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Detection of Downed Trolley Lines Using Arc Signature Analysis

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	m	meter
cm/s	centimeter per second	mH	millihenry
dB	decibel	MHz	megahertz
ft	foot	s	second
Hz	hertz	st	short ton
in	inch	t	ton (metric)
in/s	inch per second	V	volt
kHz	kilohertz	V dc	volt, direct current
kV	kilovolt	%	percent
kW	kilowatt		

DETECTION OF DOWNED TROLLEY LINES USING ARC SIGNATURE ANALYSIS

Jeffrey Shawn Peterson[1] and Gregory P. Cole[2]

ABSTRACT

The Pittsburgh Research Center[3] conducted research to study and improve electrical fault detection on coal mine direct-current (dc) trolley systems. A suspended trolley line delivers power at voltages of 300 or 600 V dc to the haulage equipment and other loads. Roof falls or other accidents may force the trolley line down so that an electrical fault current may flow between the trolley line and rail. This fault current could result in localized heating, arcing, and perhaps fire. Such faults are not always preventable by the existing circuit protection because the current magnitude is well below typical operating levels of the trolley system. The research discussed in this report studies the applicability of computerized signal analysis techniques to solve this problem. Tests were conducted at cooperating coal mines. Measurements were taken during normal loading of the trolley system (light, intermediate, and heavy traffic), during induced fault conditions (arcing and bolted faults), and during transitions between the two. These data were then used to train and test a microprocessor-based fault detection algorithm. Later, field tests of the detection algorithm found that it correctly classified the state of the trolley system greater than 95% of the time.

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[3]This research originated under the former U.S. Bureau of Mines prior to transferring to the National Institute for Occupational Safety and Health in 1996.

INTRODUCTION

Direct-current (dc) trolley haulage systems move personnel, supplies, and coal in approximately 50 U.S. mines. A suspended trolley line energized at 300 or 600 V dc provides electrical power, and a system of steel track serves as the return path. Inductance of the trolley system depends on the physical separation of the trolley line and the rail, but generally for 300-V systems, it is 0.347 mH per 300 m (1,000 ft); for 600-V systems, it is 0.368 mH per 300 m (1,000 ft) [Paice et al. 1974]. Haulage distances may extend for kilometers; therefore, significant inductances may be inherent in the trolley system. When roof falls and other events force the trolley line down near the ground return rail, this inductance facilitates continued current flow along an ionized path between the line and rail. This releases a significant amount of energy in the arc and may damage and/or ignite surrounding material. Conventional circuit breaker systems usually cannot prevent this continued arcing because the magnitudes of the currents involved may be significantly less than typical breaker trip settings. Because of the sheer size of some trolley systems, an arcing fault may exist undetected for long periods in low traffic areas.

In 1980, the former U.S. Bureau of Mines demonstrated research to detect arcing and other types of trolley faults [Paice 1978]. The system required an oscillator to superimpose a 3-kHz signal in the trolley line, a signal wire suspended parallel to the trolley line for circuit breaker coordination, and a filtering system on locomotives larger than 25 tons. Proper data had to be received via the signal wire for the circuit breakers to close. Thus, signal transmission was halted and dc power cut if the signal wire was broken. If the system detected a fault condition, both inby and outby circuit breakers would open. A third measure of safety employed conventional overcurrent tripping. Although the system functioned satisfactorily, the coal industry did not adopt it because of the complexity and cost of the hardware.

Today, the dangers of trolley-fault-induced fires and accidents still exist. As recently as 1989, a trolley system fire struck the Mathies Mine near Pittsburgh, PA, and burned for 1 month before it was extinguished. A similar fire at Mathies in 1990 prevented access to 27 million t (30 million st) of reserves and resulted in the temporary closing of the facility. It has since reopened under new ownership. The Pittsburgh Research Center (PRC) has sought new solutions that would require minimal hardware maintenance and would be cost-effective. It was unlikely that the coal industry would attempt to improve trolley circuit protection since any single company may own only a few mines with trolley systems. Additionally, coal mines that employ dc trolley systems tend to be larger, older mines in which a coal company may not be willing to invest significant resources to solve this problem.

Advances in computer software have made it possible to employ rapid classification algorithms to recognize obscure patterns or characteristics. Adept use of signal analysis techniques make it possible to develop a microprocessor-based system employing a detection algorithm. The system would monitor the trolley rectifier electrical signature, and data would be collected and analyzed to classify the present state of the trolley system, fault or no-fault. An indicator signal could be provided to break the trolley circuit or provide an audio or visual alarm if a fault was detected. This approach eliminates modification of the trolley line, feeder, or its vehicles, lessening maintenance concerns and costs.

DEVELOPMENT OF TEST PROCEDURE

Critical to developing a detection scheme was the resolution of several key elements. Finding a location to conduct early shakedown tests was of primary importance. There, safe methods to collect baseline information to assist in defining a course of action had to be found. These included defining a safe procedure for inducing faults on an existing trolley system, determining relevant electrical signature characteristics, and developing the required platform to record and analyze data.

