# Electromagnetic Radiation Behavior of Low-Voltage Arcing Fault

Charles J. Kim, *Senior Member, IEEE*

***Abstract*—A feasibility study of utilizing radiated electromagnetic energy from spark/arc source as a means of detecting arcing faults is conducted using two types of simple antenna, stick and loop. From the investigation, it is concluded that arc/spark of low voltage can be detected by portable antennas with frequency bands of low amplitude modulation and megahertz as an alternative method to the conventional arcing detection methods and their apparatus. In addition, each of the first two phases of arc process, initial glow-like discharge and transient arc development, is distinguished by the respective inception time and radiation spectral content of the captured signals by the antennas.**

***Index Terms*—Arc, electromagnetic radiation, loop antenna, spark, stick antenna.**

## I. Introduction

ARCING faults are prevalent in electrical systems and are responsible for the most devastating effect of electric fires. Arcing faults occur when insulation ages or is damaged by a variety of causes. In a commercial electrical system, faulty connections due to corrosion, faulty initial fastening, vibration, and chaffing cause 60%–80% of arcs [1].

An arcing fault is a luminous, high-power discharge between two electrical contacts, and this discharge is the main source of the release of a tremendous amount of energy to the surrounding area, damaging circuits and, on occasion, consuming a good section of conductors. The high-power discharge, however, does not usually conduct high arcing fault current in the circuit. This is particularly true when one of the contacts is the ground or equipment. In addition to the resistance of the arc, the impedance of the ground path limits the magnitude of the arcing fault current. The low level of the fault current in a high-impedance arcing fault is often insufficient to trip overcurrent protective devices installed in the source end of the circuit, resulting in the escalation of the arcing fault and the increased damage to the circuit.

In addition, the arc current does not conduct continuously; instead, its flow is transient, sporadic, and intermittent. The intermittency of the arcing fault current further exacerbates the clearing problem of arcing by the conventional overcurrent protection approach.

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The author is with the Department of Electrical and Computer Engineering, Howard University, Washington, DC 20059 USA (e-mail: ckim@howard.edu).

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Arcing fault detection researchers have focused, therefore, instead of the magnitude of the fault current, on the following alternative solution methods: frequency analysis of fault current [2], [3], random and sporadic behavior of the arcing phenomena [4], arcing voltage and current waveshapes and behaviors [5], and neural-network and expert system approaches [6], [7].

Despite the differences in the way of using the arcing characteristics, the present solution methods share a common feature: they measure voltage and current signals via voltage and current transformers at a substation or a feeder. On the other hand, a new way of detecting arcing faults finds its instrument from the electromagnetic radiation associated with the arc process.

This paper investigates the electromagnetic radiation behavior of the arcs/sparks in low-voltage electrical system as a possible means of detecting a low-voltage arcing fault in an electrical system of a confined area in residence/business, aircraft, and ship. The investigation is focused on the electromagnetic radiation behavior of the arc/spark in a 120-V system measured by two types of antennas—stick and loop. Based on the staged spark/arc events and the consequent recordings using the antennas, the magnetic radiation behavior is analyzed and its detection feasibility is discussed. Also, a further study for incorporating the detection scheme into realistic implementation for practical use is suggested.

This paper is organized as follows. Section II introduces the behavior of the arc process and the electromagnetic radiation associated with it. Section III presents the experimental set up for generating an arc/spark and for capturing the radiated signals using the antennas. In Section IV, we discuss the experiment results. Section V concludes this paper and comments on the benefit and practical use of the radiation approach.

## II. Electromagnetic Radiation From Arcs

### A. Arc Process

An arc discharge is a phase of an electrical discharge development which results from the creation of a conducting path between two points of different electrical potentials in the medium of gas or the atmosphere. If the supply of electrical charge is continuous, the discharge is permanent, but otherwise, it is temporary, and serves to equalize the potentials. Since the matter transferred in the conducting path is electrons, the nature of a discharge depends on the method for supplying electrons [8].

Consider an electrical discharge setting where voltage across a discharge spot is controlled by a variable voltage source. When the voltage across the discharge spot is raised to a sparking potential, the discharge voltage is sharply reduced as the initial breakdown phase sustains a low-current glow-like discharge. A further increase of the supply voltage would increase the electron supply, which quickly moves the discharge to the point of transient arc phase, where arc voltage is lowered and arc current is sharply increased, showing the characteristic negative–resistance V-I relationship. The current in the transient arc phase increases more rapidly with the electric field than in the glow discharge. When the transient arc phase is further advanced by high temperature or higher potential, it can develop to steady-state conductive channel phase with high gas heating and expansion [9]. In an interrupted arc, as in low ac voltage discharge, the last phase may not be developed unless it is thermally augmented by the heat of the arc.

