An Experimental Investigation of the Nonlinear Transient Electric Field Response Induced in Thin-Walled Cylindrical Ferromagnetic Shields by Short-Duration Surface Current Pulses

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Abstract—This paper presents results of an experimental investigation of the transient electric field induced at the interior surface of long, thin-walled, cylindrical, electrically-conductive ferromagnetic shields by axially-directed, unipolar, short-duration current pulses along the exterior surface. For applied pulses having a duration that was sufficiently short compared to the shield response, the transient electric field responses approached a result that depended on the total charge transported along the surface of the cylinder during the applied current pulse but was essentially independent of the particular time variation of the applied pulses. For practical purposes, such pulses can be regarded as impulses, and the resultant electric field response can be regarded as an impulse response for that charge level. Experimental results for a wide range of injected charge levels on a mildly ferromagnetic specimen are presented. Unlike the impulse response for the linear problem with a constant permeability, the impulse response exhibits nonlinear variation with applied charge level.

Keywords—ferromagnetic; shield; nonlinear; current; transient; pulse; impulse; electromagnetic pulse; EMP; electrostatic discharge; ESD; lightning

I. INTRODUCTION

Electromagnetic shielding is used to attenuate undesirable electromagnetic fields to an acceptable level. A ferromagnetic material can have a high magnetic permeability, which can be an advantage; however, the permeability is not constant, but varies with applied magnetic field intensity. As the applied magnetic field is increased from zero, the magnetic permeability typically starts at an initial value, increases to a maximum value, and then decreases to the permeability of free space, $\mu_0$, as the material undergoes magnetic saturation. As a result of the field dependent permeability, the penetration of electromagnetic fields into ferromagnetic shields is inherently a nonlinear phenomenon, which makes it difficult to predict the performance of ferromagnetic shields under intense transient field conditions. This study is intended to provide an improved understanding of the performance of ferromagnetic shields under intense transient electromagnetic field conditions.

This paper considers the fundamental problem of a long electrically conductive ferromagnetic cylinder subjected to a surface current pulse. The fields associated with the applied pulse diffuse into the shield and induce a transient electric field at the interior surface. The maximum value of the electric field transient, and the time at which the maximum value occurs are of primary interest. The emphasis of the study is on the nonlinear nature of this transient electric field response.

Previously, the results of theoretical investigations for a planar approximation to the above cylindrical problem were reported in [1] and [2]. This study presents results of an experimental investigation of the problem. In the experiment described below, a thin-walled, cylindrical, electrically conductive, ferromagnetic specimen was subjected to a wide range of injected current pulses.

The first objective of the experiment was to investigate experimentally the transient electric field response as the duration of the applied current pulses was made shorter while maintaining the total charge injected during the applied pulse at the same level. For an applied current pulse with a duration that was long compared to the response time for the shield, the transient electric field response was observed to be strongly dependent on the time variation of the applied pulse. However, as the applied pulse was made shorter while maintaining the total injected charge constant, the transient electric field response became less and less dependent on the time variation of the applied pulse. For applied pulses with a duration that was sufficiently short compared to the response time for the shield, the transient electric field responses approached a result that depended on the total charge transported along the surface of the cylinder during the applied current pulse but was essentially independent of the particular variation of the applied pulses. For practical purposes, such pulses can be regarded as impulses, and the resultant electric field response can be regarded as an impulse response. While an impulse response is well known in linear problems with a constant permeability, the existence of an impulse response for a nonlinear problem is not immediately obvious because higher amplitude pulses
might be expected to drive the shield farther into saturation than lower amplitude pulses. The total charge injected during the applied pulse is a better measure of the severity of an applied pulse than the amplitude alone.

The second objective of this experiment was to investigate the transient electric field response for different pulse levels while maintaining the pulse shape (time variation) of the short duration applied pulses the same. Experimental results for a wide range of injected charge levels for a mildly ferromagnetic specimen are presented.