Our Lake Lynn Laboratory facility near Fairchance, Fayette County, PA, was chosen as the initial test location (figure 1). The facility had an on-site trolley system that was unused for several years, but was suitable for use after refurbishing and making minor safety modifications. A 12.47/2.3-kV, three-phase transformer supplied electrical power for the Lake Lynn trolley. This fed an oil break switch and a 2,300/222-V delta-delta transformer in a rectifier building. A 300-kW, 300-V dc rectifier employed a wye-wye bridge arrangement. This was connected to 4/0 American wire gauge (AWG), figure-eight trolley wire and 1.1-m (42-in) gauge track at approximately the midpoint of a 96.3-m (316-ft) straightaway with a 4% grade. A 10-ton locomotive and several 10-ton rotary dump cars stored on a 39.6-m (130-ft) spur were available for use.

Techniques were developed at Lake Lynn to safely induce arcing faults on trolley systems. Multiple 0.3-ohm power resistors and air core inductors limited the fault current and simulated increased haulage distance, respectively (figure 2). Copper, steel, and aluminum rods served as electrodes through which the arcing current flowed. A wooden and steel bracket

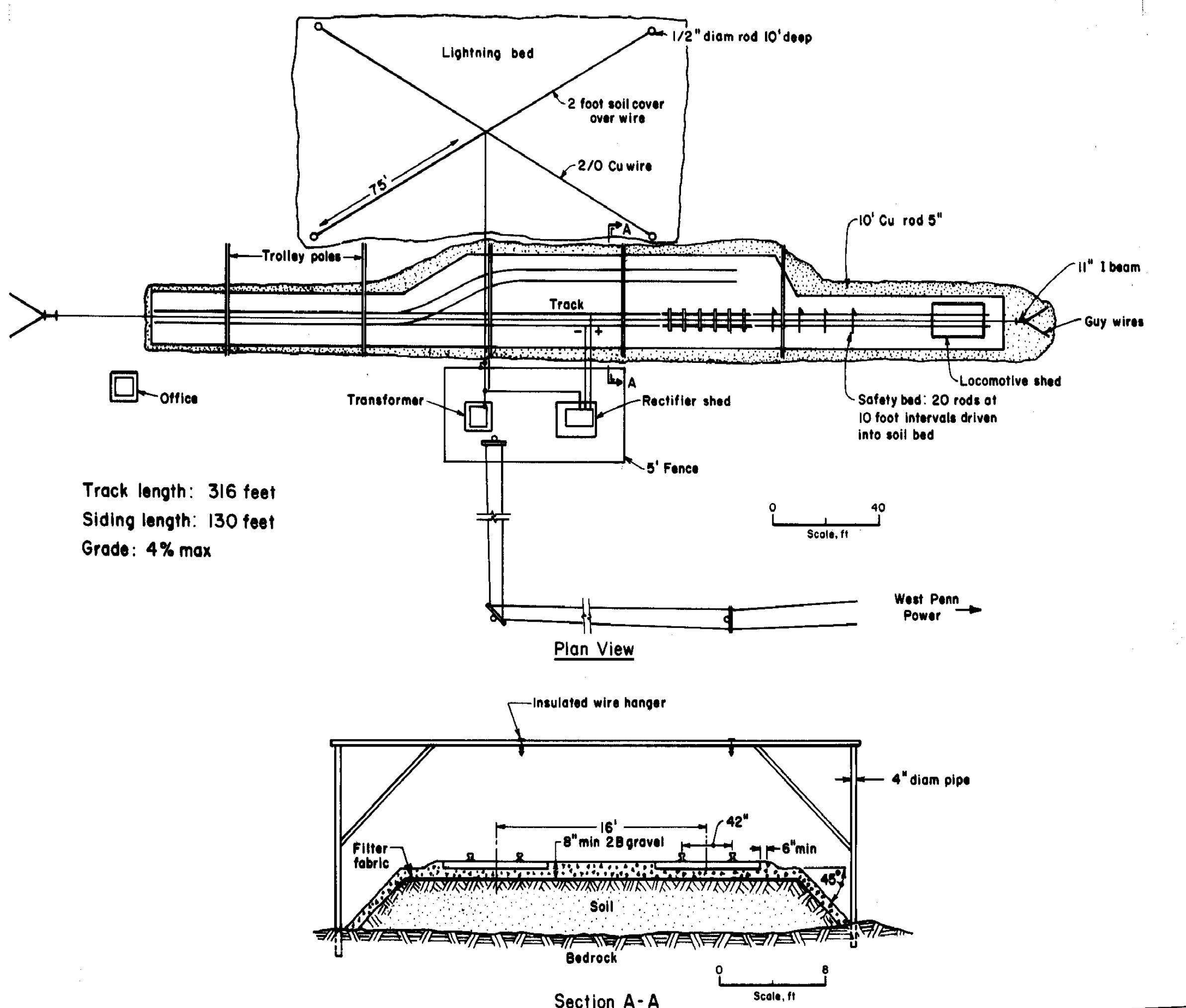

Figure 1.—Lake Lynn Laboratory trolley system.