### B. Electromagnetic Radiation From Arc

Radiation from the arc is a reflection of all of the discharge dynamics of the arc process, and these dynamics are a sensitive function of discharge conditions such as different electrode material and their interaction with an electron supply mechanism, some of which may only be known approximately. Consequently, the electromagnetic radiation associated with the arc can vary considerably from one discharge to another. The behavior of electromagnetic radiation generated from the arc process has long been studied theoretically and experimentally [10]–[13]. And it has been known that the arc radiation, in general, is dominated by the abrupt arc current changes in the arc dynamics.

The general expression for the electromagnetic field $E$ at distance $R$ by a current component of length $l$ oriented along the $x$ -axis at a given time $t$ is given as [10]

$$E(R,t) = \frac{\sin\theta}{4\pi\varepsilon_o Rc^2}\int_0^l \frac{dI}{dt}dx \tag{1}$$

where $\theta$ is the angle between the current direction and the $R$ vector, and $c$ is the velocity of light. Considering a spot arc, with the length along the $x$ -axis in the aforementioned equation ignored, (1) is simplified to

$$E_{\text{arc}}(\text{t}) = \frac{1}{4\pi\varepsilon_o c^2}\frac{dI_{\text{arc}}}{dt} = k\cdot\frac{dI_{\text{arc}}}{dt} \tag{2}$$

where $k$ is a constant.

Equation (2) indicates that the radiation field produced by the arc current $I_{\text{arc}}(t)$ is proportional to the derivative of the current $dI_{\text{arc}}/dt$ or $\dot{I}_{\text{arc}}$. Therefore, the electromagnetic field radiated by an arc requires knowledge of the arc current and its temporal evolution over the phases of the arc discharge process. Once the arc current behavior is known, from the field equation, one could then infer the frequency spectrum of the arc radiation. The transient arc phase with a rapid and strong ionization period is believed to radiate higher frequency components than the other two phases. Since the electromagnetic radiation and its spectral content are determined by the derivative of arc current, an arc current model should be developed first.

When an electric discharge initiates, a localized and isolated charged spot of capacitance $C_{\text{s}}$ starts to appear between two contacts. At sufficiently high charge densities, a strong electric field near the edge of spot causes electric breakdown, and creates an arc discharge of length of $l$ and current $I_{\text{arc}}$. The arc develops a series combination of a self-inductance $L_{\text{arc}}$ and arc resistance $R_{\text{arc}}$. Assuming that $L_{\text{arc}}$ and $R_{\text{arc}}$ are approximately time independent during the arc's lifetime, the arc current can be represented in the following series RLC differential equation [11]:

$$\frac{dI_{\text{arc}}^2}{dt^2} + 2\alpha\frac{dI_{\text{arc}}}{dt} + \omega^2 I_{\text{arc}} = 0 \tag{3}$$

where $\alpha = R_a/2L_a$ is the arc-inductive damping rate and $\omega = 1/\sqrt{L_a C_s}$ is the arc circuit's natural frequency.

For the solution of (3), we assume an overdamping condition of the arc current following the usual steep rise and exponential falling of arc current behavior. Applied with the initial condition of $I_{\text{arc}}(0) = 0$, the general solution form $I_{\text{arc}}(t) = A_1 e^{(-\alpha+\beta)t} + A_2 e^{(-\alpha-\beta)t}$ becomes

$$I_{\text{arc}}(t) = \frac{\dot{I}_{\text{arc}}(0)}{\beta}e^{-\alpha t}\sinh\beta t \tag{4}$$

where $\beta = \sqrt{\alpha^2-\omega^2}$ and $\dot{I}_{\text{arc}}(0)$ is the initial arc current rise rate.

Equation (2) is then changed to the following broadcast radiation equation:

$$\begin{aligned} E_{\text{arc}}(t) &= k\dot{I}_{\text{arc}}(t) \\ &= k\dot{I}_{\text{arc}}(0)e^{-\alpha t}\left[\cosh\beta t - \frac{\alpha}{\beta}\sinh\beta t\right]. \end{aligned} \tag{5}$$

Then, the power spectrum of the radiation can be obtained as [11]

$$\begin{aligned} P_{\text{arc}}(w) &= \left|\int_0^\infty E_{\text{arc}}(t)e^{-jwt}dt\right|^2 \\ &= \frac{k^2\dot{I}_{\text{arc}}(0)^2 w^2}{(\omega^2-w^2)^2+4\alpha^2 w^2}. \end{aligned} \tag{6}$$

The power spectrum (6) indicates that the peak of the power spectrum occurs at a frequency of $w=\omega$, which is determined by arc inductance and arc capacitance.

When the arc inductance is negligible, then the power spectrum can be approximated by

$$P_{\text{arc}}(w) \approx \frac{k^2\dot{I}_{\text{arc}}(0)^2\omega^2 w^2 R_{\text{arc}}^2 C_s^2}{1+R_{\text{arc}}^2 C_s^2 w^2}. \tag{7}$$

The approximated power spectrum (7) indicates that half its maximum value of the power spectrum occurs at a frequency of $w = 1/R_{\text{arc}}C_s$, which is again determined by the arc process characteristics of arc resistance and arc capacitance.

