The Correlation Analysis of Short-circuit Current and Magnetization of Ferromagnetic Metals

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Abstract

This paper investigates the effect of short-circuit current on non-magnetic steel pipes to explain how different materials utilize the remanence method in fire investigations to analyze the variation laws of their own remanence. This provides data support and theoretical basis for determining the cause and location of fire incidents. The results show that under the influence of short-circuit current, the non-magnetic steel pipe becomes magnetized, and the extent of magnetization depends on the magnitude of the short-circuit current. The steel pipe will not be magnetized infinitely under different short-circuit currents; instead, the remanence value will reach a certain range and then stabilize without further increase. For every 20A increase in short-circuit current, the stable remanence range of the steel pipe increases by 4-8 Gs. Finally, the regression equation between current (x, in A) and remanence value (y, in Gs) is given as $\mathbf{y = 5 \times 10^{-11}x^6 - 4 \times 10^{-8}x^5 + 1 \times 10^{-5}x^4 - 0.0019x^3 + 0.1702x^2 - 7.7229x + 144.11}$, with a coefficient of determination of 0.9997, indicating a high level of reliability in the results.

Keywords

Short-circuit current, fire investigation; remanence value, regression analysis.

1. INTRODUCTION

Short-circuit current is the phenomenon of an abnormal increase in current caused by a circuit fault. Excessively high short-circuit currents can generate a large amount of heat, leading to overheating or damage of wires and electrical equipment, and may even cause sparks, arcs, or directly trigger a fire [1]. Short-circuit faults can magnetize surrounding ferromagnetic materials, turning previously non-magnetic metals into magnets and producing remanence. In fire investigations, metal remanence is often used as an important reference to determine the location of the fire source, providing strong evidence for investigators, helping them identify the true cause of the fire, and making scientifically sound judgments.

Extensive research has been conducted both domestically and internationally on the relationship between short-circuit current and the magnetic properties of metals. Early studies focused on the impact of temperature rise caused by short-circuit currents on the physical properties of non-metallic materials [2-3]. In recent years, with the development of power systems, researchers have gradually realized that the instantaneous strong magnetic fields induced by short-circuit currents may cause significant changes in the magnetic properties of ferromagnetic metals. Experimental studies have shown that under the influence of short-circuit currents, the hysteresis loop, saturation magnetic induction intensity, coercive force, and other magnetic properties of ferromagnetic materials can undergo significant changes, which in turn affect the operational characteristics and safety of equipment [4-7]. Domestic research has mainly focused on short-circuit current analysis of high-voltage electrical equipment and its impact on equipment endurance [8-9], with only a few studies addressing the changes in magnetic properties of ferromagnetic materials. However, overall, the research is relatively scattered.

It is not difficult to observe that current research on short-circuit currents, both domestically and internationally, mostly focuses on the design of electrical equipment's short-circuit resistance [10-11] and material selection. While there is considerable attention to short-circuit currents in fire investigations, there is a lack of research on the magnetic properties of ferromagnetic metals under short-circuit current conditions. Conducting studies on the magnetic properties of ferromagnetic metals under fire conditions is of great significance for determining the ignition point and fire cause during on-site investigations. The research results can provide valuable guidance for strengthening the prevention and control of such fires.

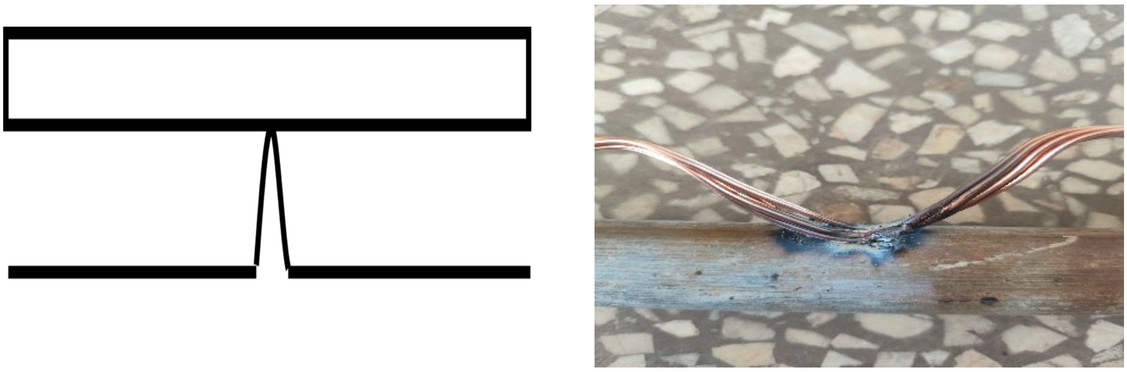
2. EXPERIMENTAL PLAN

(1) Experimental Materials

Non-magnetic round steel tube (700 mm in length, with a pipe opening radius of 15 mm), 6 mm^2 copper wire (safety current of the wire is 45 A, normal operating voltage 450 V, maximum pressure withstand voltage 750 V), ZX7-500 welding machine (industrial-grade dual voltage, dual-module AC220V-380V three-phase dual-use DC inverter, used to simulate short-circuit faults), WT103 short-circuit magnetic testing instrument (hereinafter referred to as the residual magnetism instrument) (range 0 – 20000 mT, resolution 0.1 Gs/0.01 mT, accuracy ±5%, operating temperature +5 to +40°C).

