints also predict the same direction of induced EMF in the measurement circuit. Moreover, both can easily derive the same expression for the induced EMF E in the measurement circuit:

For the s-viewpoint, the integration path ab represents the distance between points a and b on the magnet surface, whereas for the m-viewpoint it represents the theoretically shortest integration length of line segment L. The definitions of other parameters are the same for both viewpoints. $\mathbf{V}$: linear velocity of the line element relative to the magnetic field lines; $\mathbf{B}$: average magnetic induction along the line connecting a and b on the magnet surface.

Thus, the fully symmetric distribution of magnetic field lines in the experimental magnet enables both s-viewpoint and m-viewpoint to reasonably explain the experimental observations, which is the fundamental reason why the unipolar induction problem persists. Subsequent verification experiments have used permanent magnets, DC electromagnets, or AC electromagnets, all of which essentially maintain a fully symmetric field distribution during experiments, making it impossible to resolve the question. Other proposed verification schemes have been overly complex, susceptible to interference, and difficult to implement, rendering their results unconvincing. Perhaps because changes in the position of measurement line L relative to the magnet do not affect the readings, researchers failed to carefully examine and analyze the magnetic field distribution of experimental magnets, leaving the problem unresolved. Therefore, verification experiments should avoid fully symmetric magnetic field distributions.

When a unipolar induction magnet rotates, only one magnetic pole rotates along a given latitude line. If two or more poles are used instead, the magnetic field distribution changes. In bipolar or multipolar induction experiments, whether changes in the position of measurement line L relative to the magnet affect the observed results are clearly crucial for verification. This paper introduces a verification scheme using a bipolar spherical conductive permanent magnet because such magnets have a simple structure, are easy to implement, and most importantly, can perform both classical unipolar induction experiments and bipolar induction verification experiments simply by changing the orientation of the rotation axis, facilitating comparative analysis of results.

2. Reproducing Classical Unipolar Induction with a Bipolar Spherical Conductive Magnet

The principle of the spherical magnet unipolar induction experiment is shown in Figure 3 [Figure 3: see original paper]. Here, M is a bipolar spherical conductive permanent magnet. The requirement for the rotation axis orientation in unipolar induction is that the rotation axis must coincide with the line connecting the sphere' s center and the two magnetic pole vertices. In this configuration, the magnet' s magnetic field lines are fully symmetric relative to the rotation axis, with the rotation axis lying in the same plane as the magnetic field line planes. Figure 4 [Figure 4: see original paper] shows the distribution of magnetic field lines around the spherical magnet cut along its rotation axis. In Figure 3, measurement line L is connected in series with galvanometer G and then to the ab segment of the magnet surface via sliding contacts a and b to form a measurement circuit. The dashed line indicates the equatorial midline position, which is also the interface between the N and S poles. During the experiment, the magnet rotates at a constant angular velocity (approximately 240π rad/s). The experimental procedures, observations, and explanations from both viewpoints are as follows:

(1) When sliding contacts a and b are located on the same latitude line, or respectively on latitude lines equidistant above and below the equatorial midline, the galvanometer G shows zero reading when line L is stationary and the magnet rotates.

S-viewpoint explanation: The net number of magnetic field lines cut per unit time by the ab segment conductor on the magnet surface is zero, so the induced EMF in the measurement circuit is zero.

M-viewpoint explanation: The net number of magnetic field lines cut per unit time by line segment L (stationary relative to the laboratory) is zero, so the induced EMF in the measurement circuit is zero.

(2) Except for the special positions listed in (1), whenever a and b are not on the same latitude line, the galvanometer G shows a DC current when L is stationary and the magnet rotates. The current value increases with the latitudinal distance between the contacts, reaching maximum when one contact is at the equatorial midline and the other at a pole. If the contact at the pole is moved to the opposite pole, the current direction reverses.