### C. Spectral Contents of Arc Radiation

From (6) and (7), it is apparent that the spectral characteristic of arc discharge relies upon the arc process and its equivalent values of arc elements: arc resistance, arc capacitance, and arc inductance. There is a practical problem in quantitatively determining the electromagnetic radiation of arc and its spectrum power since it is almost impossible to precisely determine the arc elements due to the varying conditions of arc process and the measurement difficulties of the elements.

Some attempted to estimate the general power spectrum from the arc, considering the electron density at the electrodes, without much success, since the current density value at the electrode spot is varied in pressure, electrode material, and size [14]. It is known that relative radiation intensity is dependent on electrode materials, arc gap (length), and the influence of an external circuit. Since the values of arc elements in the arc process are not uniquely defined for all arc varieties, the majority of research therefore has relied on experiments for radiation characteristics of specific arc discharges.

An experiment of a surface sparks/arcs in ambient air observed 8–12-GHz fluctuations in the transient arc phase and nowhere else [13]. Another experiment for electromagnetic radiation from narrow electrical discharges showed that discontinuities in the discharge current and its derivatives dominated the high-frequency part of the radiated spectrum of 300-MHz band emissions [15].

On the other hand, an experimental investigation of the radiation from silver-compound contacts observed the peaks of noise at the 10-MHz band immediately after the initiation of the arc discharge and, in the ensuing transient arc discharge, the peak noise of above 100 MHz [16].

The experiment reports of the spectrum band on arc radiation, from the megahertz to gigahertz band, can provide some general spectrum distribution of the radiation, but the specific radiation characteristics from the low-voltage arc/spark discharge can only be determined by one's own experimentation. However, we can conjecture that since the voltage supply limits the electron density and its rise rate in the low-voltage arc discharge, we expect much lower spectral content in the spectrum power. Also, due to the low supply voltage, the initial slow rising glow-like discharge phase would produce relatively low spectral radiation and the ensuing rapid-rising transient arc phase, relatively high spectral radiation.

In the experiment described in the next section, we test if a simple inexpensive RF antenna in the low AM and MHz band can capture the spectral radiation and if detection of arcing with such scheme is feasible. Additionally, we test if we can distinguishingly recognize, and verify the conjecture, the first two phases of the arc process, initial glow-like discharge and transient arc phases, by the earlier inception of lower spectral content for the former and by the following inception of higher spectral content for the latter.

## III. Experimental Setup

In an ideal measurement condition, one could use a rod, a bicone, a log spiral, and a horn antenna in a shield enclosure or anechoic chamber for a complete spectrum distribution of arc radiation from the kilohertz to gigahertz bands. But for an inexpensive way for the feasibility test, we improvised two simple antennas: 1) a stick antenna of low amplitude-modulation (AM) band frequency and a loop antenna of the megahertz range frequency band.

In a stick antenna, a ferrite rod is usually used to increase magnetic flux density without appreciable energy losses at the reception frequency. The concentrated flux lines at the ends of the ferrite rod focus on the field pattern. Ferrite rods are primarily found inside an AM/FM radio. The stick antenna we used for the experiment is a ferrite rod taken from a radio. No tuner circuit is attached to the antenna, which makes the pickup frequency at a very low AM band.

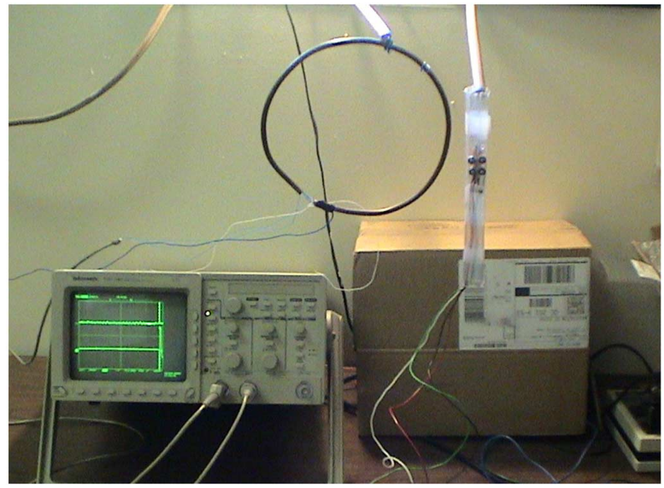

Fig. 1. Loop antenna and a stick antenna were used in radiation capture experiments.

Fig. 2. Arc/spark generation in the blade contact of a knife switch by rubbing actions.

A loop antenna is directional with a figure eight (8) pickup pattern. The number of turns of the loop antenna is determined by the overall size of the antenna, its frequency range, the tuning capacitor, and how tightly the wires are packaged together. The larger the loop is, the fewer the required turns will be. The in-house loop antenna we designed is an air-core loop antenna, suited primarily for the megahertz band and built with 1/8-in copper tube and five turns of AWG 30 wire to form an approximate 8-in-diameter loop. Fig. 1 shows the two antennas used in a test for the experiment.