(2) Experimental Design

As shown in Figure 1, a 700 mm long round steel tube is selected, and the steel tube is arranged parallel to the 6 mm^2 copper wire with a vertical distance not exceeding 20 mm. Considering that the round steel tube itself will be magnetized after the short circuit, but the residual magnetism values at different parts of the tube may not be consistent, an experimental sample is first created according to the above experimental design. The tube is magnetized under various preset short-circuit currents, and the residual magnetism values at the short-circuit point and the point farthest from the short-circuit point are measured. Data for 100 A is selected, as shown in Table 1. The final data shows that regardless of the preset current, the residual magnetism values at both the short-circuit point and the point farthest from the short-circuit point are nearly identical. Therefore, for the formal experiment, residual magnetism data is only required from the short-circuit point.



a) Schematic Diagram of Metal Short-Circuit Point Location b) Actual Image of Short-Circuit Point Location

Figure 1. Schematic Diagram of Short-Circuit Point Location

In order to investigate the effect of continuous short-circuit duration on remanence, various short-circuit currents were set, and the experimental samples were subjected to short-circuit tests with durations of 3s, 5s, and 7s. The 100A data are shown in Table 2. The data indicates that, under the condition of constant short-circuit current, despite different short-circuit durations, the measured remanence values changed very little, and it can almost be considered that they are the same within the experimental error range. This phenomenon suggests that, under the same short-circuit current, the short-circuit duration has little effect on the magnetization results. To simplify the experimental process and improve efficiency, a continuous short-circuit duration of 5 seconds was ultimately chosen as the standard short-circuit time for the formal experiment.

Table 1. Remanence Values (Gs) at the Short-Circuit Point and the Farthest Point from the Short-Circuit Point under a 100A Short-Circuit Current

		The first experiment	The second experiment	The third experiment	Average
Short-circuit point	Before the short circuit	0	1	0	0.33
	After the short circuit	13	15	13	13.67
The farthest point from the short-circuit point	Before the short circuit	0	0	0	0
	After the short circuit	12	14	14	13.33

Table 2. Residual magnetism values (Gs) for different short-circuit durations under 100A short-circuit current

		The first experiment	The second experiment	The third experiment	Average
3s	Before the short circuit	0	0	0	0
	After the short circuit	11	12	12	11.67
5s	Before the short circuit	1	1	0	0.67
	After the short circuit	12	13	12	12.33
7s	Before the short circuit	0	1	0	0.33
	After the short circuit	13	14	12	13

The final confirmed experimental procedure is as follows: Set the short-circuit trigger currents to 60A, 80A, 100A, 120A, 140A, 160A, 180A, and 200A. Use a welding machine with the earthing connection method to create a short circuit between copper wires and steel pipes, with a short-circuit duration of 5 seconds. Mark the short-circuit point on the steel pipe, and use a residual magnetism meter to measure the residual magnetism values at the short-circuit point on the steel pipe before and after the short circuit. The short circuit magnetizes the steel pipe, as shown in Figure 2. Repeat the above procedure, performing three repeated experiments for each current group.

3. DATA ANALYSIS

(1) Residual magnetism analysis

Draw Table 3 based on the residual magnetism values before and after the short circuit of the steel pipe during the inspection.

Table 3. Residual magnetism values (Gs) before and after short circuit of metal steel pipes under different short circuit currents

		The first experiment	The second experiment	The third experiment	Average
60A	Before the short circuit	0	1	0	0.33
	After the short circuit	7	7	8	7.33
80A	Before the short circuit	0	0	0	0
	After the short circuit	11	10	12	11
100A	Before the short circuit	1	1	0	0.67
	After the short circuit	14	17	19	16.67
120A	Before the short circuit	2	0	0	0.67
	After the short circuit	21	22	22	21.67
140A	Before the short circuit	0	0	0	0
	After the short circuit	27	30	29	28.67
160A	Before the short circuit	1	1	1	1
	After the short circuit	34	34	35	34.33
180A	Before the short circuit	0	0	1	0.33
	After the short circuit	41	41	40	40.67
200A	Before the short circuit	2	0	1	1
	After the short circuit	49	48	48	48.33

From the data in Table 3, it is clear that the residual magnetism value of the non-magnetic steel pipe before the short circuit does not exceed 2 Gs, which is very low and can be ignored, considered as 0 Gs. The residual magnetism values before and after the short circuit in all three experiments are very close, making the results reliable. As the short circuit current increases, the residual magnetism of the non-magnetic metal also increases, showing a positive correlation. After analysis, it is believed that this is because when the short circuit current passes through the metal, it generates a magnetic field in the surrounding space. This magnetic field causes the magnetic moments of the internal magnetic domains to align, resulting in changes in the lattice structure and consequently altering the magnetism. Based on the data in the table, it is found that within the short circuit current range of 60-200 A, the residual magnetism of the steel pipe increases by 4 to 8 Gs for every 20 A increase in current. Moreover, as the current increases, the increase in magnetism becomes relatively larger.