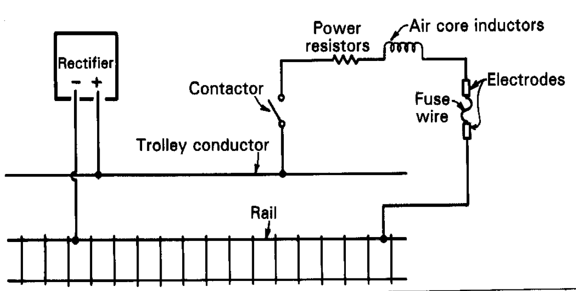

Figure 2.—Trolley arcing fault test circuit used at Lake Lynn Laboratory.

held the electrodes in place, and 18 AWG copper wire served to complete the initial current path (figure 3). After the fuse wire melted away, arcing continued between the metallic electrodes. Finally, a contactor switched the fault into the trolley circuit either manually or via a fiber optically isolated control switch. This fault circuit was simply clamped to the trolley wire and rail system. Except for the air core inductors, this equipment was later used during recording and monitoring sessions at cooperating mines. Shunts installed on the rectifier negative conductor provided the current signal, and the voltage was measured with a voltage divider installed directly across the rectifier output.

A Thorn EMI magnetic tape recorder collected early test data at Lake Lynn. This eight-channel device had a bandwidth of 40 kHz at a tape-recording speed of 150 cm/s (60 in/s). Typically, only a voltage and a current channel were recorded, but on occasion, redundant voltage and current data were collected. For safety purposes, the data channels were electrically isolated with signal conditioning modules that had a 10-kHz response. This equipment was used during the Lake Lynn phase of the

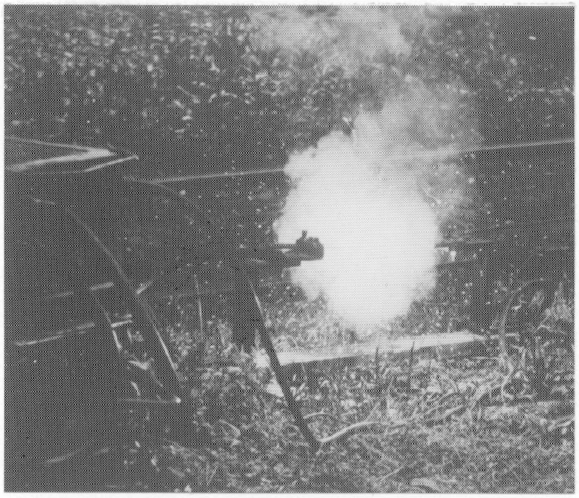

Figure 3.—Metallic electrode configuration during an arcing fault.

project and during early field tests at mines in Pennsylvania and West Virginia. To increase the bandwidth, a Honeywell eight-channel tape recorder was used during later tests. At a tape speed of 300 cm/s (120 in/s), its frequency response was 80 kHz. An ISO-4 voltage isolator provided electrical isolation for the data channels and had a bandwidth from dc to 100 kHz.

Although FM tape was an adequate choice for early data collection, several problems were inherent to the technology that made it a poor choice for later stages of the project. FM tape recorders are not designed to function reliably in hostile field environments. Proper alignment of the recording heads is critical in avoiding interchannel phase skewing. Shock and vibration hazards commonly present at test sites could possibly create such problems. Also, FM tape did not provide for on-the-spot analysis of test data; therefore, early data were analyzed later in the laboratory. To move toward the goal of developing and testing a detection algorithm, clearly the data must be collected and analyzed digitally and essentially in real time. No off-the-shelf data collection and analysis equipment was found that met exacting standards for ruggedness, versatility, and weight considerations. Therefore, it was necessary to develop a custom system component by component, each of which met specific requirements.

An industrialized PC built for field use was necessary to serve as the backbone of the data acquisition system. The PC had to be lightweight, have sufficient throughput for high-speed data collection, have sufficient space to accept full-sized cards, and be able to function on battery power. A FieldWorks 75-MHz 486 industrialized PC met these requirements. A Data Translation DT2833 was chosen as the analog-to-digital converter (ADC) for this application. The DT2833 is a 12-bit, 8-channel ADC that can write data directly to the PC's hard disk, increasing throughput. It also employs simultaneous sample-and-hold technology that eliminates multiplexing between data channels, minimizing phase shift and allowing power calculations (voltage × current). Additionally, the sampling rate of the ADC was software-selectable. The ISO-4 mentioned earlier is a four-channel device that provides electrical isolation up to 1,000 V dc channel-to-channel and channel-to-ground. It has switchable gains of ×10, ×1, ×0.1, and ×0.01 and an output of ±10 V, scaled to the input. For a digital data acquisition (DDA) system, filtering of the data channels is imperative. This called for the installation of Frequency Devices elliptic low-pass filters on each data channel. Elliptics were chosen for their sharp attenuation at the corner frequency (f_c), allowance of a large pass band compared with other types of filters, and essentially unity gain in the pass band. The f_c of these filters was switch-selectable from 200 Hz to 51.2 kHz in 200-Hz steps. Several amplifiers boosted current shunt signals to increase data resolution. These amplifiers all had frequency responses beyond 100 kHz.

