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Eddy Current Caused by Electromagnetic Induction

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Abstract: The aim of this paper is to clarify the mechanisms of heat generation in metallic pipes housing AC power cables. While many researchers—including some IEEE reviewers—attribute this phenomenon primarily to Joule heating, the experiments conducted in this research demonstrate that eddy currents are the principal cause of temperature rise in iron pipes surrounding AC conductors. The paper examines the fundamental principles of electromagnetic induction, tracing its historical development through a sequence of landmark experiments ranging from the era of Michael Faraday to Samuel Morse. This research serves as a modern follow-up to that historical lineage, providing empirical evidence to distinguish between induction-based losses and standard Ohmic heating.

Keywords: AC in live and neutral cables, eddy current, joule heating, historical experiments in electromagnetic induction.

INTRODUCTION

An Experiment on Electromagnetic Induction

Electricity still seems like a mystery to many. Fig. 1 below is a picture of an experiment designed to generate eddy currents in surrounding steel pipes using AC current in copper wires [Mohanty, I. *et al*., 2018].

In this experiment, four 2.5 mm2 Live (L) wires and four 2.5 mm2 Neutral (N) wires carry a total of 60A to power 120 incandescent bulbs. The left pipe contains four L and four N wires. In the right pipe, the four L wires are looped back through the pipe, resulting in eight L wire segments. Consequently, both pipes contain eight 2.5 mm2 wires, effectively carrying a total conductor current of 60A X 2 = 120 A.

The thermal difference is striking: the left steel pipe remains near ambient temperature, while the right pipe reaches the highest temperature (white) the infrared camera can record.

When an electrical engineer asked me to explain this, I realized my initial explanation was not sufficient. I decided to think deeply about better ways to explain it, as working engineers often prefer practical explanations over complex calculations.

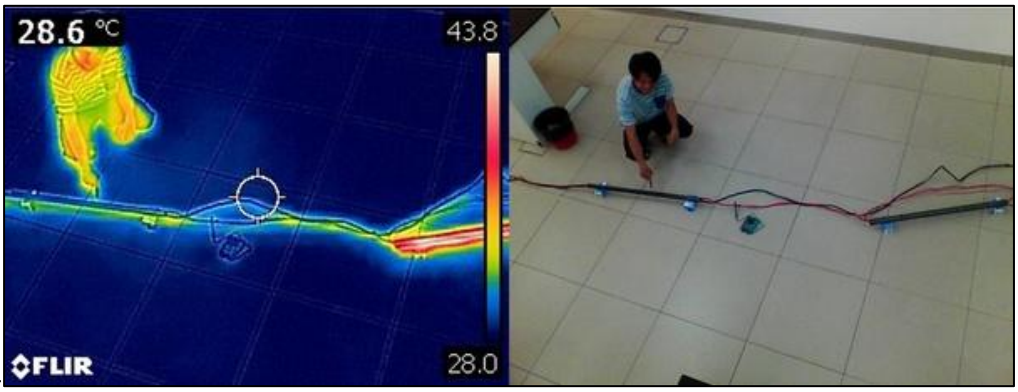

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Fig. 1: Infrared camera depicting heat on two steel pipes covering eight 2.5mm2 wires carrying 60A.

The "Snake Theory"

This phenomenon can be explained by the "Snake Theory." Imagine a "snake" of current flowing left in the L wire; at that exact moment, an identical "snake" of current flows right in the N wire. Because these sinusoidal waveforms are 180o out of phase, their magnetic fields superimpose and cancel each other out, resulting in almost no heat generation in the surrounding steel pipe [Jayakumar, R. 2011].

The Bend Analogy

Alternatively, consider an AC waveform entering and then leaving a specific point on a wire. One can visualize a "positive bump" (peak) arriving at the point and a "negative bump" (trough) departing from it. If the wire is bent 360o at that exact point, the "positive bump" enters the bend while the "negative bump" leaves it. Even when a load is connected at this bent point of the wire, the current entering through the L wire and returning through

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the N wire remains180o out of phase [Pou, J. *et al*., 2004].

In the left pipe, these opposing “bumps” cancel their magnetic effects. In the right pipe, however, the looped L wires cause the “bumps” to align and amplify, inducing heavy eddy currents and hysteresis loss in the steel pipe, causing it to heat up significantly.

