New Insight into the Detection of High-Impedance Arcing Faults on DC Trolley Systems

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***Abstract*—High-impedance arcing faults are difficult to detect with conventional switchgear, and the presence of these faults in coal mine power systems represents a significant fire hazard. Research was performed to identify plausible techniques that would discriminate between the high-impedance arcing faults and legitimate load currents on the dc trolley system. This paper briefly summarizes that effort and focuses on the frequency characteristics of the arc current. After the arc was modeled as a stochastic process, good agreement was obtained between experimental observations and mathematical predictions.**

***Index Terms*—DC power systems, dc trolley systems, electrical safety, ground-fault detection, high impedance, mine power systems.**

I. Introduction

RAIL HAULAGE remains an important materials-handling technology for underground coal mines, even though its use for hauling coal has been largely supplanted by belt conveyors. Moreover, electrically powered locomotives, personnel carriers, and maintenance vehicles are safe and efficient and, unlike diesel-powered equipment, do not pose air-quality concerns. Although the use of electricity permeates every aspect of the workplace and society, it too can pose hazards. The incident rate is so small, however, that these are sometimes forgotten or overlooked. This research was directed at one such problem that occurs infrequently, but which has the potential for serious consequences.

An unintentional connection between an energized power conductor and a grounded element, i.e., a ground fault, can present both a shock and a fire hazard. Protective devices, such as circuit breakers, are used to detect faults and to interrupt the flow of current to the fault location. Sometimes detection is difficult or impossible because the current flow to the fault may appear identical to the current flow to a legitimate load, e.g., a locomotive motor. This is the concern here, where a so-called high-impedance fault appears as a legitimate load current to the traditional circuit breaker. The energy of the fault current, however, may be going into an arc that will ignite any surrounding coal or combustible materials. A few such ignitions occur each year and are normally extinguished before any serious damage is done. Occasionally, they are not discovered in time, and a serious fire results.

Researchers at Pennsylvania State University's Mine Electrical Laboratory developed system concepts for economical fault detection schemes that would meet the needs of the mining industry. One of these schemes was based on the differences between legitimate load and fault currents in the frequency domain. Much of the research focused on studying the frequency spectra of both normal and abnormal events on the dc trolley system. Toward this end, a significant modeling effort was undertaken to both understand the experimental observations and to allow predictions of spectra for more general situations. This aspect of the work is summarized in the remainder of the paper [1].

II. Theoretical Analysis of the Arc Current

The analyses were performed by first modeling the voltage and current waveforms of an unfaulted system. Then, a system with a deterministic arc process was examined with some initial simplifications; these were removed as the models evolved. Finally, a stochastic model was used to obtain an accurate representation of the arc process found on the dc trolley systems (in underground mines). This is outlined here, and a more complete development can be found in [2].

A. Analysis of Arc Currents Undergoing a Deterministic Process

It is a well-known fact that, if a rectified dc supply voltage is impressed on a linear load, then the resulting current will be a linear mapping of the impressed voltage, i.e., the voltage and current spectra will be the same. On the other hand if the load is nonlinear, then new harmonics will be created, and because an arc represents a nonlinear load, it would seem reasonable that these "new" harmonics would be indicative of arcing within the system. This can be illustrated for a simple deterministic case in which the arc current i is given as a function of the impressed voltage v and the constant k with $n = 1$

$$i = kv^{-n} \tag{1}$$

and the voltage is

$$v = U_{\rm dc} + u_{\rm ac1} \cos 3(\omega t) \tag{2}$$

where $U_{\rm dc}$ is the dc component and $u_{\rm ac1}$ is the amplitude of the fundamental ac component of the voltage from the

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rectifier. The magnitudes of all other harmonic components of the voltage are assumed to be zero, thereby simplifying the analysis at this stage. If the voltage defined by (2) is applied to an arc, defined in (1), then the resulting arc current will be

$$i = \frac{k}{U_{\rm dc} + u_{\rm ac1}\cos 3(\omega t)}. \tag{3}$$

Usually, $u_{\rm acl} \gg U_{\rm dc}$, and $-1 \leq \cos 3(\omega t) \leq 1$. Let $\alpha = u_{ac1}/U_{\rm dc}$, and $\beta = 3(\omega t)$. The arc current can then be expressed as a series expansion as

$$\begin{aligned} i = \frac{k}{U_{\rm dc}}\Bigg[&\left(1+\frac{\alpha^2}{2}+\frac{3\alpha^4}{8}+\cdots\right)-\left(\alpha+\frac{3\alpha^3}{4}+\cdots\right)\\ &\cdot\cos\beta+\left(\frac{\alpha^2}{2}+\frac{\alpha^4}{2}+\cdots\right)\cos 2\beta-\left(\frac{\alpha^3}{4}+\cdots\right)\\ &\cdot\cos 3\beta+\left(\frac{\alpha^4}{8}+\cdots\right)\cos 4\beta-(\cdots)\cos 5\beta+\cdots\Bigg]. \end{aligned} \tag{4}$$