DATA-RECORDING SESSIONS

PRC researchers visited several coal mines in Pennsylvania and West Virginia to conduct tests of 300- and 600-V dc trolley systems under various operating conditions. These conditions comprised traffic present on the system at any given time: large- and small-vehicle traffic; pump activity; and heavy, intermediate, and minimal loading. Typically, voltage was measured across the rectifier output, and current signatures were derived from shunts. Test lengths varied from several seconds to as much as 45 s, depending on the existing conditions of the trolley system. These tests represent the no-fault portion of the data collected. Duplication of these tests with the inclusion of induced arcing or bolted faults comprised the faulted data tests. Carefully selected sites both on the surface and underground and at various distances from the trolley rectifier served as fault locations, ensuring observation of a variety of possible test conditions. During arcing fault tests, as the electrode material melted away, the gap resistance increased until the arc was effectively quenched. Most arcing faults continued until this occurred; only a limited portion were intentionally extinguished prematurely.

Throughout the recording sessions, personnel at the fault site and at the trolley rectifier maintained voice contact via walkie-talkies or mine telephone, which allowed proper test co-ordination. During tape recording sessions, voice annotation and manual logging detailed information about the starting and ending of faults and any other relevant information, such as types of traffic on the system during a test.

Test data were collected with the PC-based data acquisition system using a C programming language custom program, XTRIG3. This program allowed recording on two, four, or six channels at rapid sampling rates. Data collection could be initiated and terminated simply by a key press of the PC. Data recordings were collected and stored in individual data files with descriptive names. These were also logged manually along with other pertinent details of the test.

DATA ANALYSIS

The bulk of the analysis relied on examining the data in digital form. An important part of the project was the application of a new software technique requiring digital data accessible from a computer. Tests recorded early in the project on FM tape (analog form) were digitized upon returning to the laboratory. This was not necessary after deployment of the portable PC-based recording system.

A brief discussion is necessary to cover the basic principles of DDA to clarify the parameters of the system. The basic goal of recording data digitally is to make it accessible to computer-based analysis and manipulation programs. It is also important that noise and distortion be kept to a minimum when recording digitally. One source of noise generation in DDA is aliasing. This occurs in sampled systems when input frequencies interact with the DDA sampling rate. Without the proper filtering, input signals above the Nyquist rate (one-half the sample rate) would generate false frequency components in the sampled data. Coordinating the corner frequency setting of the low-pass filters with the sample rate eliminates this effect. Reducing data distortion required sampling the data in "window"-grouped samples of a power of two in length. These windows are the basis of the fast Fourier transform (FFT) calculations. The windows also need to span one cycle of the fundamental frequency of the alternating current (ac) power distribution, 60 Hz. Both conditions are necessary to optimize the FFT calculation. Having one cycle of the fundamental frequency span this window reduces the effects of leakage. This occurs when energy at a given frequency smears into adjacent frequencies of the spectrum. Leakage has the effect of broadening the lobes (spectral lines or peaks) of the FFT and making them less distinct. Considering these factors, along with a minimum desired bandwidth of 20 kHz, a sample rate of 61,440 Hz was chosen. This met antialiasing criteria by having a Nyquist rate ($0.5 \times 61{,}440 = 30{,}720$) greater than the desired bandwidth. The rate also reflects acquiring 1,024 (2^{10}) points in the span of one 60-Hz cycle. It creates a window that is a power of two in length (2^{10}) for the FFT and spans the fundamental frequency, reducing leakage in the FFT calculation.

Several additional sample rates were briefly tested during high-frequency analysis of the data. These tests were conducted with the use of both the PC and FM tape-based systems. Exploiting the high bandwidth properties of the FM tape systems allowed frequency analysis up to the 40- and 80-kHz ranges. These ranges exceeded the parameters of the PC-based system alone. However, used with the FM tape system, the PC-based system successfully digitized the data to resolve the higher frequencies. By slowing the playback of the FM tape recorder by one-half or one-fourth of the record speed, it was possible to double or quadruple the effective sample rate of the DDA system. This resulted in effective sample rates of 122,880 and 245,760 Hz, easily encompassing the 40- and 80-kHz ranges, respectively. These higher ranges were the maximum frequency responses of the two FM tape recorders used.