S-viewpoint: As the latitudinal distance between a and b increases, the net number of magnetic field lines cut per unit time by the ab segment conductor on the magnet becomes non-zero, inducing a DC EMF in the measurement circuit and producing a galvanometer reading. When the contacts are at the equatorial midline and a pole respectively, all magnetic field lines emanating from the N pole and returning to the S pole are cut, maximizing the net number of field lines cut per unit time, thus maximizing the induced EMF and current. Moving the pole contact to the opposite pole reverses the direction of the cut field lines, thereby reversing the induced EMF direction.

M-viewpoint: The EMF is induced by line segment L cutting magnetic field lines. Other explanations are identical to the s-viewpoint.

(3) When moving measurement line L while the magnet rotates, changing its proximity to the magnet does not affect the galvanometer reading.

S-viewpoint: Since the EMF in the measurement circuit is contributed by the ab segment conductor on the magnet, changes in the position of line L outside the magnet cannot affect the induced EMF in the measurement circuit.

M-viewpoint: Due to the fully symmetric distribution of magnetic field lines relative to the rotation axis and the constant rotation direction and angular velocity of the magnet, the analysis above shows that the EMF induced in line L depends only on the positions of contacts a and b on the magnet, not on the length of L or its position relative to the magnet. Therefore, moving L does not affect the galvanometer reading.

Additional experimental steps could be listed, such as the magnet being stationary while line L circles around it (producing EMF), or the magnet and line L rotating synchronously (producing no EMF). In summary, both viewpoints can provide reasonable explanations for all experimental results of unipolar induction.

3. Verification Experiments with Bipolar Spherical Conductive Magnets

The principle of the bipolar spherical magnet verification experiment is shown in Figure 5 [Figure 5: see original paper]. The rotation axis orientation for the bipolar induction verification experiment is obtained by rotating the experimental magnet’ s axis from Figure 3 by 90° about the sphere’ s center, so that the rotation axis passes through the sphere’ s center and coincides with the interface between the N and S poles. During bipolar induction, two magnetic poles rotate along the same latitude line, hence the name “bipolar induction.”

Bipolar induction produces AC EMF, so an oscilloscope O is connected in series with line L in Figure 5 to more intuitively observe the induced AC EMF in the measurement circuit. As seen in Figure 4, the spherical magnet’ s magnetic field lines are symmetrically distributed on both sides of the magnetic pole interface (with opposite field line directions). The magnetic field line planes, composed of large loops containing smaller ones, are perpendicular to the magnetic pole interface and coincide with radial extensions of the interface. In the unipolar induction axis orientation of Figure 3, the magnetic field line planes lie in the same plane as the rotation axis and the meridian lines, the magnetic pole interface coincides with the equatorial plane, and the magnetic field lines around the magnet are fully symmetric relative to the rotation axis. Therefore, changes in the position of line L relative to the magnet during the experiment do not affect the induced EMF in the measurement circuit. However, in the bipolar induction axis orientation of Figure 5, the original equatorial midline (the circular line at the magnetic pole interface) with its symmetrically distributed field lines becomes a meridian circle, and the magnetic field line planes become perpendicular to the rotation axis. Consequently, the distribution of magnetic field lines around the magnet is no longer fully symmetric relative to the rotation axis. Figure 6 [Figure 6: see original paper] shows the distribution of magnetic field lines around the experimental magnet cut along the rotation axis (which is also the magnetic pole interface). The long arrows represent magnetic field line planes, with thickness decreasing from magnet outward indicating decreasing field line density. In this axis orientation of Figure 5, if we assume the magnet is stationary and contacts a and b on the magnet circle it once along their respective latitude lines together with measurement wire L, it is clear that—unlike the situation in Figure 3—the net number of magnetic field lines cut by line L differs when it is near or far from the magnet. The closer L is to the magnet, the more field lines are cut; the farther away, the fewer. Therefore, if changing the position of line L relative to the magnet in Figure 5 also shows no effect on the readings, the m-viewpoint can be directly judged incorrect. However, the actual verification results are the opposite, and some experimental observations can only be reasonably explained by one viewpoint, with the other viewpoint unable to provide a reasonable explanation even with the assistance of Faraday’ s law of electromagnetic induction (since AC EMF is induced, Faraday’ s law can be invoked). The following are several sets of verification experimental steps.