The experiment setup consists of two components: 1) arc/spark generation and 2) arc radiation measurement using the antennas. The arc/spark generation is performed in a simple ac circuit with a resistive load which can be switched on or off by a knife switch. The 100–V ac source for the circuit is supplied from an outlet of the laboratory. We produced arcs/sparks by partially opening/closing and rubbing the contact blades of the knife switch. A photo of the arc/spark generated from the contact blades of the knife switch is in Fig. 2.

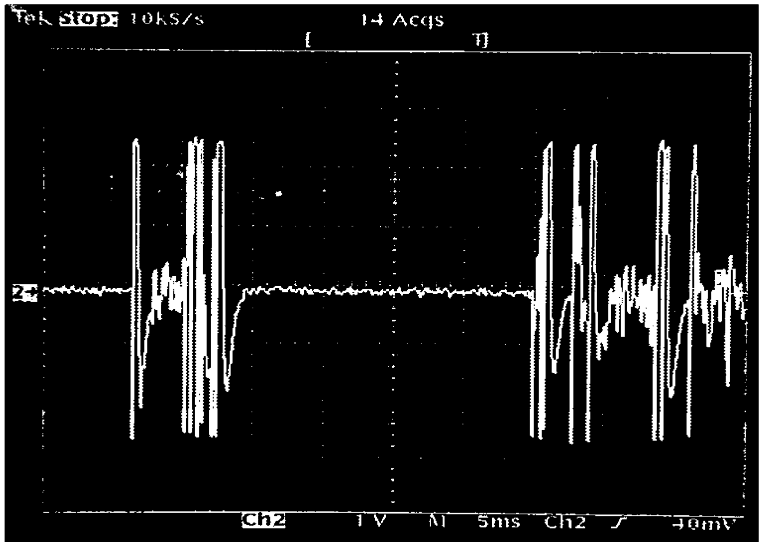


Fig. 3. Electromagnetic radiation capture by the stick antenna. Time scale in the 10-division capture period is 5 ms/div.

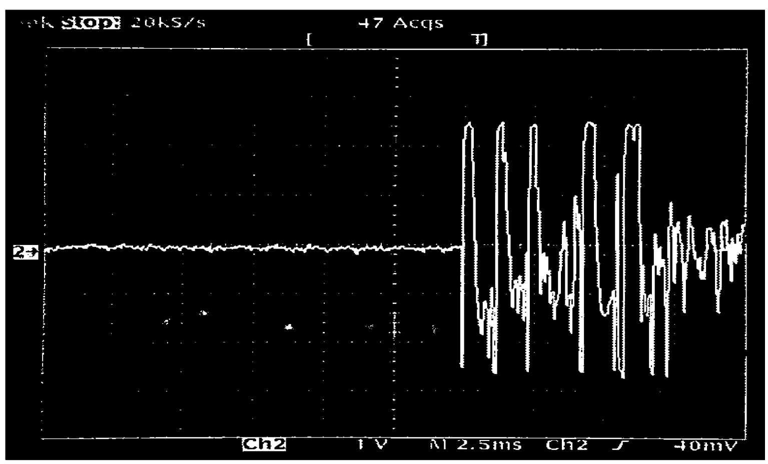


Fig. 4. Second arc/spark signal of Fig. 3, but in a shorter time/div for a detailed waveshape.

The terminal ends of the antenna were directly connected to a digital storage scope—a Tektronix TDS340 two-channel digital real-time oscilloscope, with a maximum sampling rate of 500 million samples per second, and the captured radiation signal was stored in the scope memory. No additional circuitry, such as amplifier, filter, or tuner, was used in the measurement.

## IV. Results of Experiments

We conducted three types of masurements of radiation by using the antennas, separately and together: stick antenna, loop antenna, and stick and loop antennas. Single antenna tests were used to obtain radiation behavior in different frequency bands and for assessing the detectability of the applied antennas for arc/spark. The dual antenna tests were used to examine whether the first two phases of arc development could be distinctively recognized by, presumably, the earlier pickup by the stick antenna of the lower frequency component radiated from an initial breakdown of glow-like discharge followed by the loop antenna pickup of the higher frequency radiating from the ensuing transient arc phase.

### *A. Radiation Signal Capture by Stick Antenna*

The scope capture shot in Fig. 3 is produced by a stick antenna test of spark/arc radiation. The scale of the time axis, $x$-axis, is 5 ms per division, thus the entire screen covers 50 ms of a capture period. The capture consists of multiple arc/sparks generated in the capture period.

