POWER SPECTRUM ESTIMATES OF HIGH FREQUENCY NOISE GENERATED BY HIGH IMPEDANCE ARCING FAULTS ON DISTRIBUTION SYSTEMS

A Thesis

by

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Approved as to style and content by:

(Chairman of Committee)

(Member)

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(Head of Department)

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ABSTRACT

Power Spectrum Estimates of High Frequency Noise Generated By High Impedance Arcing Faults on Distribution Systems. (December 1979)

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Chairman of Advisory Committee: Dr. B. Don Russell

High impedance faults remain a serious danger to the public. Existing technology attempts to clear these low current faults through detection of 60 Hz current threshold violations. That approach has been ineffective due to the low current nature of these faults. A relaying technique which uses the high frequency content of current produced by these faults has been proposed by Russell and Aucoin of Texas A&M University.[1] This research was undertaken to characterize the magnitude and spectrum that might be expected during low current ground faults. Filter/amplifier equipment and FM instrumentation recorders were used to record staged fault current tests. The recorded data were digitized and analyzed by using a mini-computer.

It has been shown that high frequencies are in fact produced by high impedance arcing faults. These high frequency currents propagate well in the 2 to 40 kHz range with little or no attenuation from distributed line parameters. Capacitor banks do provide high frequency ground paths as expected. The faults produced by 7,200 volt distribution systems are generally arcing faults, if more than a few milliamperes flow. The frequency spectrum of these arcs extend to well above the 10 kHz range.

DEDICATION

To Linda, John, Mom and Dad.

ACKNOWLEDGEMENTS

The author would like to acknowledge the help and encouragement provided by his committee, particularly from Dr. B. Don Russell, Chairman. Also, Lee Ann Mallory for her undying efforts to decypher the scribbles which often attempted to pass for text. Finally, my wife, Linda, who deserves full credit for whatever success I am or may become.

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INTRODUCTION

Protection Philosophy

When man first began to use electricity commercially, one of the first problems faced by engineers was that of finding a reliable means of interrupting short circuits (faults) when they occurred. There have always been two reliability considerations involved in this interruption: dependability and security. The first (dependability) is that the interruption device must perform its function every time it is called upon to do so. The second (security) is that the interruption device must not perform its function unless it is called upon to do so.

The simplest interruption device, the fused link, is a good example of the trade-offs required in protecting a modern-day power system. As an example, assume that a device which normally draws 5 amperes (rms) is to be protected by a fuse. Assume further that the device to be protected is usually expected to draw no more than 50 amps if it fails. Fuse selection in this case is reduced to the question of selecting a device which will interrupt 50 amps of current if over 5 amps is conducted through it, and remain intact under all conditions at currents below 5 amps.

The easiest choice would be a 5 amp fuse. However, on a hot day in an enclosed fuse holder which is mounted on a vibrating platform, the fuse might possibly fail at a current somewhat less than 5 amps.

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This would interrupt service to a device which is performing perfectly. Choosing then a 10 amp fuse, to insure reliability of service to be protected device, the device is left unprotected against failures which cause fault currents between 5 and 10 amps. As these fault currents approach 10 amps, the probability that the fuse will interrupt the current increases, so that at some point above 10 amps, the probability that the device is protected is very near 1.

Similar dilemmas are faced by power system relay and protection engineers every day. A trade-off always exists: continuity of service versus the reliability of fault identification and interruption. In addition, an actual power system has a constantly varying demand, complicating the previous case. The gap between protective relay settings and actual load is usually significant since the relay settings are estimated using faults of low impedance.

One kind of fault which is not covered by present protection techniques has been termed a high impedance fault. [1] It usually involves a high impedance path to the power system neutral, resulting in low fault currents. Since the high impedance fault usually involves ground, attempts have been made to install ground relays to detect the small fault currents. However, the neutral current may already be quite high due to normal system imbalance which some utilities allow to run as high as .50 per unit.

It would appear from the lack of success of previous work that a new approach to the problem should be attempted. Although several researchers [2][3] have suggested an increase in harmonic current at the fault might be useful, none have suggested that the arcs and sparks accompanying the high impedance arcing fault phenomena might prove useful. The research reported herein is an investigation into that area of study.

LITERATURE REVIEW

To investigate the seriousness of the problem of high impedance faults, and to search for possible solutions, Pennsylvania Power and Light Company (PP&L) gathered data on instances of downed conductors.[4] In a breakdown of 390 cases of downed conductors on 12 KV overhead distribution lines in 1974-75, they found that overcurrent protective devices did not operate for 23% of the cases where the feeder had bare wire conductors, and 72% of the cases where the feeder had XLP covered conductors. These figures indicate the severity of the problem, and that it is a frequent one. Their data can be further broken down according to protective equipment:

Table 1.

Performance Analysis of Overcurrent Protective Devices

Type Device	No. of Occurrences	% of Failure to clear fault
Breaker	113	57%
3ØO C Relay	55	40%
1ØO C Relay	84	20%
Fuse	138	15%

It should be noted that the high percentage of breaker failure was the result of a large number of insulated conductors on those circuits. The report did not indicate the amount of time that faults persisted before clearing.

PP&L also conducted a survey of numerous utilities concerning the clearing of line faults.[4] Of the 83 replies to the survey, 61% indicated they had experienced problems with clearing faults due to fallen conductors. Of those who had experienced problems, 82% had ground relays installed in the system.

In a follow-up questionaire, the utilities were asked to further described their problems with clearing downed conductors.[5] Of the 18 companies which responded, 5 indicated they had no problems with clearing downed conductors. The others indicated they had anywhere from 0.1 to 15 incidents per year of failure to clear downed conductors. The majority of problems stated were total failure to clear (most frequent reply), slow clearing (virtually impossible to detect) or multiple reclosures with failure to lock out (caused by long cycle times).