For ease of analysis and calculation, during verification experiments the plane formed by line L and the line ab on the magnet surface must remain in the same plane as the rotation axis, and L should not have unnecessary folds. The magnet' s rotation angular velocity is .

(1) Keeping line L at an appropriate distance from the magnet, slowly move contacts a and b apart starting from the equatorial midline. As the distance between a and b increases, the oscilloscope O begins to display a sinusoidal EMF, with amplitude increasing as the distance grows, until a and b reach the upper and lower rotation axes respectively. The reverse process produces the same result. The positive and negative peaks of the sine wave correspond to moments when the magnetic pole vertices coincide with the measurement circuit plane.

For the observations in step (1), the s-viewpoint, m-viewpoint, and Faraday' s law can each provide reasonable explanations, which will not be elaborated here.

(2) Keeping contacts a and b at an appropriate distance apart, when line L is gradually moved away from the magnet, the sinusoidal amplitude gradually decreases. Conversely, the closer L is to the magnet, the larger the amplitude, approaching maximum as L gets infinitely close to the magnet.

M-viewpoint: Line L cuts magnetic field lines that rotate with the magnet and have a density distribution along latitude lines. When facing the N and S poles, the cut field lines have opposite directions, inducing a sinusoidal EMF. The greater the vertical distance between contacts a and b, the more field lines are cut by L at the same position facing the poles, so the sinusoidal EMF amplitude increases with ab distance, and vice versa. Since the magnetic field line density is maximum at the pole vertices, the sinusoidal peaks occur when L is directly opposite and closest to the pole vertices. As seen in Figure 6, the farther L is from the magnet, the fewer field lines are cut per unit time when the magnet rotates to the same position, resulting in smaller sinusoidal EMF amplitude, and vice versa. The induced EMF in the measurement circuit can be determined by:

where E is the amplitude, determined by: $= E \sin$ 훼 where l is the length of line segment L; V is the linear velocity of line element dl relative to the magnetic field lines; B is the average maximum magnetic induction on line segment L when the magnetic pole vertex coincides with line ab. $E = 0$ (×) 퓝퓝

For the experimental result that the sinusoidal EMF amplitude increases as L approaches the magnet and decreases as it moves away, neither the s-viewpoint alone nor Faraday' s law alone can provide a reasonable explanation; only a combination of both yields a 勉强 (strained) explanation: Based on analysis of unipolar induction results, the s-viewpoint holds that when the magnet rotates in a constant direction, the conductor on the magnet' s pole surface cutting magnetic field lines induces a DC EMF, turning the conductor on the pole surface into a DC power source. The polarity of the EMF at any two points on the pole surface depends on the magnet' s rotation direction and which pole the conductor faces; the magnitude depends on the magnetic field line density (magnetic induction) at the conductor' s position and the magnet' s angular velocity. Since the rotation direction and angular velocity are constant, the EMF between any two selected points on the pole surface is also constant. Because the magnetic field line density (magnetic induction) on the pole surface follows a normal distribution, the induced DC EMF values along latitude lines also follow a normal distribution. Therefore, the induced EMF introduced into the stationary measurement circuit by sliding contacts a and b is an AC sinusoidal EMF. Let this sinusoidal EMF be *e_{ab}*. Since changes in L' s position do not affect *e_{ab}*, *e_{ab}* is constant as long as a and b remain fixed on the magnet. According to Faraday' s law, the changing magnetic flux in the closed measurement circuit induces an EMF, denoted *e_f*. Let the total induced EMF in the measurement circuit be e. Since *e_{ab}* and *e_f* are sinusoidal waves of the same frequency but opposite phase in the measurement circuit, when L moves away from the magnet, the closed loop area increases, the rate of magnetic flux change increases, *e_f* increases, and because *e_{ab}* is constant, e decreases. The converse is also true. When L approaches infinitely close to the magnet, *e_f* approaches zero, . This seems to provide an explanation.