LITERATURE REVIEW

A study was made to show continual upgrade in the understanding of electromagnetic induction.

In 1820, Hans Christian Ørsted (Danish) noticed a compass needle when placed near a current carrying wire. So, he is credited with the discovery of the connection between electricity and magnetism [Brain, R. M. *et al*., 2007].

In 1820, André-Marie Ampère (French) showed that parallel wires carrying currents attract or repel each other, depending on whether currents are in the same (attraction) or in opposite directions (repulsion). This laid the foundation of electrodynamics [Hofmann, J. R. 1996].

In 1821 Michael Faraday (British) invented the motor soon after the discovery of the connection between electricity and magnetism discovered by Ørsted. He connected the positive of a battery to a wire; this wire goes to a switch and then goes on to a nail hammered into a piece of wood. On this nail is hooked a copper wire, such that it is free to move. The freely hooked copper wire goes down into a container of liquid mercury. At the edge of the container was an electrode to which the negative of the battery was connected. A cylindrical permanent magnet (PM) was placed in the center of the mercury bath. Upon switching on this circuit, the freely hooked wire moved continuously around the PM. This was the first motor known to science. For the next few decades all motors had this structure i.e., a vertical motor. Then in 1834 a German man in Russia, Moritz von Jacobi created the first motor having the horizontal structure, basically replacing the freely hooked copper wire suspended in mercury with bearings. But because electricity was expensive, the advent of motors had to wait for Thomas Edison’s first electric grid. A staff of Edison, Frank Julian Sprague in 1886 invented the first practical DC motor [Thomas, J. M. 1991].

Soon after inventing the motor Faraday deduced that if electricity can produce magnetism, magnetism should be able to produce electricity. So, shortly after he invented the first motor, he also invented the first generator. There are many children and some adults also asking why we can’t get a generator to turn a motor and let that motor in-turn drive the generator rotor thus producing non-ending energy. This is not possible because as the motor drives the generator’s shaft (rotor) it generates current in the generator’s stator coils which becomes increasingly magnetic, thereby holding onto the rotor with a stronger force. Therefore, the motor will slow down thereby not being able to produce much current in the generator coils. Therefore, it is not possible to get a motor and generator to perpetually provide each other energy. However, there are many who dwell on free energy theories; this author believes it may be possible because most of science assumes machines are in a controlled environment, i.e., in a box. But, on the Earth’s surface there is a large magnetic field. This magnetic field is created by electrons which are released by iron atoms at the outer core which travel parallel to each other, making the outer core a solenoid. Then there is gravity processed by Earth and an atmosphere of air that is continuously in motion (energy). Rivers are continuously flowing and already providing free energy named hydroelectric energy, making hydroelectric dams the most profitable industry on Earth. Then there is the sun which exports energy to Earth. So far human technology has only been able to tap the free energy provided by rivers as well as the sun; however, the current state of solar PV is not practical because of its intermittent nature [Cantor, G. 2016].

In 1831 Faraday invented the transformer as he coiled a piece of wire (primary) on one side of a doughnut shaped iron, he could detect electricity at a piece of wire (secondary) coiled at the other end. But the electricity at secondary could only be detected as he switched on the current at the primary. As he continuously switched the primary, the current at the secondary is also continuous. Brooding over this, Faraday came up with Faraday’s law of induction which states that induced voltage is directly proportional to the rate of change of flux. This is how an induction cooker works; the frequency of electricity is increased to a high level and induces fast vibrating voltage in the iron pot which causes electrons within the pot to vibrate fast which heats up the water in the pot [Guarnieri, M. 2013].

Faraday basically created the most important inventions of the modern electric world, the motor, generator, and transformer. The unit of capacitance

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is farad, named after him. He coined the words anode, cathode, electrode, and ion. Faraday constant is the charge on a mole of electrons (about 96,485 coulombs).