The utilities were also asked to describe factors to which they attributed success in clearing downed conductors. For relaying practices the utilities responded that they set ground relays low enough to detect most ground faults. However, two utilities stated that ground relays were impractical since they could not be set lower than phase relays which is the conclusion also reached by PP&L. On questions concerning grounding and line design practices, most companies reported that designs which produced a high magnitude of available fault current seemed to help. PP&L indicated that this is not a significant factor in downed conductor faults.

In summary, PP&L stated:

> "It appears that many of these companies are willing to tolerate the decreased customer reliability resulting from loss of coordination which accompanies their lowered relay settings. . .these companies. . .seem to

rely on techniques which our work indicates are not sufficiently reliable for our purposes".[4]

Clearly, dependence on overcurrent protective schemes offers little hope for a reliable solution to the high impedance fault problem.

A recent example of high impedance fault problems occurred during the ice storm which devastated Dallas, Texas during the early part of 1979. Hundreds of conductors were down, a few remained energized. One was energized in an alley where neighborhood children discovered it. One child dared another to touch the smoking conductor. He did and died as a result. There is currently no commercially available technology to protect the public in cases such as this.

The PP&L study indicated the futility of using 60 Hz relaying techniques against a fault of high impedance. However, Warrington [2] indicates that non-linear resistance at the arc may produce harmonics in the arc current. Kaufman and Page [5] predicted from the physics of the arc phenomena itself that a substantially modified current waveform could be expected due to the arcing phenomena. In addition, Beasley [6] studied the pre- and post-arc sparking and found that significant magnitudes of currents in the spark were produced by short rise time, short fall time currents. Beasley further calculated an estimated frequency spectrum produced by sparking current waveform and demonstrated through calculation and experiment that frequencies into the gigahertz range were produced by that phenomena.

Given that low frequency relaying techniques had failed to identify a characteristic of high impedance arcing faults useful in their interruption, an investigation was undertaken in the frequency range above that normally considered power frequencies to determine to what extent, if any, the sparks (or other phenomena) associated with arcs in the fault produced high frequency current. And further, to determine to what extent those high frequencies propagate on a power distribution system.

THE MECHANICS OF ARCS AND SPARKS

The actual phenomena being dealt with under the name high impedance fault is actually considerably more complex than simply a fault of high impedance. The PP&L study indicated that in every test case they ran which conducted more than just a few milliamperes, arcing was present. Beasley [6] notes that laboratory measurements made in his work revealed that a small current continuous arc with a conduction current in the order of milliamperes did not produce radiated radio frequency noise of measurable amplitude. However, he also pointed out a slightly more complex model of arcing than was considered by Kaufman and Page [5] who dealt only with the phenomenon of 60 Hz and a few harmonics, at relatively low voltages.

Kaufman and Page show a very clean fault model as indicated in Figure 1. According to their model, when the gap voltage reaches the value e_r, an arc is formed and the gap voltage is reduced to the value e_{arc}. Beasley [6] on the other hand pointed out in his paper that prior to the formation of a continuous arc, several repetitions of sparks may occur if the path impedance is sufficient. The peak current produced during the spark, for Beasley's case at least, was nearly an order of magnitude greater than the resulting sustained arc current. (Figure 2) Thus it was proposed that the pre- and post-phenomena might include frequencies well above those normally associated with power systems.

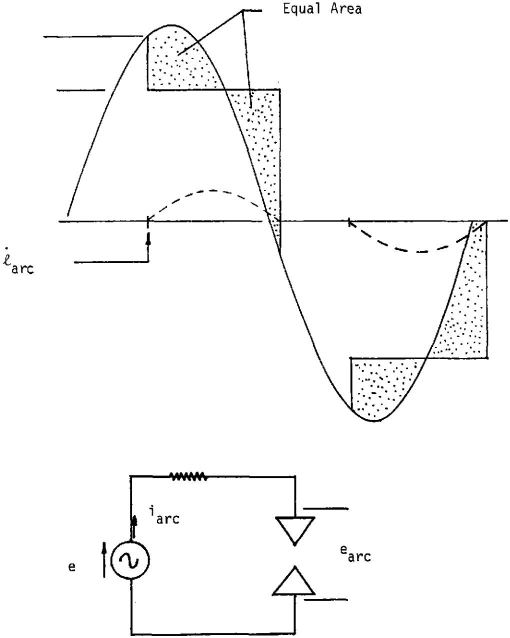


Figure 1 Kaufman-Page Arc Model

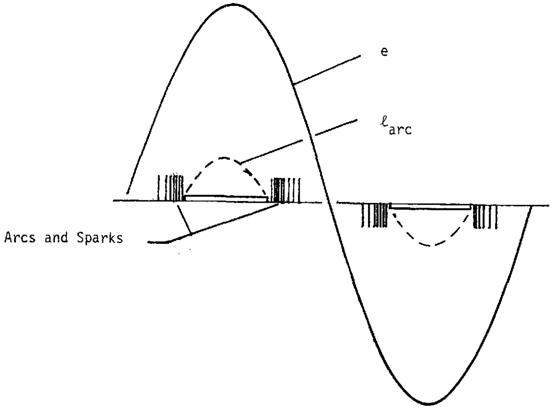


Figure 2 Beasley Radiated Arc Model

SIMULATED FAULT MEASUREMENTS

G. K. Laycock of Cambridge pointed out in his dissertation that FM instrumentation recorder measurement techniques tend to fail due to the limited dynamic range of the input device. [7] Thus cautioned, it was decided that in addition to the pre-fault calculations of Aucoin [1], that a series of laboratory simulations of high impedance faults should be conducted. These simulations were to represent, as closely as possible, the physical phenomena expected during field fault tests. The results would yield at least a preliminary verification of the judgement concerning the frequency spectrum and magnitude which might be expected during field tests.