Fig. 4, with a portion (the second signal group) of Fig. 3 in smaller scale—2.5 ms/div—shows the details of the captured signal characteristics: rather constant magnitude of dominant sinusoids with short-lived spikes especially in the negative cycles of the signal. The captured sinusoids by the stick antenna are of very low frequency of approximately 1 kHz with the noisy spikes in the 5–6-kHz range. The main reason for the constant magnitude of the signals is believed to be the saturation of the stick antenna output. It is clear, however, that the arc/spark can be detected by the radiation pickup from a simple stick antenna.

### *B. Radiation Signal Capture by the Loop Antenna*

The loop antenna, with higher frequency and a greater field of view, captures the short-lived repetitive arcs/sparks separated by

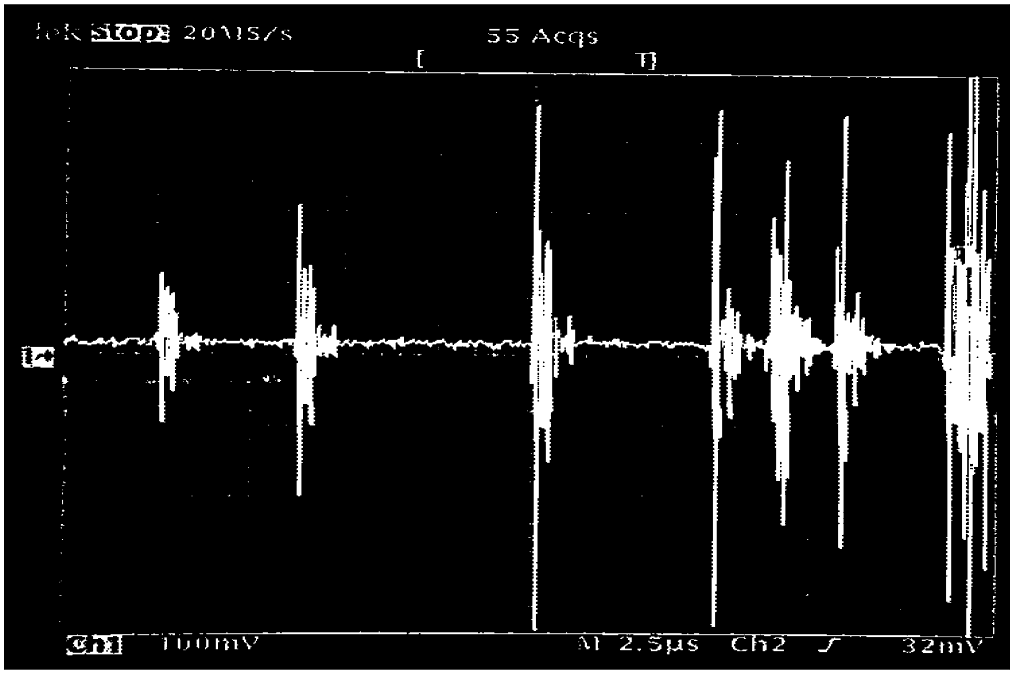


Fig. 5. Loop antenna captured signal with 1–2 MHz frequency contents.

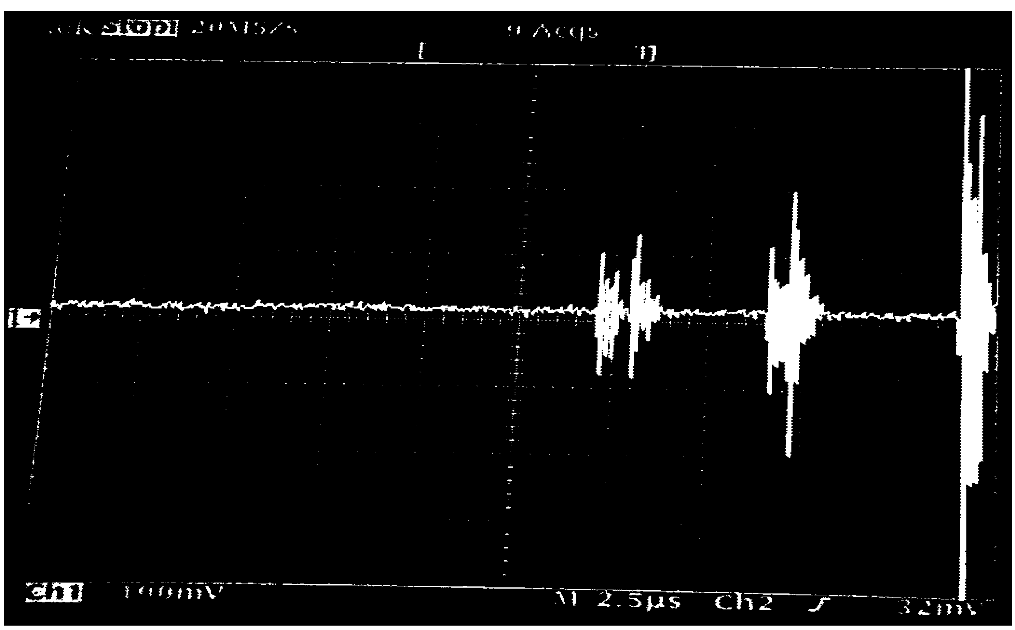


Fig. 6. Loop antenna-captured signal of radiated bursts, some with even less than a 1-$\mu$s pause period.

only 2–5 $\mu$s (see Fig. 5). The frequency of the captured signals is in the range of 1–2 MHz.