Of particular note in (4) are the higher harmonics, i.e., the second, third, and so on, which are not present in the impressed voltage, and which would not occur if the load were linear. The magnitude of these harmonics is also enhanced.

Assume the following voltage function:

$$v = ki^{-1.2} + 35 \tag{5}$$

where i is the arc current, v is the arc voltage, and k is a constant with units of voltamperes. The assumption that the trolley system is a purely resistive network, with an equivalent value of R, will again be used for this analysis. This assumption is reasonable because the trolley resistance is the primary limiting factor for the current during a high-impedance arcing fault condition; the distributed inductance and capacitance of the trolley system also act to restrict the arcing fault current under a high-impedance fault condition. In this study, the distributed inductance and capacitance can be considered as a separate network connected in series with the arc load. This assumption does not make a significant difference in the analytical results, but does greatly reduce analytical complications during the development. It can be shown, using a numerical technique to solve for the arc current, that the resulting current flow will be

$$i_{k+1} = i_k - \frac{Ri_k + \dfrac{11\,000}{i_k^{1,2}} + 35 - 350\sin\omega\tau}{R - \dfrac{13\,200}{i_k^{22}}}. \tag{6}$$

when $2n\pi + \pi/3 < \omega t < 2n\pi + 2\pi/3$, $n = 0, 1, 2, \cdots$, where R is the equivalent resistance of the trolley network viewed from the voltage source, k is the iterative step, and the constant 350 is the magnitude of dc voltage, and 11 000 is the selected value of the constant k in (5). Both constants were selected based on laboratory observations.

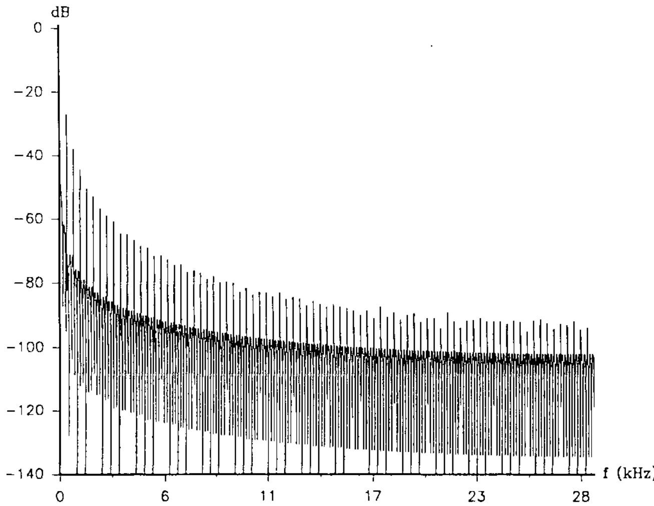

Fig. 1. Normalized spectrum of the arc current for $R = 0.4\ \Omega$.

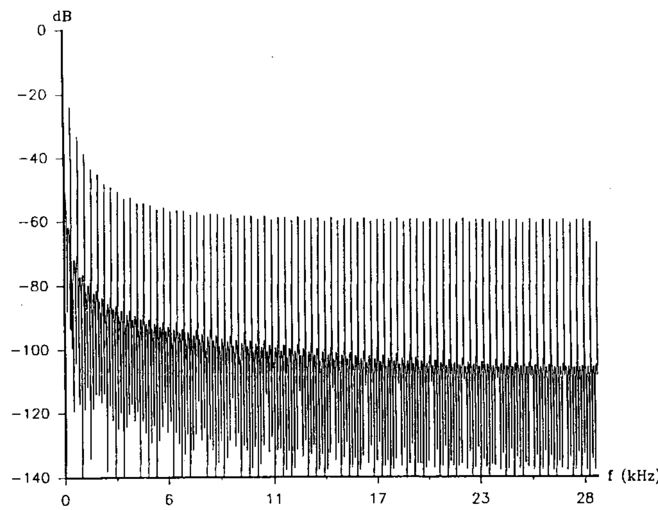

Fig. 2. Normalized spectrum of the arc current for $R = 0.495\ \Omega$.