The laboratory test set-up is depicted schematically in Figure 3. A high impedance 120/14,000V neon light transformer was connected to a jacobs ladder-type electrode arrangement. The electrodes were placed close enough so that spontaneous arcing was produced as voltage was applied. A Hewlett-Packard amprobe was used to observe the current waveform produced by the arc. A Rockland variable cut-off frequency bandpass filter and Tektronics spectrum analyzer were used as frequency observation devices.

Figure 4a shows the unfiltered predominantly 60 Hz current at the primary of the transformer. The spikes appear as suggested in the classic arcing model, at the point where current begins to flow. Using the Rockland filter as a 2-10 kHz bandpass filter, Figure 4b was observed. Each spike corresponds in time to a fault arc inception at each half cycle of the 60 Hz waveform. It was noted that disturbing

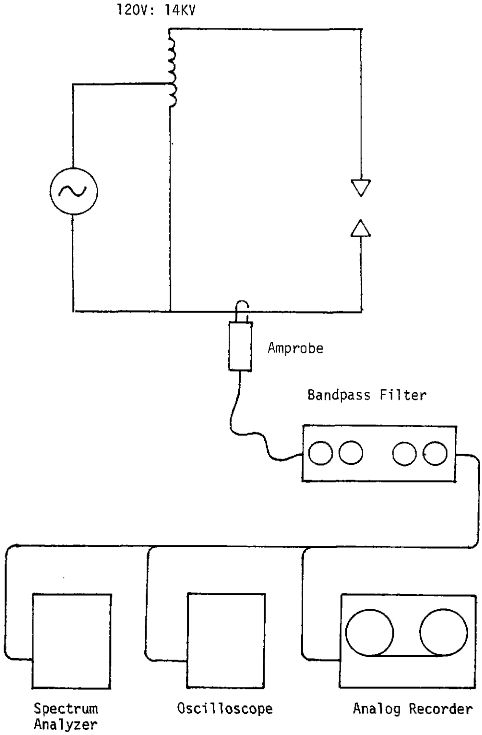


Figure 3 Lab Test Arrangement For
Simulation of High Impedance Faults

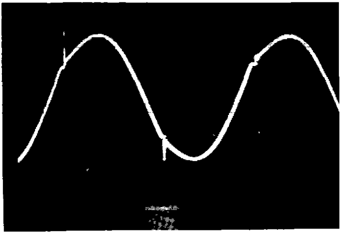


Figure 4a Unfiltered current

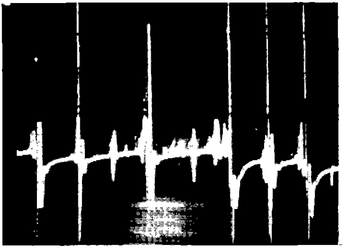


Figure 4b Current filtered 2-10kHz

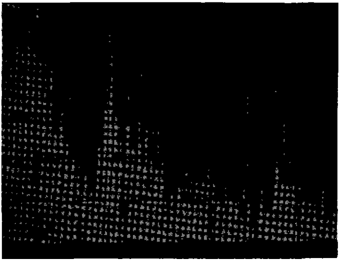


Figure 4c Output of spectrum analyzer

the arc by blowing on it could delay arc onset to higher voltage levels, thus producing high transients in the current when the arc finally formed. Figure 4c is a spectral analyzer output taken over a scan period of 10 seconds. The first "dip" in the data is where the arc was left relatively undisturbed. The arc was then disturbed by the blowing technique described earlier. The vertical scale is 10 db per graticule. Note that noise magnitude varied over 40 db from the disturbed to undisturbed case in the 2-10 kHz range.

Thus, laboratory simulation indicated that at least 40 db dynamic range could be expected from an arcing fault of this nature. In addition, Aucoin's prediction of generally present wideband noise was also verified.

However, since a dynamic range of 40 db would be required for noise signal variation alone, and instrumentation recorder dynamic ranges are on the order of 50 db, some method of assuring that precisely the proper filter/amplifier arrangement was used to place the maximum signal expected as closely as possible to the upper limit of the dynamic range of any recording equipment used. Aucoin's estimate [1] indicated that at frequencies above the 2 kHz range, the predominate signals would lie at least 20-40 db below the value of 60 Hz arc current. From these estimates, and laboratory determined data, amplifier/filter system was designed.

Since the PP&L study [4] showed that arcing accompanied the high impedance faults they staged, and Beasley [6] demonstrated that an arc produced on power systems generates high frequency components of current flowing in the arc and their propagation characteristics should be studied in an effort to identify high impedance arcing faults reliably and command their interruption. Hence, the research reported in this thesis was performed.

A series of design specifications was derived for the instrumentation system required to measure the high frequency components of arcing high impedance faults and record them for later analysis. A frequency range of 2 kHz and 80 kHz was chosen as the bandwidth objective after considering the following: (1) the PP&L report [4] indicated that significant amounts of energy (up to 5% in some cases) were being delivered at frequencies up to the 20th harmonic of the fundamental 60 Hz waveform and (2) the best recorder available for the research had a bandwidth of DC-80 kHz.

THE MEASUREMENT SYSTEM

Input/output characteristics for the devices used to measure and record the data are as follows:

Table 2.

Input/Output Characteristics of Measuring and Recording Devices

Device	Frequency	Max Input	Min Input For Full Scale	Max Output	V Gain	Dynamic Range
Op amp filter	DC-100kHz	±15v	$16\mu v_{pp}$ 1/1 $\frac{s+N}{N}$	±15v	10	See Appendix A.1
Current Transformer	1kz-35MHz	27a @60hz	--	300v	.1	See Appendix A.2
Recorder	DC-80kHz	±20v	.57vpk	10vpk	1	47db See Appendix A.3

Other measurement considerations involved the frequency response of the relaying Current Transformer (CT's) at power system substations which were to be used for the measurements. The most common current transformer used nationally is of a type which is normally linear up to 400 Hz.