A third objective of this study was to investigate the nonlinearity of the phenomenon by examining the ratio of the peak response to the injected charge. Unlike the impulse response for the linear case with a constant permeability, the results for the nonlinear case with a field dependent permeability are found to vary with the injected charge level.

II. PROBLEM DESCRIPTION

This study considers a thin-walled, cylindrical, electrically conductive, ferromagnetic shield subjected to axially-directed, unipolar, short-duration current pulses injected uniformly along the exterior surface as shown in Fig. 1. This configuration has application to cable shields and conduit protected wires.

The pulses considered here are unipolar pulses of the form

\[ I(t) = A \left[ \exp\left(-\frac{t}{t_r}\right) - \exp\left(-\frac{t}{t_f}\right) \right] \]  

(1)

where \( A \) is an amplitude factor, \( t_r \) is a time constant associated with the rise time, and \( t_f \) is a time constant associated with the fall time. This idealized pulse shape is shown in Fig. 2.

By definition, the total charge injected during a pulse is

\[ Q = \int I(t) dt \]  

(2)

For a pulse of the form (1), the total charge is

\[ Q = A(t_f - t_r) \]  

(3)

As the fields associated with an applied pulse diffuse into the shield, a transient electric field is induced at the inner surface. It is this transient electric field response that is of concern. An idealized electric field response, \( E(t) \), is shown in Fig. 3. The peak value, \( E_{\text{peak}} \), and the time at which the peak value occurs, \( t_{\text{peak}} \), are of primary interest.

III. EXPERIMENTAL SETUP

The specimen under test was inserted as the center conductor in a coaxial transmission line configuration, which in turn was enclosed within a shielded room. One end of the cylinder was enclosed by an end-cap to which a sense-wire was attached to the inside. The other end of the specimen was connected to a conduit stub that penetrated the wall of the shielded room such that the sense-wire extended through the wall to allow measurements to be made outside of the shielded room. A cylindrical shroud was placed around the test specimen to form a coaxial transmission line, which was terminated by a load resistor. A capacitor discharge pulse generator was used to generate short-duration pulses, which were injected onto the end-cap of the cylindrical specimen and
passed along the test specimen, through the load resistor, and back to the pulser via the shroud.

The pulse generator consisted of a fixed capacitor, $C$, and an adjustable spark gap that was used to set the maximum voltage for the applied pulse, $V_p$. The capacitor and spark gap were located in a housing pressurized with sulfur hexafluoride ($SF_6$) gas. The firing voltage for the spark gap, $V_s$, was determined by the $SF_6$ gas pressure and the gap spacing. When the charging voltage reached $V_s$, the spark gap fired, and the capacitor, $C$, was discharged along the specimen and through the load resistor, $R$.

A current probe was used to measure the actual current pulse injected onto the test specimen. The applied current pulse was integrated to determine the charge transported during the pulse. The integration was performed numerically using the digital oscilloscope and software. A conversion factor was applied to convert the integrated result to coulombs.

The sense-wire attached to the inside of the end-cap was used to monitor the induced voltage. The open circuit voltage is proportional to the electric field and the length of the specimen. The sense-wire was terminated by a $56\Omega$ resistor connected to the exterior wall of the shielded room.

The test set up conveniently allowed the generation of pulses with different amplitudes and time constants, but approximately the same value of charge by changing the value of the load resistance, $R$, while maintaining the firing voltage $V_s$ constant. The value $V_s$ was controlled by adjusting the spacing between the electrodes in the spark gap. For a fixed $V_s$, the amplitude and time variation of the applied current pulse were modified by changing the value of $R$ by substituting resistors. This allowed the generation of applied pulses with different amplitudes and time constants while maintaining approximately the same value for $Q$. Since the value of $C$ in the pulse generator was fixed, the maximum charge that could be injected was

$$Q = CV_s$$  \hspace{1cm} (4)