A computer simulation can then be used to obtain actual values for the arc current. If a trolley system resistance of 0.4 Ω is chosen, the current spectrum shown in Fig. 1 results. The simulation can be repeated with different values of system resistance to approximate different distances between the fault and the rectifier, or different levels of fault severity. The current spectrum shown in Fig. 2 was obtained by increasing the resistance to 0.495 Ω. This would illustrate the practical effect of a fault located more distantly than the one simulated previously, or it could be considered to simulate a smaller, less intense fault.

It is interesting to compare Figs. 1 and 2, where the only difference between the two cases is the magnitude of the fault current. Surprisingly, it is found that the amount of harmonic enhancement is actually increased with smaller levels of fault current. This is very important, because it is the smaller arcing fault currents that are most difficult to detect conventionally and, therefore, the most hazardous ones, because they are more likely to result in a fire. Furthermore, a large legitimate load, such as a locomotive, would not be able to mask these higher

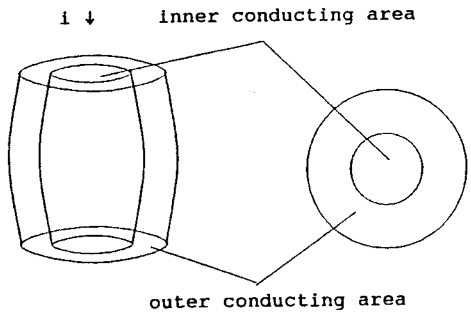

Fig. 3. Configuration of the arc shape for the stochastic model.

harmonics. This is another important result, insofar as the application of this theory to the practical problem is concerned.

The foregoing results were based on the assumption that the arc process is deterministic. This is inconsistent with data collected during this research, and it is known that environmental factors, for instance, can result in a stochastic process. The next step was to then examine the arc current when a random process is occurring.

B. Analysis of Arc Currents Undergoing a Stochastic Process

Environmental factors will introduce random continuity and conductivity changes in the arc by changing the arc's thermodynamic characteristics. The specific effects created by changes in the surrounding air, or any of the other environmental factors, are not of interest; rather, it is simply accepted that these factors will cause continuous and random changes. The goal was to study the behavior of the arc current while under the influence of this random process.

The effects can be more clearly demonstrated by assuming a dc voltage absent of any ripple or harmonics. Here, the arc is considered to exist between two cylinder-shaped electrodes, and it is assumed to have a bucket-like shape, as shown in Fig. 3. Imagine that, when the arc current flows from one electrode, through the arc, to another electrode, there are a number of current lines, each carrying a small amount of the total current, through the arc. For the purpose of this analysis, the cross section of the arc can be considered to have two areas: an inner and an outer conducting area, as shown in the figure.

The current lines through the inner area are more stable than those through the outer area, i.e., they have less chance of being interrupted, because of the relatively better thermal and ionic balance that exists there as compared to the outer area, where environmental factors may have a much more pronounced effect. The current lines through the unstable outer area have an almost equal probability of being randomly broken up and reestablished, due to the severe thermal and ionic unbalances in the outer area. Consequently, the amplitude of the current through the outer area will change rapidly, in response to the rapid change of the current lines, whereas the current through the inner area could be considered to be continuous and constant in amplitude. If the major part of the arc current flows through the inner area, a stable and smooth arc current would result, showing a rapid change in amplitude.

Assume that each current line through the arc carries an equal and very small amount of the current δI and that there are N current lines through the arc. Then, $\delta I = I/N$, where I is the magnitude of the current through the arc. Neglecting the transient time of a current flowing through a current line when this current line is breaking and reestablishing, each current line through the outer area of the arc can be expressed by the following step function:

$$\begin{aligned}\delta i &= \delta I[U(t-T_0) - U(t-T_1) + U(t-T_2) \\ &\quad - U(t-T_3) + \cdots] \\ &= \delta I \sum_{k=0}^{\infty} (-1)^k U(t-T_k) \end{aligned} \tag{7}$$

where $U(t - T_k)$ is a step function, and $0 = T_0 < T_1 < T_2 < T_3 < \cdots$.

When the sign in the front of each step function turns out to be positive, that current line is said to be linked (at a moment of $t = T_k$, $k = 0, 2, 4, \cdots$). Here, T_0 is the starting time of this current line. When the sign turns out to be negative, that current line is broken (at a moment of $t = T_k$, $k = 1, 3, 5, \cdots$). Here, any time duration of $\delta t = T_{k+1} - T_k$ is considered to be randomly distributed.