(2) Regression analysis

Summarize the average values of the above experimental data and plot the line chart shown in Figure 2:

From Figure 2, it can be observed that as the short-circuit current increases, the residual magnetism value of non-magnetic metals also increases, showing a positive correlation between the two. By inputting the data into Origin software, with the independent variable x as short-circuit current (A) and the dependent variable y as residual magnetism value (Gs), the regression equation between short-circuit current and residual magnetism value can be obtained as follows:

$$y = 5 \times 10^{-11}x^6 - 4 \times 10^{-8}x^5 + 1 \times 10^{-5}x^4 - 0.0019x^3 + 0.1702x^2 - 7.7229x + 144.11$$
$$R^2 = 0.9997$$

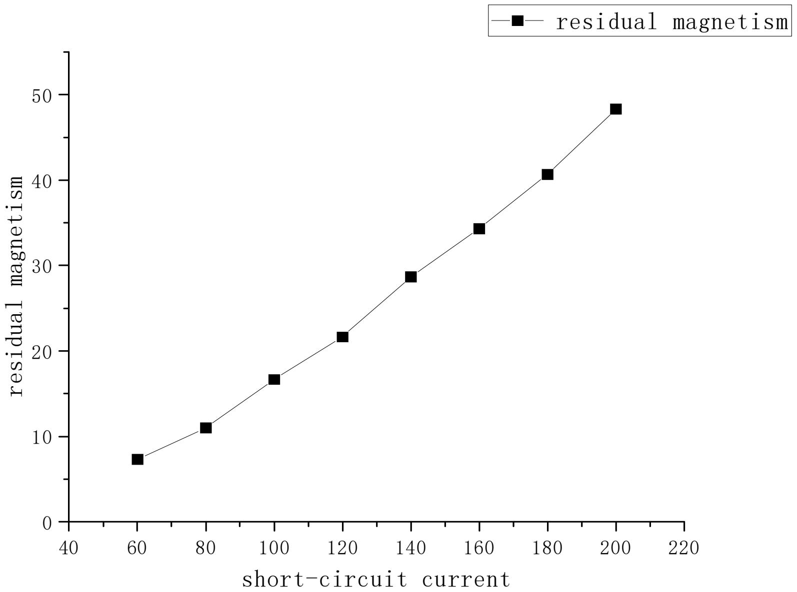


Figure 2. Variation curve of residual magnetism values after short-circuit of non-magnetic metals

In order to evaluate the fitting effect and reliability of the proposed formula, the coefficient of determination (R^2) was used as the evaluation metric. The coefficient of determination ranges from 0 to 1. When it equals 1 or is close to 1, it indicates the highest reliability; otherwise, the reliability is lower. The R^2 value in the equation is 0.9997, which is close to 1, indicating that the formula has a high reliability.

Subsequent supplementary experiments were conducted, selecting short-circuit currents that were not included in the formal test for magnetization, in order to verify the prediction accuracy of the formula. The short-circuit current was set to 150A, and after conducting three experiments, the data are shown in Table 4. Let x equal 150, and substituting this value into the equation gives a predicted value of y = 33.43, i.e., the predicted value is 33.43.

Table 4. Residual Magnetic Flux Values (Gs) of Steel Pipe Before and After Short-Circuit at 150A

		The first experiment	The second experiment	The third experiment	Average
150A	Before the short circuit	0	0	0	0
	After the short circuit	32	31	31	31.33

As shown in Table 4, the average value of the three experiments under the 150A short-circuit current is 31.33Gs, with a deviation of 6.7% from the predicted value. This indicates that the formula is highly reliable, as the error between the predicted and actual values is small, not exceeding 10%, and can be used as a practical reference.

4. CONCLUSION AND DISCUSSION

Under the action of short-circuit current, non-magnetic round steel pipes experience magnetization, and the degree of magnetization is closely related to the magnitude of the short-circuit current. Specifically, the larger the short-circuit current, the stronger the magnetization of the steel pipe. However, it is important to note that there is a limit to the magnetization effect of the steel pipe under different intensities of short-circuit current. The magnetization does not continue to increase with the duration of the short-circuit; instead, the magnetization gradually saturates and eventually reaches a stable remanence value. Based on experimental data, a certain quantitative relationship between the short-circuit current and the remanence of the steel pipe has been observed. Through further analysis and regression calculations, a regression equation between current and remanence value can be derived. Verification shows that the predicted results of this equation are highly reliable. Therefore, this regression equation not only accurately reflects the impact of short-circuit current on the magnetization process of the round steel pipe but also holds strong application value and practical significance.

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