While the early time characteristics of the applied pulse (especially the rise time) were affected by the transmission line properties of the test configuration, the long time characteristics of the applied pulse were essentially those of capacitor discharge in an RC circuit and were determined primarily by the voltage, $V_s$, the capacitor, $C$, and the load resistor, $R$. For a simple RC circuit,

$$I(t) = \frac{V_s}{R} \exp\left(-\frac{t}{RC}\right)$$  \hspace{1cm} (5)

From (2) and (5), the total charge is simply

$$Q = \int I(t) dt = -CV_s \exp\left(-\frac{t}{RC}\right)_{0}^{\infty} = CV_s$$  \hspace{1cm} (6)

It is noted that the early time behavior of the applied current pulses exhibited a burst of noise. One component appears to be due to the initiation of discharge in the spark gap. Also, the test specimen and shroud formed a coaxial transmission line with a fixed configuration. Since the transmission line was not always terminated in its characteristic impedance, there were reflections in the early times of the current pulse.

**IV. EXPERIMENTAL RESULTS**

For the results presented here, the pulser had a fixed capacitance $C=0.02$ microfarad and could generate pulses with voltages in the range $0 < V_p < 5 \times 10^4$ volts so the maximum charge that could be stored in the capacitor and injected onto the specimen was approximately $Q=0.001$ coulomb.

To investigate the effects of applied pulse duration on the shield response, the ferromagnetic specimen was subjected to a sequence of pulses using several values of $R$, which were changed while maintaining $V_s$ constant. The nominal values of load resistance used in the test sequence were: $250\Omega$, $125\Omega$, $50\Omega$, $25\Omega$ and $17\Omega$ for which the nominal RC time constants were $5.0\mu s$, $2.5\mu s$, $1.0\mu s$, $0.5\mu s$ and $0.34\mu s$ respectively. The maximum possible amplitudes were $2.0 \times 10^{-4} A$, $4.0 \times 10^{-4} A$, $1.0 \times 10^{-3} A$, $2.0 \times 10^{-3} A$, and $2.5 \times 10^{-3} A$, respectively. As the value of $R$ was reduced from the highest value, the applied pulse had a larger amplitude, but a shorter duration. This procedure was repeated for selected voltages in the range $0 < V_p < 5 \times 10^4 V$. At each pulse setting, the signals were averaged over 32 pulses.

To illustrate the procedure some results from pulse tests on a low carbon steel foil specimen are presented here. The cylindrical specimen was fabricated from ferromagnetic foil wrapped over a non-conducting mandrel for physical support. The foil was a mild 1010 steel, with No. 1 temper that complies with Federal Specification QQ-S-698 [3]. The thickness of the foil was nominally 1 mil (0.001 inch). The inside diameter of the ferromagnetic specimen was nominally 1/4-inch: $6.48 \times 10^{-3}$ meter (0.255 inch). The wall thickness was approximately $6.86 \times 10^{-3}$ meter (0.270 inch). The length of the specimen was 1.83 meter (72 inches).

An idealized sense-wire voltage response $V_s(t)$ is shown in Fig. 5 to illustrate the quantities of primary interest: the peak value, $V_{\text{peak}}$, and the time at which the peak value occurs, $t_{\text{peak}}$.

![Figure 5. An idealized sense-wire voltage response $V_s(t)$](image)

For ease of comparison, the results are presented in terms of the voltage response measured on the sense-wire since the objective of this study was to investigate the nonlinear nature of the impulse response rather than the absolute value of the
electric field. The electric field can be estimated by dividing the measured voltage response by the length of the specimen exposed to the pulse.

The test sequence is illustrated by the oscillographs shown in Fig. 6 for the test sequence for $V_{in}=4.7\times10^4$ volts, which is the highest value for $V_{in}$ that was used. The results are shown from the lowest amplitude, longest duration pulse using $R=250\Omega$ on the bottom to the largest amplitude, shortest duration pulse using $R=17\Omega$ on the top. As the applied pulse duration was made shorter, the voltage response tended toward a result that did not depend appreciably on the time variation of the applied pulse. The sequence was performed at other selected voltages (not presented here) and demonstrated similar results. (The burst of noise at the start of the sense-wire response is believed to be due to an unidentified leakage path and not part of the diffusion signal.)