The previous equation is actually a random rectangular wave function because of the random distribution of δt. The standard rectangular function and its Fourier transform are given as

$$\mathrm{rect}\,(t) = \begin{cases} A, & |t| < \dfrac{\tau}{2} \\ 0, & |t| > \dfrac{\tau}{2} \end{cases} \tag{8}$$

and the Fourier transformation of the rectangular function is

$$F[\mathrm{rect}(t)] = \frac{2A}{\omega} \sin \frac{\varpi \tau}{2} \tag{9}$$

where A is the magnitude of the rectangular function and, here, $A = \delta I$ for the above expression for a single current line; τ is the time width of a single rectangular function, or a single time interval in this single current line expression, δt. As the standard rectangular function implies, $\tau = 0$ means that no current ever exists in that particular current line, and $\tau = \infty$ means that the current through a particular current line will not be interrupted. Of particular interest in this work is the case when each value of $\tau = T_{2j+1} - T_{2j}$, for $j = 0,\ 1,\ 2,\ \cdots$, lies between 0 and ∞. A set of the time intervals for a single current line, $s(\tau)$ with τ as a random variable, $0 < t < \infty$, can be defined to study the influence of τ on the arc current.

If $s(\tau)$ for a current line is widely distributed between 0 and ∞, the components of this current through this current line will be widely spread over a very broad frequency band; on the other hand, if $s(\tau)$ is principally distributed in a certain narrow time range, the components of this current will fall mainly in a certain frequency band.

Suppose that n current lines, out of a total of N lines which make up the whole arc current, pass through the inner area.

The total arc current I can then be expressed as follows:

$$\begin{aligned} I &= n\delta I + \sum_{m=1}^{N-n} \delta i_m \\ &= n\delta I + (N-n)\delta I \left[\sum_{k_1=0}^{\infty} (-1)^{k_1} U(t - T_{k_1}) \right. \\ &\quad \cdot \sum_{k_2=0}^{\infty} (-1)^{k_2} U(t - T_2) + \cdots \\ &\quad \left. + \sum_{k_{N-n}=0}^{\infty} (-1)^{k_{N-n}} U(t - T_{k_{N-n}}) \right]. \end{aligned} \tag{10}$$

The term of $n\delta I$ represents the stable or smooth portion of an arc current through the inner area ($\tau = \infty$), while each summation of the step functions represents the current flowing through each current line in the outer area of the arc. The number of the current lines through the outer area is $N - n$. The portion of the current through the outer area is the sum of these currents through the $N - n$ current lines.

When most of these step functions simultaneously turn out to be positive at a certain moment, and all change sign at the next moment, a rapid change in the amplitude of the current in the time domain will map itself into the frequency domain as high-frequency components. Conversely, as most of these step functions change sign slowly, a slower change in the current amplitude will follow, and then low-frequency components would appear in the arc current. This random process will continue as long as the arc persists and, therefore, it is expected that both low- and high-frequency components will exist whenever the set of time intervals $s(\tau)$ for a current line is widely distributed.

The frequency distribution of the entire arc current will, however, depend not only on the distribution of the time interval $s(\tau)$ of each of the current lines, but also on a set of joint time intervals $S(\tau)$ of all the current lines through the outer area, and on the ratio between the outer area and the inner area of the arc. The values of $s(\tau)$ and τ are usually too difficult to be determined, even in a given well-defined condition, because of the highly dynamic nature of an arc. This makes a precise quantitative analysis of the frequency distribution of an arc current impossible. Nevertheless, the variation of the frequency distribution of the arc current responding to the changes of these variables can be qualitatively analyzed to serve the purposes of this work. The most observable consequence of the stochastic processes inherent to the arc is the changing frequency distribution. Although it is impossible to quantify this effect, it is possible to explain qualitatively its ramifications.

First, the effect of the joint time interval of the current lines in the outer area of the arc $S(\tau)$ on the frequency distribution will be examined. If the value of the time interval $s(\tau)$ of each of the current lines has a high probability of falling within a certain range, then the distribution for the joint time interval $S(\tau)$ for all the current lines is most likely to fall in the same distribution range. A stationary random process results, in which major components of the arc current will appear in a certain frequency band. If the value of $s(\tau)$ is widely distributed, then it is likely that the same will be true for $S(\tau)$ and, consequently, a white-noise-like (nonstationary) process will result in which the frequency components are widely distributed.