The small signal high frequency response of current transformers (CT's) has not been studied. Power system relay engineers therefore have been interested only in the large transient saturation effects of current transformers as exhibited by the data presented in the Power System Relaying Committee of IEEE Report on Transient Response of Current Transformers.[8] However, general opinion of the industry is that signals up to 10 kHz will reliably pass through existing CT's under normal conditions.

CT ratios used in distribution systems also vary quite a bit. Texas Electric Service Company of Ft. Worth, Texas, where several of the staged fault tests were conducted, indicated that a 600:5 CT would be used in each phase and neutral of the line under test. The 60 Hz fault current availability at the test site was calculated to be approximately 2100 amps, although high impedance faults on the order of 10 to 20 amps were expected. No other current was expected to be on the faulted phase.

The measurement parameters of the system were thus defined:

Fault current expected	20 amps max. (60 hz level)
CT ratio	600:5
CT secondary current	20/120 = .1667 amps
Pk amps	1.414 x .1667a = .235pk
Pk 10kHz value expected	0.235 ÷ 100 (40 db) = 2.35ma
Current/voltage transformer	2.35ma ÷ 10 = .000235v 0.235mv

Thus the maximum estimated signal to be measured was 235μv. (Well above that required for 20 db signal to noise ratio as calculated in Appendix. In addition, the 60 Hz component and its harmonics had to be removed to avoid saturation of several amplifier stages which would be required to bring the fault signal up to the level required by the recorder (approximately 1vpk). The filter specifications were set so that 2 kHz would be the low frequency 3db point, and that 60 Hz should be notched to reduce the effect of power frequency current on the data.

The filters were roughly linear between 30 kHz and have variable gain from 20 to 60 DB. See Appendix.

STAGED FAULT TESTS

Three series of staged high impedance fault tests were performed. The first at Rochester Gas and Electric (RG&E) in Rochester, New York on November 11, 1978. Prototype amplifiers and the Rockland bandpass filter were used to prefilter and amplify the arc current. The CT loop interface was provided by RG&E. It consisted of a 1A to 1V transformer/shunt arrangement.

The test site consisted of several types of surfaces on which a conductor might fall. They included: macadam, reinforced concrete sidewalk, non-reinforced concrete sidewalk, and sod. The soil was primarily a sandy loam which was fairly dry the day of the test.

The test site was fed from a single phase tap from a 10mva feeder of a 34.5/12 KV substation 0.6 miles away. The current flowing at the test site was subject only to the single phase line parameters with very little exposure to potential phase to phase coupling, as the lateral tapped off from the first pole out of the substation. In addition, the feeder served a load of nearly 100 amps per phase which tended to mask the noise produced by the arcs with noise produced by loads associated with the feeder.

Figure 5b shows a similar test at TESCO discussed later. Figure 5a shows the arcing produced on sod by a 336 mcm covered conductor with 4" of covering stripped back. The 60 Hz value of the fault shown was on the order of 20 amps. Figure 6 shows one 16 ms sample of the noise data produced by an arc similar to that shown in Figure . The positive and negative half cycle correlation of the noise bursts can readily

Figure 5a RG&E Field Test 7-11-78

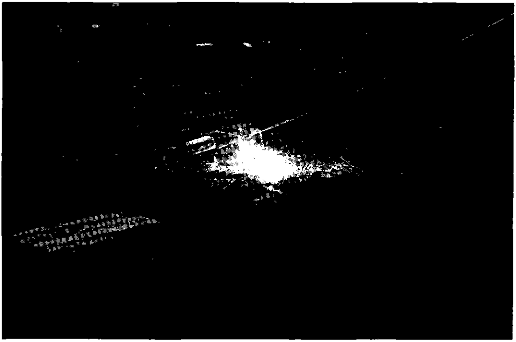
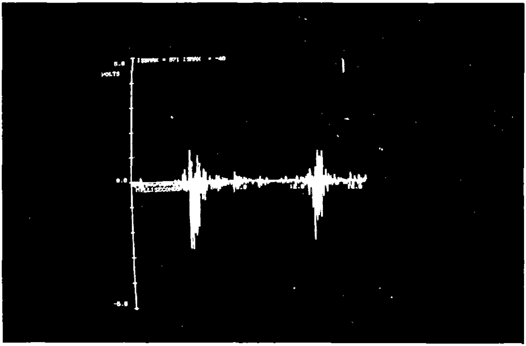
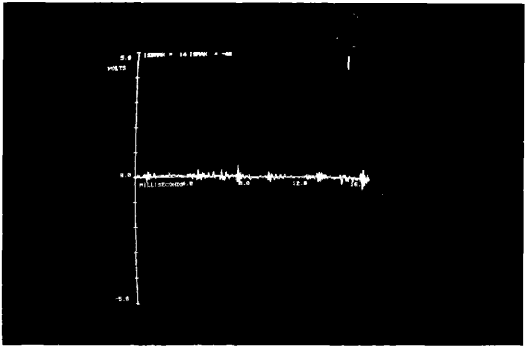


Figure 5b TESCO Field Test 2-2-79



a) System with arcing fault



b) Normal System

Figure 6 Waveforms of 2-40kHz raw data from RG&E field test reproduced on graphics display. (one cycle of data) be seen. Figure 6b shows the normal noise band produced by feeder load.

There were several factors which indicated that further testing would be necessary before any conclusive characterization of the faults could be made.

1) The single phase line was tapped off the feeder at the first pole outside the substation.
2) The arc noise was superimposed on normal feeder load produced noise.
3) The effect of the nearby capacitor bank on the 3 phase feeder was indeterminate.
4) The operational amplifiers were band limited to about 20 kHz in the field test configuration and higher frequency data was desired.

Given those system limitations, it was considered necessary that a second series of staged fault tests be conducted. Therefore, a second series of tests was scheduled with Texas Electric Service Company (TESCO) in Ft. Worth, Texas. A new filter amplifier system was developed to yield improved high frequency response [see Appendix] and higher gain than the system used at New York. The first attempt to use the new system failed due to using 0.01 ohm shunts in the current transformer (CT) lines. The arcing signal produced was below the input noise level of the amplifier/filter system and no useful data was recorded in the high frequency range.