To investigate the response for various charge levels, the resistance was fixed at $R=17\Omega$ to give the shortest duration pulse, and the firing voltage $V_{in}$ was changed by adjusting the spark gap spacing. The peak voltage of the measured response is plotted versus the injected charge in Fig. 7.

V. DISCUSSION OF RESULTS

The results selected for presentation in this paper are intended to illustrate the procedure and findings. As illustrated in Fig. 6, for applied current pulses with a duration that was long relative to the transient response, the responses can be seen to be strongly dependent on the time variation of the applied pulse. However, as the applied pulses were made shorter while maintaining the total injected charge constant, the transient electric field responses can be seen to be less and less dependent on the time variation of the applied pulse. For applied current pulses of sufficiently short duration, different applied pulses yielded essentially the same transient voltage response as long as the injected charge was the same. Such short-duration current pulses can be regarded as impulses with a magnitude $Q$, and the corresponding transient voltage response as an impulse response.

It is important to note that the suitability of a particular applied pulse as an impulse is not an inherent property of the pulse but depends on the time variation of the applied pulse compared to the response time of the shield under consideration. Consequently, an applied pulse may be a good approximation to an impulse for one shield but may be a long pulse for another shield. It is advisable to use an applied pulse such that several time constants have elapsed before the peak of the transient response. For the results presented here, the fastest applied pulse that could be generated was marginal as an impulse for this specimen, but was a good approximation for another specimen with a greater wall thickness and later occurrence of the peak of the transient response. While the transient voltage response was approximately invariant for pulses with the same charge, the transient voltage response did depend on the level of charge that was transported along the specimen during the applied current pulse. Thus, the value of $Q$ is a better measure of the severity of the applied current pulse than the amplitude alone. Experimental results for a range of injected charge levels are presented. Fig. 7 shows the maximum values of the voltage responses plotted versus injected charge for measurements made with selected voltages in the range $0<V_{in}<5\times10^4$ volts, which corresponded to selected values of charge in the range $0<Q<1\times10^6$ coulomb. This curve characterizes the performance of the specimen for short duration pulses in the nominal range $0<Q<0.001$ coulomb. For a constant permeability, the results would be a straight line.

The nonlinearity of the phenomenon is more evident by considering the ratio of the peak response voltage divided by the injected charge as shown in Fig. 8. As the applied charge is increased, the results start from a value near $Q=0$, decrease to a minimum, and then increase. For a constant permeability, this ratio would be a constant (horizontal line) with no variation.

VI. CONCLUSION

Results for a ferromagnetic specimen subjected to a wide range of injected current pulses are presented. For applied current pulses with a duration that was sufficiently short relative to the internal response, the internal responses approached a result that depended on the total charge transported along the surface of the cylinder during the applied current pulse but was essentially independent of the particular time variation of the applied pulse. For practical purposes, such applied pulses can be regarded as impulses, and the resultant response as an impulse response. The impulse response allows the results for one applied pulse to be used to predict the performance of the shield for another applied pulse with the same total charge as long as the applied pulses are of sufficiently short duration compared to the shield response. The maximum values of the impulse responses for a range of applied charge levels were determined for a mildly ferromagnetic specimen. The nonlinearity of the phenomenon is readily evident by considering the ratio of the peak response to the applied charge $Q$. It is emphasized that the impulse characteristic of an applied pulse is not an inherent property of the applied pulse but is relative to the response time of the particular shield under consideration.

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REFERENCES


Figure 6. Response waveforms (right column) for various drive pulses (left column). The pulser voltage was approximately 47 kV and the load resistance was varied from 250 Ω (bottom) to 17 Ω (top). The vertical scales are 300 milliamps/division and 3.4 volts/division, respectively, for the drive and response sets of plots. The horizontal scale is 4 microseconds/division for both sets.
Figure 7. Peak sense-wire voltage versus applied charge, Q.

Figure 8. Peak sense-wire voltage to applied charge Q.