Fig. 6 shows another signal capture of the loop antenna of the megahertz band bursts. Figs. 5 and 6 are clear enough to make it feasible to detect arcs/sparks utilizing the electromagnetic radiation using a simple loop antenna.

### *C. Radiation Signal Capture by Stick and Loop Antennas*

Fig. 7 shows the capture signals of two antennas with 1 $\mu$s/div. It is apparent that the loop antenna picks up the signal better from high frequency up to about 10 MHz. On the other hand, the signal captured by the stick antenna misses the high-frequency content of the arc process, except a few blips registered in the signal coupled with the loop antenna pickup bursts.

The capture shot of Fig. 8 now shows the slow-changing signal from the stick antenna, in which there are many high-frequency spikes of the megahertz band captured by the loop antenna.

Fig. 9 shows another captured signal by the two antennas, in this case, in the low-frequency spectrum, with 1 ms/div. Now, the captured signal from the stick antenna is more prominent. A

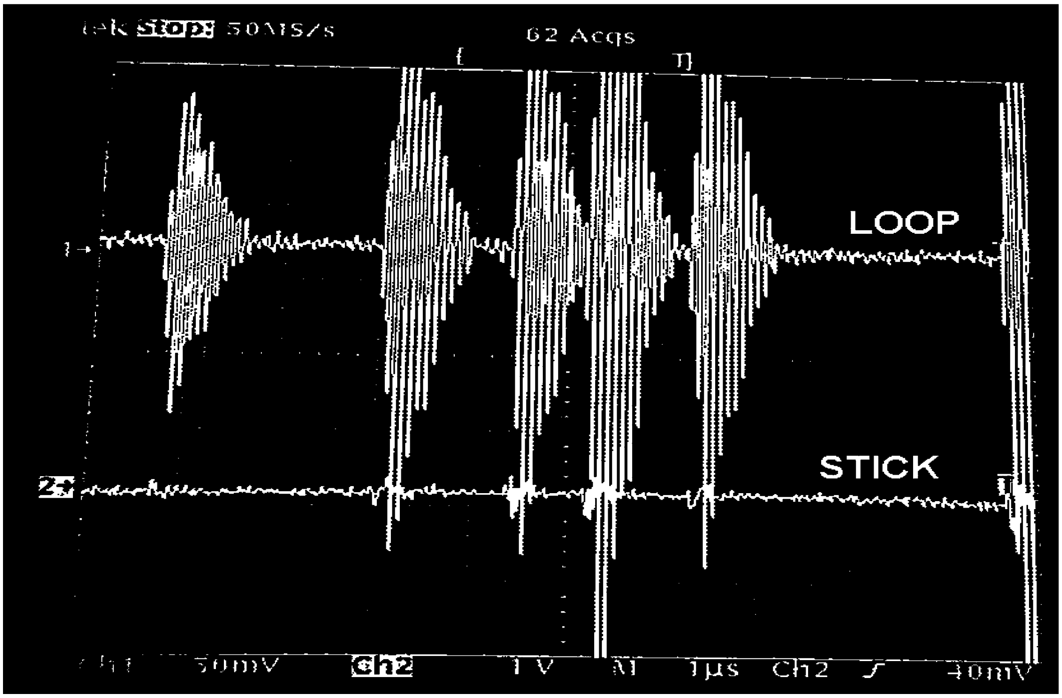


Fig. 7. Signal captured by the loop and the stick antennas with 1 $\mu$s/div.