After digitally recording and storing the data files to disk, they were analyzed using a commercially available software package, DADiSP (by DSP Development Corp.). The FFT analysis concentrated on the magnitude components of the frequency spectrum. Analysis was completed using a window length of 1,024 points; additional limited tests were conducted using a 2,048-point window. The initial digital analysis employed a rectangular windowing scheme. This means applying a weighting function of 1 to each of the sample points in the window according to the equation

$$w[n] = \begin{matrix} 1, & 0 \le n \le M \\ 0, & \text{otherwise} \end{matrix}, \qquad (1)$$

where n = the sample point,

$w[n]$ = the weighting factor at sample point n,

and M = the window length.

From this, the resultant signal is simply

$$h[n] = k[n]w[n], \qquad (2)$$

where $h[n]$ = the resultant signal,

and $k[n]$ = the sampled input signal.

Because the sample rate accounted for encompassing the fundamental frequency within the window, nothing was gained when special windowing functions such as the Hanning or Hamming algorithms were used. These algorithms force the data to be periodic within the window, improving resolution by minimizing leakage. The recording sample rate accomplished this without applying another transformation to the data.

Regions of interest were then extracted from the tests and divided into successive windows. These regions included trolley loads, arcing loads, light loading (little trolley activity), and transition points to and from arcing. Using DADiSP, FFT's were generated for each window. Key areas would be zeroed in upon, with an average FFT generated from the windows spanning each area. Using the average of several adjacent spectra reduced noise, providing better harmonic resolution.

At this point, some observations can be made about the trolley signals:

1. Spectra based on the voltage output of the rectifier show a strong fundamental frequency of 360 Hz with many harmonics. This represents the voltage ripple generated from the fully rectified three-phase ac inputs to the rectifier. This effect appears in the dc current and power wave forms as well.

2. The most promise lies in the dc current signal output of the rectifier. There are several reasons for this. First, the system is monitoring the very phenomenon to be interrupted in case of a fault. Secondly, the current FFT's show a wider variation in components when comparing normal and faulted spectra (figure 4) than does the voltage. Figure 4 shows that there are significant differences in the two current spectra up to 10 kHz, whereas the two voltage spectra are comparatively the same above 5 kHz.

With regard to the frequency content of the signals, there were also some conclusions:

1. Most of the frequency content for all of the modes observed is contained in the 0 to 20-kHz range. Further, neural network tests conducted on the data suggest that there will be sufficient information in the 0 to 10-kHz range. Detection algorithms built keying upon the 10- to 20-kHz band had significantly worse root-mean-square errors and classification rates than algorithms using 0 to 10-kHz data.

2. The high-frequency analysis yielded no telltale frequency components unique to an arcing fault, i.e., no magnitude components in the 20- to 80-kHz range proved to be consistently unique to an arcing fault.