Ultimately, Pearson high performance 0.1V per amp CT's were purchased and used as input devices to the filter arrangement and a third series of test was conducted at TESCO.

A fully instrumented test was conducted on the system of Texas Electric Service Company (TESCO) near Ft. Worth, Texas. The feeder that was to be faulted served a newly developed subdivision. Only two houses were complete at the time of the test. One house was served from Phase B, the other from Phase C. Phase A was therefore chosen as the fault phase so that the only signals recorded at the substation would be those produced by the fault.

The feeder under test (#3531-White Substation) had recently been constructed. It is a 336 mcm ACSR: 3 phase, 4 wire; grounded Y; 7,200/12,470 V; feeder with grounds at every pole. The fault location was chosen near the end of its 0.6 mile length so that the distributed line parameters might have as much effect on the data as possible. There were no capacitors on the line. Fault current availability was calculated by TESCO to be nearly 2,100 amps for a single phase to ground bolted fault at the fault site.

Weather conditions at the test site prior to the test had been very wet and cold. The soil, which was predominately a sandy clay shale, had been frozen in the weeks preceding the test, and only thawed a few days prior to the test.

At the substation, two Pearson CT's were inserted into the relaying CT lines as shown in Figure 7b. The CT shown on the left is connected to measure only Phase A (faulted phase) current, while the CT shown on the right is connected to measure zero sequence current, (Ia + Ib + Ic).

Figure 7a shows the connection of the two filter/amplifiers used

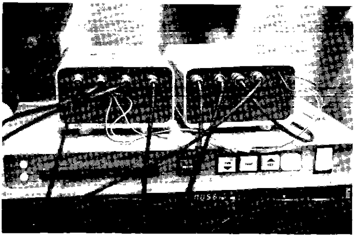


Figure 7a Filtering and signal conditioning system in field use

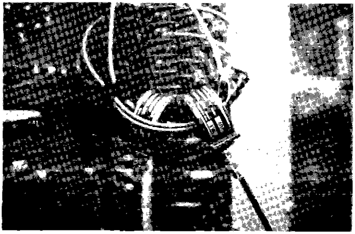


Figure 7b Pearson current transformers in field use

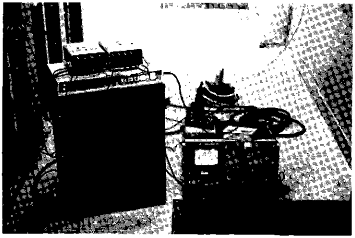


Figure 7c Recording equipment in field use for TESCO test 2-2-79

during these tests. Figure 7c is the complete recording set up as installed in White Substation to measure the faults. A small transformer (120/2.4V) was used off of Phase A Potential Transformer (PT) to give the current data a phase reference.

The Ampex FM instrumentation tape recorder was configured for 7 channels of simultaneous DC-65 kHz recording. Only one record head was used of the two available so that the data would remain as closely time synchronized during later playback as possible. The dynamic skew characteristic of the recorder (see Appendix) calls for a maximum reproduced time error between adjacent tracks of 0.4 micro-seconds. As much as 5 micro-seconds error might be expected from channel one to channel thirteen. To put the potential time error in perspective, it was conceivable that a 1/4 cycle phase error of a 50 kHz signals could occur from one edge of the tape to the other.

At the fault site, a 100a fuse was attached to Phase A in a fused cutout. A 4/0 ACSR conductor was strung to the ground. A porcelin insulator (Johnny Ball) was attached to the conductor near its end and a nylon handline passed through the other end as shown in Figure 8. A lineman in a bucket truck wearing 35 Kv rubber gloves handled the handline thus controlling when and where faults occurred.

Each fault test followed generally the same procedure. First the 4/0 conductor was raised clear of the ground using the handline. The fused cutout was closed in. The fault line then became energized. The substation crew was notified by radio that the fault crew was ready to generate a fault. If all recording equipment was ready, the substation crew instructed the fault crew to go ahead in 1 minute. No further radio communications were allowed at the substation during the actual fault due to RF injection into the tape recorder. At 15 seconds prior to the fault, the recorder was started. Normally about 1 minute of arcing was allowed to persist before the line was raised and the cutout opened.

Five of these faults were run during this series at TESCO. None of the five drew over 50 amps again demonstrating the dangerous nature of high impedance faults. The first four faults were caused as shown in Figure 5b. The fifth was caused by tamping a metal stand with a 1' square steel base into the ground 1 or 2 inches and lowering the line into the pipe extending upward from the base.

No significant increase in fault current was noted even though the 'fault interface' area had been increased several fold.

Following each fault run, the tape was rewound and played back into an oscilloscope to observe the quality of data that had been recorded. Figure 8 shows a typical observation. The arcing noise is not periodic, but repetitive in nature. The noise bursts occur as during the time predicted by the classical arcing model. The magnitude of the arcing bursts shown (1.5 V noise peaks at the recorder) or about .5 amp peaks (after filtering) on the actual feeder. Obviously no RMS estimate of the energy can be made without extentive analysis, since the energy varies significantly from half-cycle to half-cycle.

The recordings made during the tests were returned to the Electric Power Institute's Laboratory for analysis.