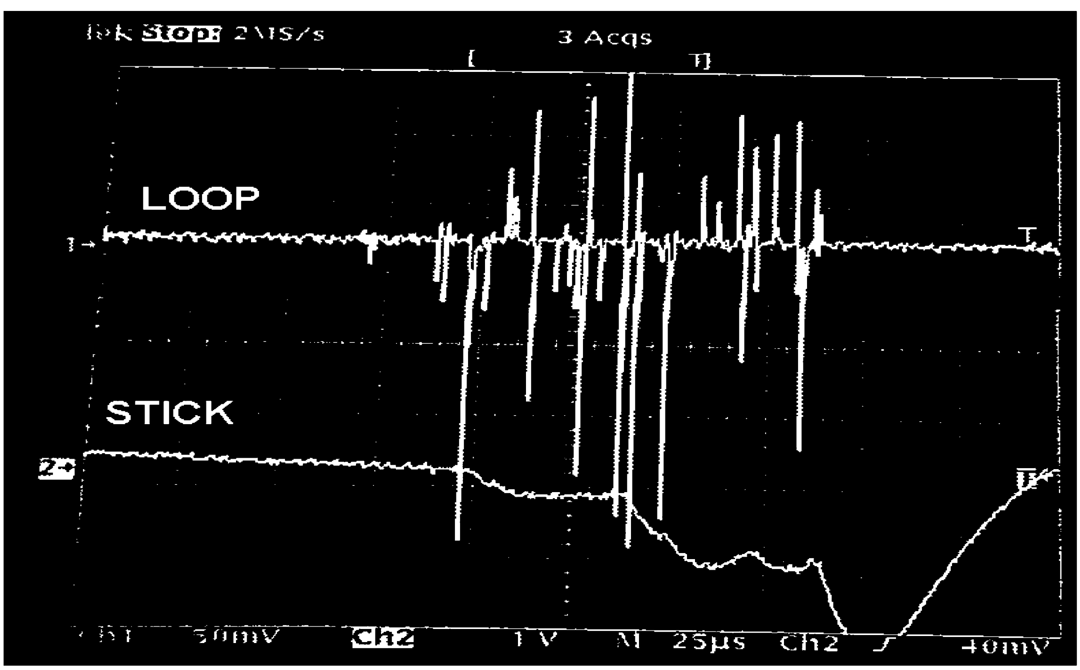


Fig. 8. Signal captured by the loop and the stick antennas with 25 $\mu$s/div.

careful look at the inception time of the signal sees that the stick antenna-captured radiation signal is slightly ahead of that of the loop antenna, which is more apparent in Fig. 10.

Fig. 10 of another spark/arc event, with 0.25 ms/div, clearly shows that the inception of the lower frequency signal captured by the stick antenna is about 0.25 ms ahead of the inception of the higher frequency signal captured by the loop antenna.

Due to the frequency sensitivities of the antennas, employing two simple antennas alone cannot completely characterize the electromagnetic radiation behavior associated with the staged arc/spark processes. Rather, from the experiments, we could only see whether the radiation contains the spectrum bands of the antennas. The limitation notwithstanding, the experiment shows that the spectral content of arc radiation is broad, from a few kilohertz to tens of megahertz, and the captured signals are distinctive enough to be used for the detection of such arcs/sparks. Also, the experiment shows that the inception time of the lower spectral content is believed to be the low-rising glow-like discharge, which is ahead of that of the higher spectral content, presumably from the transient arc phase.

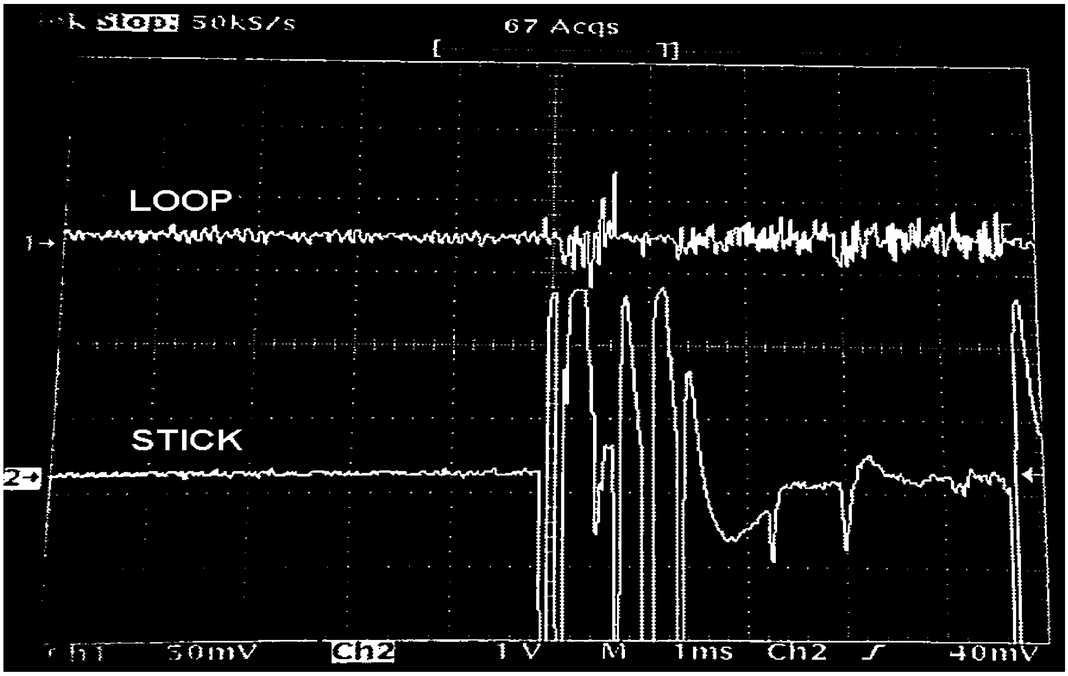


Fig. 9. Inception of radiations captured by two antennas with 1 ms/div.