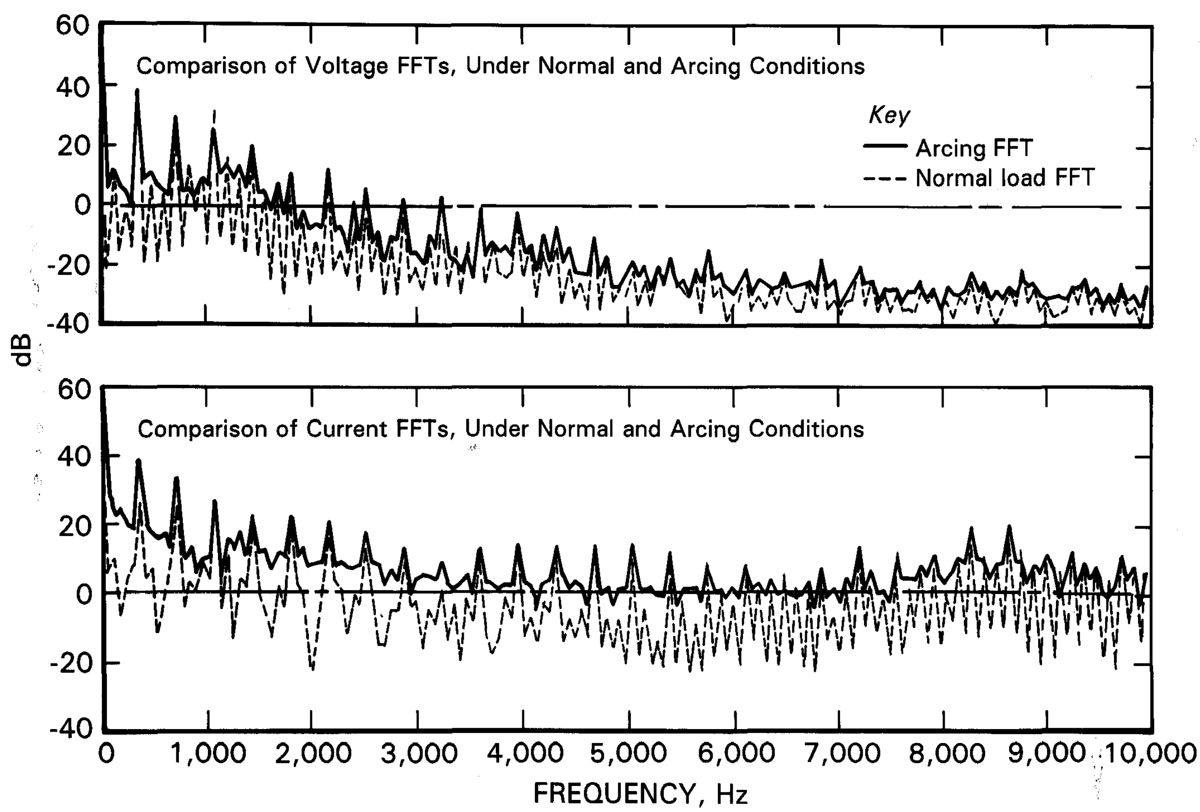

Figure 4.—Comparisons of the variations between the current and voltage fast Fourier transform spectra under normal and arcing fault conditions.

DETECTION ALGORITHM

Artificial neural networks (ANN's) formed the basis of the new fault detection algorithm. It is a technology that mimics the learning ability of neurons in the human brain. The power of the ANN lies in its ability to learn by example and model nonlinear phenomenon. Problems that are very difficult to model by a direct equation can be successfully modeled with an ANN. The paradigm used in the solution explained here is the Back Propagation network, an architecture that performs well on pattern classification problems.

Part of the process of developing an ANN solution is the training phase. During this phase, the data are presented to the network for training. Key areas representing all of the normal and fault conditions are extracted from the field test recordings. The corresponding FFT spectrum components are generated to create teaching patterns and are split into a training and test set. Along with each generated pattern is the correct classification value for that pattern, either a +1 for normal or a −1 for a fault. The ANN learns by randomly selecting patterns from the training set. It calculates an output based on the input pattern and compares it with the desired output. Error values calculated from that comparison are used to correct the network architecture to be closer to the desired output. This process runs repeatedly until the accuracy becomes acceptable. The input is then switched to the test set where the network does a one-time pass to generate independent error values. The purpose of this is to test the network on controlled data not used in training and check that the training set was not memorized. A network that memorizes the training data becomes too specific and will not perform well on new patterns. Further, examining the network output and its variances between the set values of ±1 (normal or fault) help identify weak areas in the training set. As the neural network predictions gravitate toward each extreme, it signifies a high level of confidence in the classification. When the output shifts toward the zero range, network confidence decreases and suggests possible weak areas. Additional training patterns could then be added to help improve network accuracy.

Figure 5 shows the topography of the neural network deployed for field testing. It consists of 23 input nodes, 11