Real-life arcs can be of either type, and a given arc will be both, depending on the stage of development. As the arc stabilizes and, in the absence of strong and changing environmental factors, it will behave in a stationary random fashion. Regardless of the process, high-frequency components will be generated, and these will uniquely distinguish an arcing fault current from a legitimate load current. However, the specific frequency distribution, e.g., bandwidth and specific frequencies, depends on the type of process that is dominant within the arc. Practically, this means that it is not possible to look for frequencies between 35–40 kHz, for example. Rather, any frequency not found in the normal load current is indicative of an arcing fault, whether it is, for example, 17, 45, or 79 kHz. Experimentally, this has been found to hold true. Moreover, the relative magnitudes of the frequency components have also been observed to change, in what appear to be a random fashion.

The ratio of the outer to the inner area of an arc will essentially determine the relative magnitude of the arc current at a specific frequency, when normalized to the average arc current. The relative magnitudes of these components vary as the ratio of these two areas changes. It is known that, in an actual arcing fault situation, the electrodes for the arc may not have a cylinder-like shape, and the arc itself may not have a bucket-like shape. Therefore, for an arbitrary and free-forming arcing fault, the terms "inner and outer areas" must be relaxed to mean the relatively stable portion and the unstable portion, respectively.

III. Experimental Validation

Laboratory experiments were performed to study the characteristics of arcing faults, primarily to assist the theoretical modeling effort. Subsequently, in-mine experiments were performed to determine the validity and applicability of the theoretical results, some of which have been described in this paper. A special challenge was devising a method for creating actual arcing faults in the mine without creating a life-threatening hazard.

A rugged metal enclosure, mounted on rubber tires, was constructed to house the electrodes and contain the arc. This "arc box" contained adjustable mounting gear for the electrodes, so that different diameter rods could be used, and with different gap dimensions. One electrode holder was solidly connected to the metal box; the other was insulated from the chassis. Large-diameter cables (4/0 AWG) were connected into the trolley circuit. Thus, the arc box allowed full-scale arcing faults to be created while safely containing the arc and associated energy inside of the arc box.

Both copper and steel electrodes were used, ranging in diameter from 3/8 to 3/4 in. The copper electrodes were cut from salvaged lengths of trolley wire, and the steel electrodes were cut from sections of steel "rebar." All electrodes were initially 12-in long. The initial gap was approximately 1/4 in and was bridged with 20–gauge copper wire, which quickly melted, thereby facilitating the formation of the arc. Depending on the system voltage and the arc current, the arcs would last for 10–40 s. Typically, they would extinguish when the gap became too great to sustain the arc. In some cases, as the electrodes were burned away, the gap would reach several inches before the arc ceased.

Large-current-limiting resistors were connected in series with the arc-box circuit to limit the fault current to the range of interest. The most probable range of arcing fault currents is known to be 100–400 A. A remote-controlled contactor was used to start or interrupt the flow of current to the resistors and arc box. The frame of the arc box was connected to the track, and the "hot" electrode was connected in series with the resistors and contactor. The contactor was connected through a fuse to the trolley wire.

The instrumentation consisted of the Data 6000 Signal Analyzer, instrumentation tape recorder, isolation amplifiers, oscilloscope, meter, shunts, and voltage dividers. The shunt, used to measure the current flow to the trolley wire, was installed at the rectifier and in series with the trolley feeder. The instrumentation was then set up at some distance from the instrumentation, but mine-duty walkie-talkies were used to keep the two groups of researchers in constant contact.

Tests were conducted on two different coal mine trolley distribution systems. The results confirmed the theoretical predictions and, specifically, that the spectra for both normal loads and arcing faults behave similarly to the theoretical predictions and the laboratory observations. Normal load currents contained only low-frequency components (less than 10 kHz), whereas arcing fault currents contained high-frequency components (greater than 20 kHz). Additional enhancement of the harmonics, as the fault current decreased in magnitude, was also observed.

IV. Conclusion

The results of an extensive experimental program, in conjunction with theoretical analyses, have demonstrated the efficacy of discriminating between high-impedance arcing fault currents and legitimate load currents on the dc trolley systems used in mines. A mathematical model has been developed to explain the behavior of current spectra from high-impedance arcing faults that has been useful in both explaining observed behavior and in predicting behavior for the general case. The arc behaves as both a stationary and nonstationary random process at different times. This causes frequency components to be created and, as such, this is more important than the nonlinear aspect of the arc. The developed theory was successful in explaining this, and the experimental observations confirmed it.

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