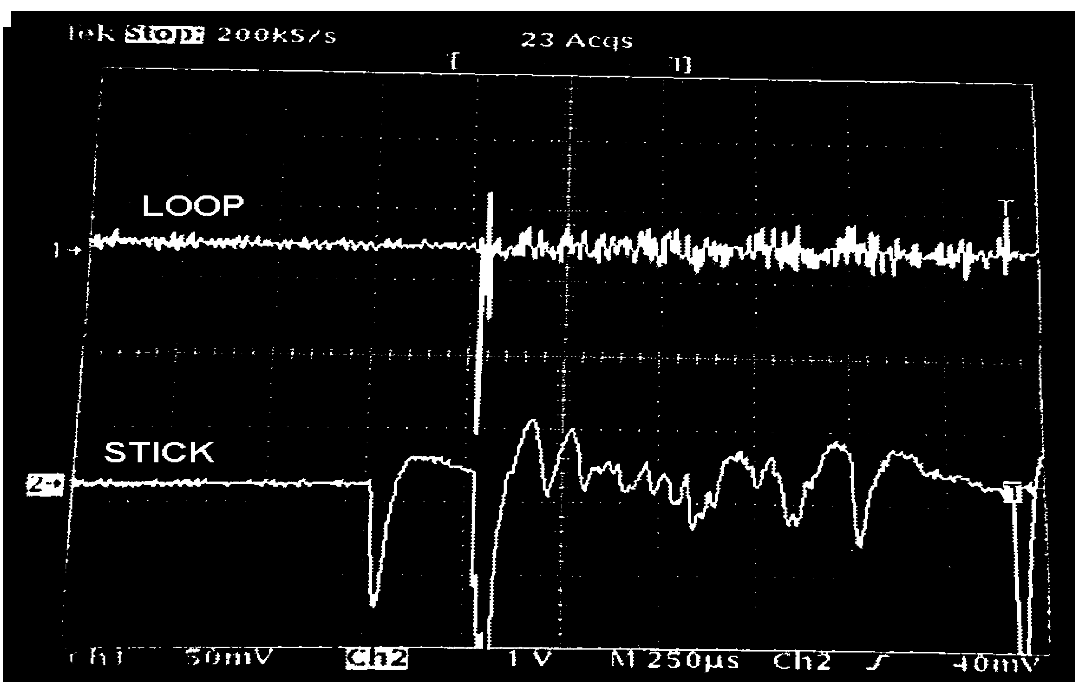


Fig. 10. Inception of radiation signals captured by two antennas with 0.25 ms/div.

## V. Conclusions and Discussions

We conclude that the arc/spark fault can be detected by signal captures of the electromagnetic radiation associated with the arc/spark using simple stick and loop antennas as an alternative method to the conventional detection approaches of utilzing intrusively measured voltage and current. The stick and loop antennas with frequency bands of low AM and megahertz, respectively, are effective in detecting the arc/spark of the low-voltage circuit.

Also, the first two phases of the arc process: 1) initial breakdown of glow-like discharge and 2) transient arc, and their respective radiation frequency contents are distinguishly observed in dual antenna experiments. The inception time difference between two bands of radiation frequency, earlier of lower frequency than of higher frequency, could become a discriminatory tool for detecting only genuine arc/sparks against other electrmagnetic interence signals, especially in aircraft and ship electrical system environment, which would come with the same inception time. In this regard, we need more and further experimental evaluation.

Even with the promising results of detecting arc/spark by capturing electromagnetic radiation signals, practical use of it would not be possible without further improvement. One is to develop a detection and discrimination algorithm which can determine the detection threshold automatically under varying levels of ambient radiation and differentiate the arrival times of different spectrum contents. Another is to conduct more experiments on radiation capturing sensitivity with respect to the distance of antenna from arc/spark sources. Also, more additional works would be needed in specifying the antenna tuning circuit for the best performance in sensitivity, range, and directionality of capturing the radiated signal. Ideally, though, we envision experiments with a full set of antennas, rod, bi-cone, log spiral, and a horn, in an anechoic chamber for complete spectrum distribution characteristics of arc radiation.

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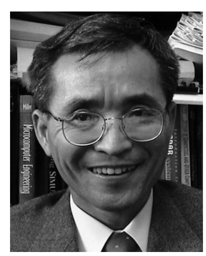


**Charles J. Kim** (M'90–SM'06) received the Ph.D. degree in electrical engineering from Texas A&M University, College Station, TX, in 1989.

From 1990 to 1994, he was a Postdoctoral Research Associate and then became a Research Faculty Member at Texas A&M University. From 1994 to 1998, he was an Assistant Professor at the University of Suwon, Suwon, Korea. Since 1999, he has been with the Department of Electrical and Computer Engineering at Howard University, Washington, DC. His research interests include power system protection and incipient fault detection, intelligent systems application to failure diagnosis and prediction, power-line communications, and embedded computing.