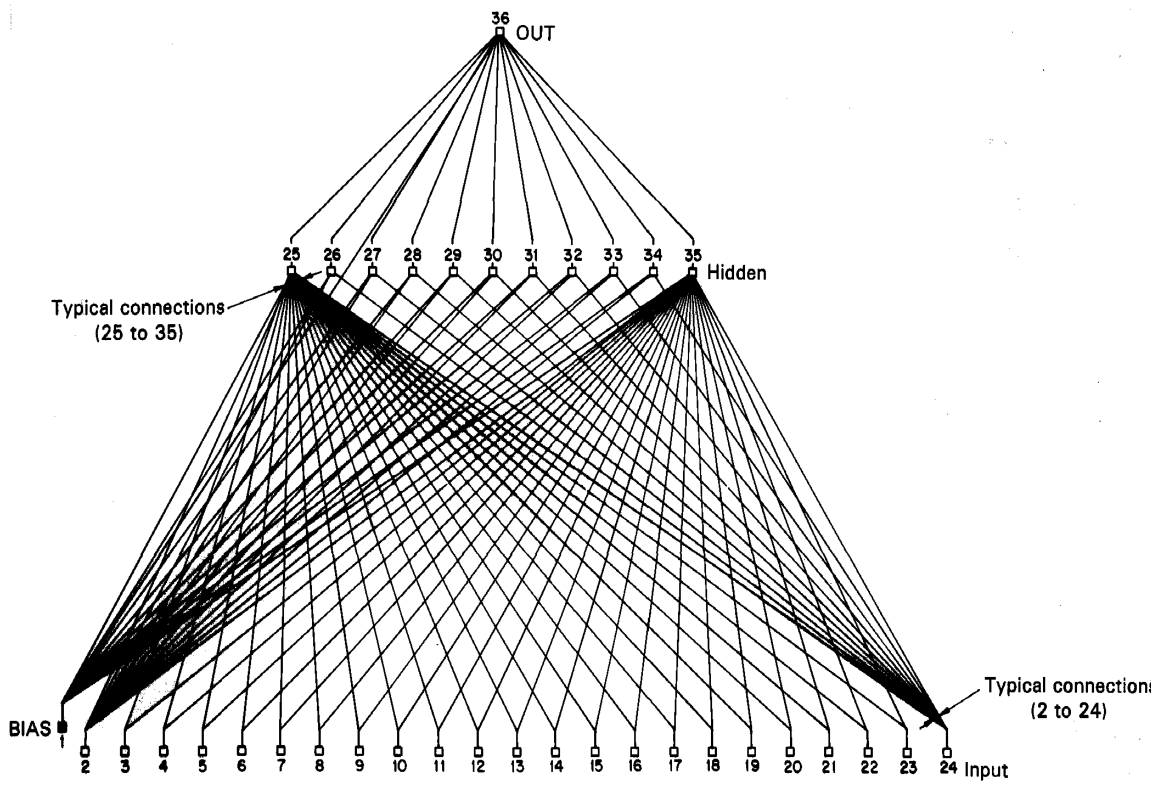

Figure 5.—Topography of the neural network showing the layers and interconnections.

hidden nodes, and 1 output node. Each node, or processing element, represents a single neuron that, when grouped together, form a network. The 23 inputs to the network are the FFT spectrum components of the current. They cover the 60-Hz harmonics starting at 1,440 Hz and ending at 2,760 Hz. Connections from the input layer to the hidden layer and from the hidden layer to the output node form the "memory" of the network. It is through these connection weights, adjusted during the training phase, where the network learns the solution.

After training and testing the network in the laboratory, it was converted into a C language module. This is done last because learning is disabled after conversion. This module was then incorporated into a program written to run on the DDA platform, where it was taken into the field for further testing.

TROLLEY SYSTEM MONITORING SESSIONS

The monitoring program used to test the neural network detection algorithm is DOS-based and written in the C programming language. Installed on the DDA platform, it runs in an online mode examining the system status approximately once per second.

During each pass, the program simultaneously acquires a buffer of data from two input channels. Both channels monitor the rectifier current, with the secondary channel having one-half the gain of the primary. This allows for maximum resolution with a higher gain on the primary channel while providing a backup channel in case of clipping. Data are clipped when the input signal range exceeds the DDA input range. If clipping occurs on the secondary channel, the buffer is ignored as the current levels are now approaching the normal circuit breaker settings. Conversely, the buffer is also ignored if the average current is below the minimum level (200 A), where arcs are less likely to be self-sustaining [Hall et al. 1978].

Buffers of valid data are logged on the DDA hard drive. This provides valuable data for analysis back at the laboratory. The logs provide information on rectifier usage, are the source for additional training patterns for new networks, and allow for manual checking of network accuracy. After logging the buffer, it is processed via an FFT. Each buffer holds sufficient data to compute four FFT's. The four spectra are averaged, with the resulting pattern used as input to the detection network. Using the average of several spectra helps reduce the noise level in the FFT's.

The network classification is output to the user via the DDA display after several postprocessing steps. First, the raw network output is time-stamped and logged to the DDA hard drive along with several other parameters. Next, the raw output is "normalized" to ± 1. For deployment purposes, the varying degree of confidence in the raw output has no use. The desired network output, especially if interfaced directly to the circuit breaker, is a normal or fault indication. There are two steps to the normalizing process. The first is to set a maximum threshold value to be considered a fault. With network output ranging between -1 (fault) and $+1$ (normal), a maximum threshold of -0.5 was set. This means that all values below -0.5 are considered a fault, whereas all values above are considered normal. Figure 6 illustrates the normalizing scheme, with the results displayed above the corresponding rectifier current log. Region A is where the fault occurs in this test amid normal loading from the locomotive. Applying the threshold increases the accuracy of the network through accepting only classifications with a high degree of confidence, thus decreasing the chances of a false alarm. After setting the threshold, the second step is to round the output to either a $+1$ or -1 value and display it on the DDA screen.

The monitoring program has some additional user functions and logging abilities. The program operator can manually toggle a flag indicating the presence of an arcing fault on the system. This is a helpful option for field testing in the monitor mode and provides validation data for off-line analysis. The flag is also logged to disk along with the time-stamped network output. Another function of the program deals with the output of the network to the user. Output of the system status is via audio and visual display. The addition of sound allows the user to maintain awareness of the program while keeping watch on the various hardware connected to the trolley system during the monitoring sessions.

The performance of the final detection network proved to be excellent. Accuracy of the network is calculated based on the results from running in a "monitoring" mode. This was done to keep data used for training purposes isolated from the data used for testing and verification. In 62 monitoring passes, the network correctly classified the normal/fault status of the system 97.9% of the time. Of the 2.1% wrong classifications, 1.9% were missed fault classifications and 0.2% were false alarms. It is important to eliminate the occurrence of false alarms. In the production-oriented environment of coal mine haulage, false alarms could result in costly and unnecessary interruptions. As an additional measure to further decrease the chance of false alarms, the system could be set to wait for several fault indications in sequence before activating an alarm or circuit breaker. This additional step would slow the response time to approximately once every 3 s.