Faraday was different from the scientists before him in having come from a poor family. The scientists before him were mostly aristocrats. He was mostly self-educated. At age 14 he started work at a book making factory. Here he read all the books in print and became quite knowledgeable. The chief scientist of England of that time heard of his diligence in learning and took him in as a technician. Faraday realized that he had just gotten the chance to work in one of the most advanced labs in the world and fully utilized his time performing experiments. He was not treated right, especially by the wife of the chief scientist. He fought through this and eventually became better than the chief scientist. Later, Queen Victoria wanted to give him the title 'Sir' but he refused, stating that he must remain plain to the last. He is currently generally regarded as the father of electricity. Other than science and engineering, Faraday can be respected as one who broke the aristocrat-commoner barrier. This was a time of slavery and even White slavery where there is little mobility of people from one status to another. It was his work in science and engineering that enabled him to break this huge barrier. A note to students of engineering is that a dedicated inquiry into this field is a sure way to break down barriers in society. Many aristocrats of that age thought of themselves as being of a superior race. Of course, Africans, Indians or Chinese of that time had little freedom in European countries, but it would be easy to imagine an African person who devoted himself to science, breaking the superiority complex of White rulers. Of late however, there have been many infiltrations by evil people into science. An example of the possibility of nefarious people utilizing science for evil ends is a person who can use a few keystrokes on his computers to hack into another person's car, causing it to crash. The time has come for religion and philosophy to intervene in the progress of science [Karunakaran, P. 2018].

In 1824, William Sturgeon (English) invented the first electromagnet by winding 18 turns of bare copper wire in a varnished iron horseshoe. His 200 grams electromagnet could lift nine pounds of iron. Because he used uninsulated copper wire, the turns around the horseshoe had to be a single layer making it not possible to increase the number of turns to increase the magnetic strength [Gorman, M. 1968].

In 1827 Georg Ohm (German) came up with the relationship between Voltage, Current and Resistance: V=IR. This is now called Ohm's law and is the most important formula in all of electricity [Grant, P. M., & Thompson, J. S. 2019].

In 1831 Joseph Henry (American) discovered mutual inductance indecently of Faraday, but Faraday published his results earlier. Henry made the electromagnet practical. Basically, by wrapping wires around a horseshoe and electrifying it with DC. He found out it got hot, so he wrapped the bare wire with silk thread and was finally able to lift up 3300 lbs. With this invention, he was able to later invent the first doorbell and electric relay. Henry also invented the earliest ancestor to the DC motor. The SI unit of inductance is named Henry after him [Oehser, P. H. 1947].

In 1833, Wilhelm Eduard Weber (German) together with Gauss developed the first electromagnetic telegraph. Weber in volt/second is the unit for magnetic flux [Sutrave, A. 2020].

In 1834, Moritz Hermann Jacobi (German-speaking Russian) improved on Faraday's vertical motor and Henry's similar horizontal 'rocker' which moved back and forth, to create the first horizontal motor that looked like today's motor. He used a battery and his motor to power a boat that carried 14 people across the river Neva [Vogt, A. 2012].

In 1835 Samuel Morse (American) perfected the telegraph and got the patent for it in 1845. The Morse Code was also created by him. He got one of the first government funding for a practical invention and the telegraph spread across the USA in a very short time. There was no question among the politicians of the day that something had to be done to unite the USA and other than railroads, telegraphs were chosen [Morse, S. F. B. 2014].

CONCLUSION

This paper presents an experiment on electromagnetic induction, demonstrating how it generates eddy currents. While many researchers attribute the heating of iron pipes surrounding power cables solely to Joule heating, it is essential to clarify the specific conditions under which these various thermal processes occur.

Contrary to the common misconception that Joule heating only occurs when a cable's current-

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carrying capacity is exceeded, it actually occurs whenever current flows through a conductor with resistance. However, when cables are housed in metallic conduits, three distinct mechanisms contribute to the total thermal load:

- Eddy Current Loss: Induced by the alternating magnetic field circulating within the conductive pipe.
- Joule Heating (Ohmic Loss): Caused by electrons colliding with ions within the conductor; this occurs at all levels of current flow.
- Hysteresis Loss: In a ferromagnetic material like iron, this loss does not involve a "flow" of electrons as seen in a wire. Instead, it involves magnetic domains—microscopic pockets where atomic magnetic moments are aligned. When an AC field is applied, these domains must rotate to align with the flipping magnetic field. This process is much like a crowd of people having to turn 180° every time a bell rings; the domains do not flip perfectly or instantaneously. They encounter internal "friction" during realignment, requiring energy to overcome this molecular-level resistance. This energy, which is not transferred to the secondary circuit, is dissipated as heat. The term "hysteresis" is derived from the Greek word for "lagging behind," referring to how the material's magnetization lags behind the alternating magnetic field.

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