In addition to simply staging fault tests, several normal events

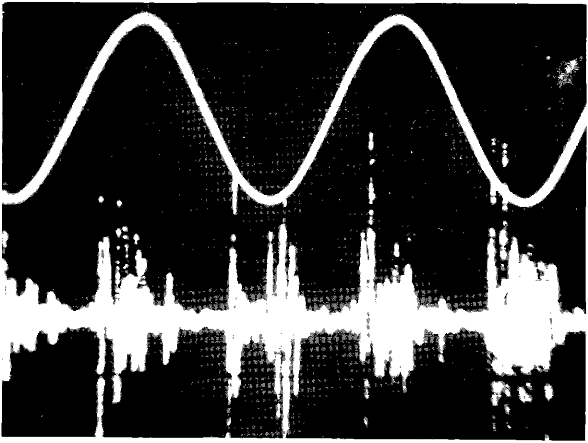


Figure 8 Scope traces of arcing-TESCO field tests 2-2-79
Top: Phase a voltage
Bottom: 2-65kHz summation of currents with gain of 66dB

were observed to see how much high frequency current might be produced from these type events. Figure 9 is a 5 second record of the noise produced by a capacitor bank switching. The transients were limited to a cycle or two and did not exhibit the characteristic sectoring observed in arcing faults. Two feeders were tied together using a hand operated air switch to produce the currents shown in Figure 9. No distinguisable noise was produced.

The normal switching transients which were observed included air switch operating, capacitor switching, large motor starts, and breaker operations. All seemed to be limited to at most a few cycles, while noise produced by the arcs was sustained for seconds.

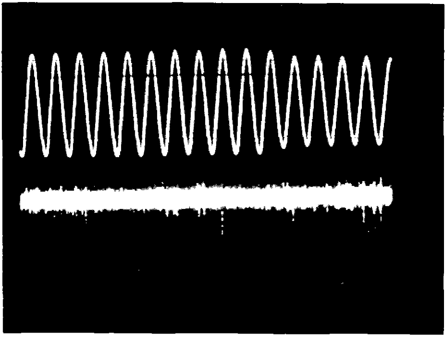


Figure 9a Capacitor Bank Operation (Close)

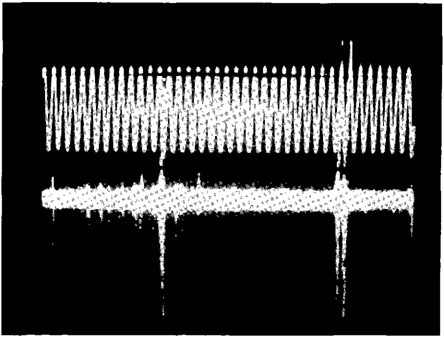


Figure 9b Feeder Tie Switch Close

SAMPLING THE RECORDED DATA

EPI Facilities

The Electric Power Institute provided all the equipment necessary for data analysis. The Ampex recorder capabilities have already been discussed. (See also recorder specifications Appendix A). Digital Equipment Corporation PDP-11/34 mini-computer was used for digitizing and analyzing data. Figures 10 and 11 show the general configuration of the recorder and computer during playback and digitizing.

The mini-computer is equipped with a 16 channel, 12-bit analog to digital converter. The sample rate is controlled externally by a function generator and frequency counter arrangement (Figure 10). The tape recorder may be slowed by a factor of 64 so that much higher effective sample rates may be achieved.

Sampling Techniques

An excellent discussion of sampling technique may be found in Reference [9]. A comparison of the continuous time Fourier transform and the discrete time Fourier transform indicates the importance of the proper sample rate criteria and define what is commonly called the Nyquist rate.

Consider a discrete-time sequency x(n) which is created from a

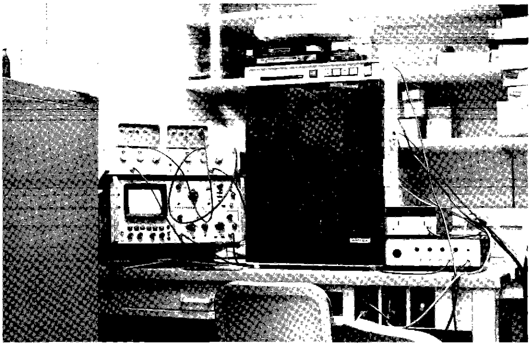


Figure 10 Recorder arranged to input data to computer

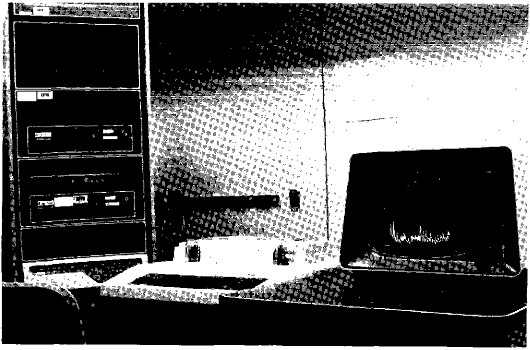


Figure 11 PDP-11/34 Computer, Decwriter and graphics terminal

continuous function x(t) where x(n) = x(nT) n=1, 2, 3, . . .

T is called the sample period. 1/T is the sample rate or sampling frequency. A simpler explanation of sampling errors due to insufficient sample rate may be found in Gardenhire's paper on sampling [10]: "If a time function contains only frequency components below F cycle per second, 2F samples per second suffice to represent it perfectly and permit perfect recovery". This theory is practically useless, in the stated form, because in practice there is seldom such a thing as a function containing absolutely only frequency components below F cycles-per-second. Also, filters cannot be built that are capable of cutting off perfectly above frequency F, and natural phenomena do not often occur in this manner.

One illustration of the error produced by insufficient sampling rate is called aliasing. That is where a high frequency, sampled too slowly, will appear to be a lower frequency as shown in Figure 14. Here, the sample string of each of the two waveforms will be identical while it should be obvious, even to the casual observer that the continuous-time domain functions which produced them are considerably different.