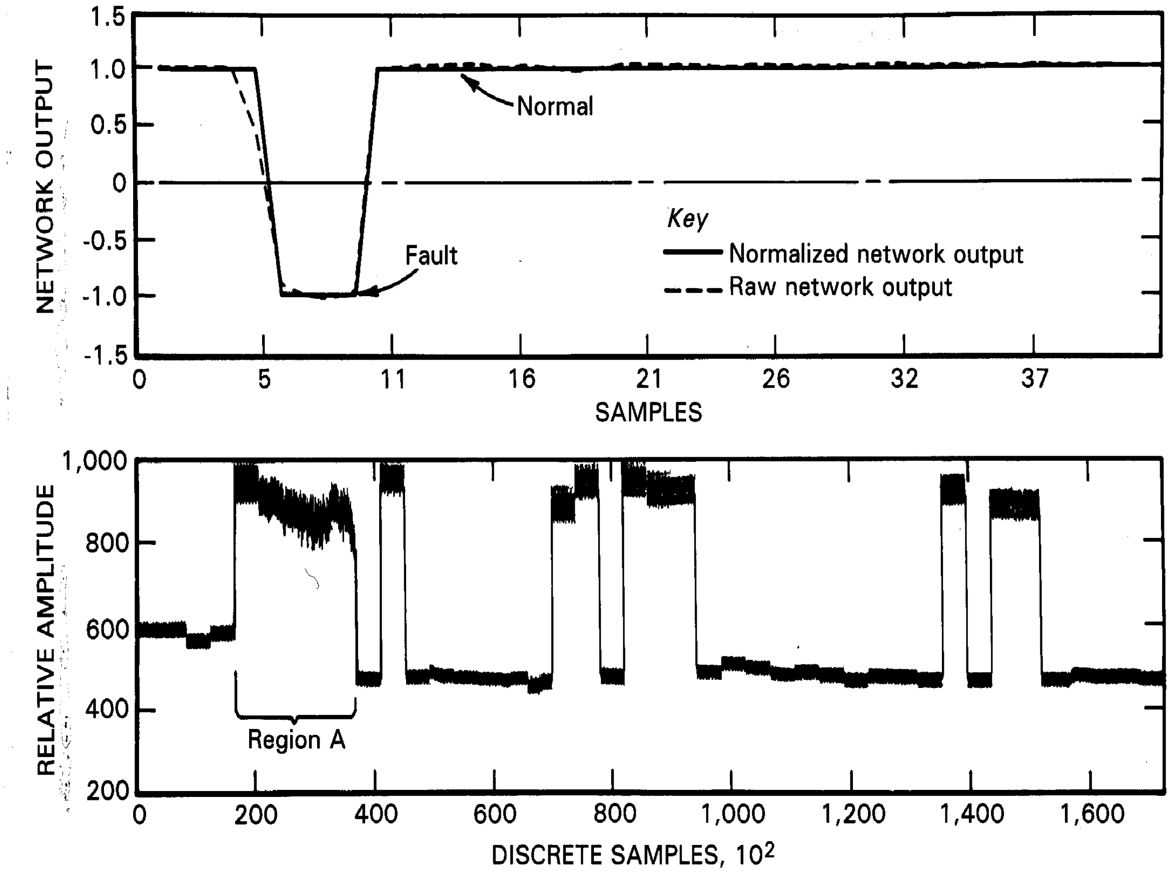

Figure 6.—Comparison of the raw and normalized neural network output with the corresponding rectifier current signal. Region A is where the fault occurs in this test amid normal loading from the locomotive.

It was originally planned that a single neural network be trained to generalize across different mine dc trolley systems. This was not accomplished for several reasons. The data gathered from the different mines may not have provided a sufficient generalized profile. Further, the variations between mines may be too complex to model with the existing technique. These variations can include different rectifier types, operating voltages, equipment running on the system, and system size and complexity. The network discussed here is rectifier-specific, i.e., it was trained solely on patterns obtained from a single mine rectifier. This means that in deploying this network to mines, it would have to be trained for each individual mine system. Deploying the network manually or in a self-learning configuration could achieve this.

CONCLUSIONS

The monitoring test results have displayed the network's ability to accurately detect faults on dc trolley systems. Arcing faults are successfully detected using only the frequency content of the rectifier current and the imposed fault signal. Used with the existing overcurrent circuit breakers, this scheme can add another layer of protection for both mine personnel and material. Self-sustaining arcs caused by roof falls or similar events could be extinguished before igniting adjacent material and causing fire hazards. This system can be implemented using a self-contained microprocessor mounted on each rectifier, where it would monitor the dc current and provide an improvement over prior techniques in terms of both cost and complexity.

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