The next verification is the sleeve temperature rise experiment. Figure 7 [Figure 7: see original paper] shows the principle of the sleeve temperature rise experiment. Here, T is a cylindrical sleeve made of copper sheet with sufficient mechanical strength (a spherical cover could also be used for better results). The sleeve' s diameter is slightly larger than the spherical magnet' s diameter, and its height is two-thirds of the magnet' s diameter. The sleeve is positioned around the middle of the spherical magnet, with its midline coinciding with the magnet' s midline. It can rotate independently or synchronously with the spherical magnet.

(3) With the sleeve stationary and the spherical magnet rotating at constant angular velocity, the sleeve temperature rises significantly after several minutes.

M-viewpoint: Similar to step (1), but here the cylindrical sleeve T has countless line segments L simultaneously cutting magnetic field lines, inducing EMFs of different magnitudes and directions at different sleeve positions that can form closed paths and generate circulating currents (eddy currents), causing the sleeve to heat up. Selecting almost any two points on the sleeve yields measurable sinusoidal EMF.

The s-viewpoint alone cannot explain this observation. Therefore, recourse must be made to Faraday' s law: the sleeve T contains countless closed loops in which changing magnetic flux induces AC EMF, generating eddy currents that raise the sleeve temperature.

(4) When the spherical magnet and sleeve rotate synchronously, the sleeve shows no temperature rise.

M-viewpoint: The magnetic field lines rotate synchronously with the sleeve, so there is no relative motion between the sleeve and field lines, no cutting of magnetic field lines, and thus no induced EMF or eddy currents.

Faraday' s law alone can also explain this: there is no magnetic flux change in the closed loops on the sleeve, so no EMF is induced and no eddy currents are generated.

From the explanation of unipolar induction, the s-viewpoint would predict that the conductor on the sleeve rotating synchronously with the magnet cuts oppositely directed magnetic field lines when facing the N and S poles, inducing DC EMFs of opposite polarity that can form a current loop and generate circulating currents, so the sleeve should heat up. However, the actual observation is negative.

Since the sleeve T rotating synchronously with the magnet shows no induced EMF, it follows that a rotating conductive magnet in bipolar induction also will not have induced EMF. Therefore, for the experimental results of step (2), neither the s-viewpoint alone nor Faraday' s law alone can provide an explanation; and because $e\_\{ab\} = 0$, the previous explanation combining the s-viewpoint with Faraday' s law for step (2) is also incorrect. Only the m-viewpoint can provide natural and reasonable explanations for all experimental results of bipolar induction, indicating that in bipolar induction experiments, the EMF in the measurement circuit is generated by line segment L that is stationary relative to the laboratory, and also demonstrating that during bipolar induction experiments, the magnetic field lines move with the magnet.

Since the bipolar induction experimental results show that the experimental magnet' s magnetic field lines move with the magnet, and since the unipolar induction in Figure 3 and the bipolar induction in Figure 5 use the same magnet with only different rotation axis orientations, does this mean the m-viewpoint is correct and the answer to the unipolar induction problem is clear?

The conclusion that magnetic field lines move with the magnet is indeed difficult to imagine. If true, it would mean that no electric field is produced around a moving magnet. The true cause of electromagnetic induction and electromagnetic forces in magnets (including DC electromagnets, though electromagnetic effects caused by electromagnetic waves are not considered here) would be the relative motion between charges and the perpendicular component of magnetic field lines, whether the charges move relative to the field lines or the field lines move relative to the charges, with identical results. Further reflection reveals that the issues involved are truly profound.

Due to the author' s limited knowledge, the analysis and conclusions presented may not be correct. The author would greatly appreciate criticism and corrections from relevant scholars.

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Author Contribution Statement:

Zhang Xueliang: Conceived the research idea, designed the research scheme; data acquisition, provision, and analysis; conducted experiments; drafted the manuscript; revised the final version.

Note: Figure translations are in progress. See original paper for figures.