The high-frequency current signal being measured is actual falling off quite rapidly with increasing frequency due to the LC equivalence of the distribution system as well as that of the relay CT and the Fourier series coefficients tend to zero. In addition the

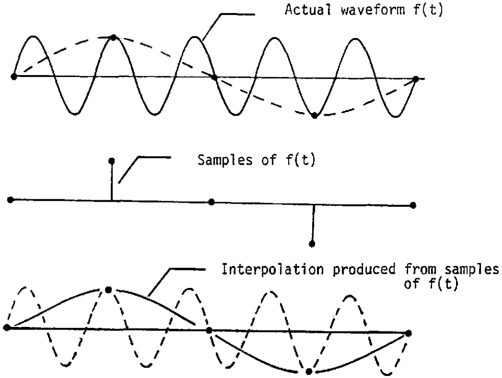


Figure 12 Graphic Representation of the Aliasing Phenomena

high frequency of interest is considerably below that which was present on the recorder. The maximum recorded frequency is that which is of concern in the selection of the sample rate.

Since the highest frequency of interest was near 40 kHz, and the recorder was capable of recording 80 kHz, it was determined that 65 kHz would be a good compromise bandwidth adjustment on the recorder. This selection insured accurate reproduction of the 40 kHz signal and also served to minimize the sample frequency required to prevent aliasing.

As a matter of convenience, it was decided to use 4096 samples per cycle of the 60 Hz waveform so that convenient divisions could later be used to speed up the FFT (Fast Fourier Transform) process. The effective sample rate thus became 4096 x 60 = 245,760 s/s or nearly 4 times the high end break frequency. This would produce between 10 and 15% [10] interpolation error at 65 kHz but less than 10% at 40 kHz which is acceptable for the analysis methods to be used.

Thus the sample frequency was selected for convenience and checked for error due to aliasing. While a minimum of aliasing exists (less than 10%), the uniform roll-off expected from the data would minimize the effect of any aliasing error as the data was analyzed.

Data Storage

The analysis technique to be used required large blocks of data that could be averaged after some manipulation. The PDP 11/34 computer equipment available includes a hard disk (RK05J type) which could be used as a long term storage medium. In addition to simply sampling the high frequency current signal generated by the faults, it seemed desirable to preserve the relative position of each sample within the 60 Hz current present in the system during the arc. A computer program was written which sampled the data at an effective rate of 245,760 s/s, and also sampled another track of the recorder on which was recorded the unfiltered, unamplified predominantly 60 Hz current produced by the fault, to determine which portion of the 60 Hz current was in the positive half cycle. The data was stored in integer form without change. If the 60 Hz current was negative, the value of the high frequency sample was negated and then stored in a random access memory buffer. When the buffer filled, it was written to disk for semi-permanent storage.

The 12 bit analog to digital converter produced offset binary code. Offset binary yields all positive binary values ranging from 0000_H to $07FF_H$ for signals varying from -5v to +5v. The fact that all the A/D values could be expected to be positive greatly simplified the preservation of zero crossing information as mentioned earlier. The Fortran programs used to analyze the data were required only to use the absolute value of the data if zero crossing information was not desired. Conversion time 16 bit integer to 32 bit floating point numbers was accomplished during the FFT process.

ANALYSIS

The Fourier Transform

A form of the discrete Fourier Transform is used to transform the sampled data into the frequency domain for analysis. The averaging of the periodograms produced was done by a modified Welch Spectral estimate technique discussed later.

Two assumptions are made at this point which, though not entirely valid, have little effect on the ultimate results of the data analysis.

First, the process being measured is not necessarily periodic. Figure 13 shows the filtered data as recorded during one of the arcing tests at Texas Electric Service Company. While there may be certain similarities from cycle to cycle of the 60 Hz waveform, it should be obvious that the waveform it not strictly periodic.

Second, the data records do not start exactly at a zero crossing since small noise bursts on the unfiltered 60 hz waveforms may have influenced the determination of zero crossing when the data was first digitized. Several occurrences of this were observed but it was decided that these variances were very short compared to 4096 samples and that any effort to estimate the actual zero crossing might render future duplication of the research more difficult and leave the results in doubt. The error involved was less than ±4 samples of 4096.

The discrete Fourier transform (DFT) of a finite length sequence x(n) is given as

$$X(n) = \sum_{n=0}^{N-1} x(n)e^{\frac{-j2\pi nk}{N}} \quad 0 \leq k \leq N-1$$

otherwise. When limited spectral resolution is required, and speed of calculation is important, several algorithms called "Fast Fourier Transformers" (FFT)[9] may be employed.

The computer system available for this research computed one 4096 point complex Fast Fourier transform in approximately 24 seconds. Since hundreds of these transforms would have to be computed, it was decided to form the data into two cycle records at a time, loading the first cycle of real data into the real part of the array and the second cycle of real data into the imaginary part. Thus one complex Fast Fourier transform computes two cycles of FFT's in roughly the same 24 seconds. By exploiting the odd and even properties of the Fourier Transform, it is possible to separate the results of the two mixed calculations as shown below.

let x_1 (n) be one 4096 sample record

let x_2 (n) be the next 4096 sample record

and each having the DFT. $X_1(k)$, $X_2(k)$, and $X(k)$ and let $X_{OR}(k)$, $X_{ER}(k)$, $X_{OI}(k)$, and $X_{EI}(k)$ denote the odd and even real parts of G(k) and the odd and even imaginary parts of G(k).

Assume that X(k) is the Discrete Transform of x(n) and that X(n) is a complex discrete sequence made up of $x_1(n) + j\ x_2(n)$.

$$X(k) = \sum_{n=1}^{N-1} [X_1(n) + yX_2(n)]e^{\frac{-y2\pi}{N} kn}$$

$$X(k) = \sum_{n=1}^{N-1} X_1 e^{\frac{-y2\pi}{N} kn} + y \sum_{n=0}^{N-1} X_2(n)e^{-y\frac{2\pi}{N} kn}$$

$$X(k) = X_1(k) + j\ X_2(n)$$

$$X_1(k) = X_{ER}(k) + X_{OI}(k)$$

$$j\ X_2(k) = j\ X_{ER}(k) + j\ j\ X_{OI}(k)$$

$$X_2(k) = -X_{OR}(k) + X_{EI}(k)$$

where subscripts O, E, R, I denote odd, even, real and imaginary respectively.

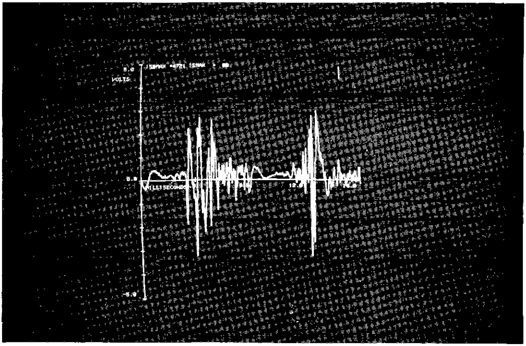
So, the composite result is separated with minimal computation time added since only addition and subtraction are required.

By exploiting the odd and even properties of the Fourier Transform, it was possible to reduce computation time by nearly half.

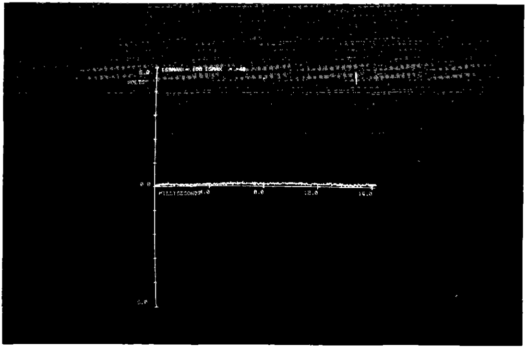
Averaged Periodogram

Figure 13 shows the filtered current data recorded and sampled over 2 cycles of the 60 Hz current, (a) during arcing, (b) no arcing present. Again, recall that the assumption of periodicity has been made. Figure 14 a and b show the result of Fourier Transforms of these cycles of data. If the filtered current data was in fact periodic instead of being rather random in nature, a study of one cycle of data would be sufficient to determine the time and frequency-domain characteristics,

Some estimate of how the energy delivered at the fault appeared

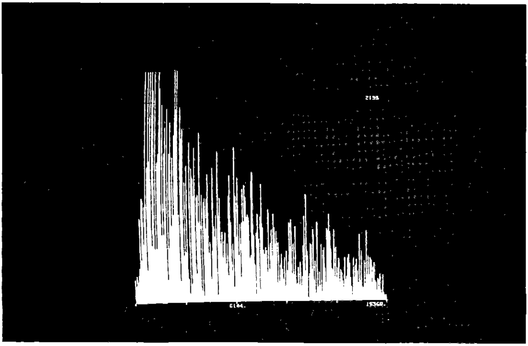


a) Waveform while arcing in progress

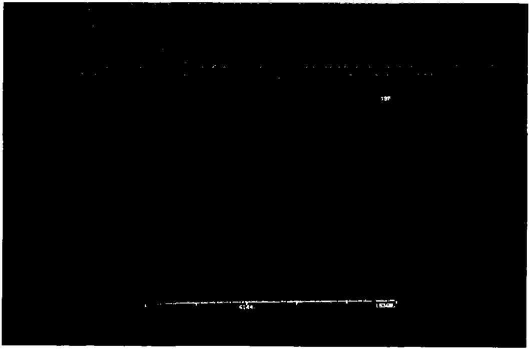


b) Normal System (unfaulted)

Figure 13 Waveforms of 2-65kHz raw data from TESCO field test 2-2-79 reproduced on graphics display (one cycle of data)



a) System with arcing fault (one cycle)



b) Normal System (one cycle)

Figure 14 FFT's of data from TESCO field test 2-2-79 (frequencies in Hz) in the frequency domain must be made. There are several techniques available which provide methods of making spectral power estimates from long records of data subdivided into smaller parts. Two of the simplest are described by Welch [11] and Bartlett [9].

Bartlett's procedure for generating a smoothed spectral estimate from a long record of data, is simply to divide the long record into short records. If the data sequence x(n), 0 to n, N-1 is divided into K segments of m samples each, so that N = kx then the segments become,

$$x^{(i)}(n) = x(n + im - m),\ 0 \leq n \leq M - 1,\ 1 \leq i \leq K$$

then K periodograms are computed using the FFT algorithm described earlier. The superscript (i) denotes which of the K periodograms is to be treated, as follows:

$$I_n{}^{(i)}(w) = \frac{1}{n} \sum_{n=0}^{N-1} x^{(i)}(n)\ e^{-jwn}\ {}^{2},\ 1 \leq i \leq k$$

then $I_n{}^{(i)}(w)$ is a series of K records of FFT results which may now be averaged.

$$B_{xx}(w) = \frac{1}{k} \sum_{i=1}^{k} I_n{}^{(i)}(w)$$

Bartlett further showed that the expected values of the spectral estimate $E[B_{xx}(w)]$ is in fact $E[In^{(i)}(w)]$ [9].

Welch enlarged the averaging type spectrum estimate procedure to include two additional capabilities. First, while Bartlett required that his K records be consecutive, statistically independent and non-overlapping, Welch shows that his estimator requires only stationality. In other words, Welch treats the case where records overlap. Secondly, Welch used non-tangent records (As Bartlett used) in an attempt to reduce the variance of his method.

Welch's overlapping technique also tends to reduce the variance of the spectrum estimate. As he states in [11] "If the total number of points N cannot be made arbitrarily large, and we wish to get a near maximum reduction in the variance out of a fixed number of parts then a reasonable recording is to overlap the signs by one half their length, i.e. to let D = L/z" He chooses to use the variance expected by using a data window described as having the shape $1 - t^2$: $-1 \leq t \leq 1$

$$\text{Var } \{P(fn)\} \approx \frac{11P^2(fn)}{9K}$$

However note that since the records are overlapped by one half their value, K is twice its precision, so the variance of the estimate becomes,

$$\text{Var } \{P(fn)\} \approx \frac{11}{18}\, p^2(fn)$$

Original analysis plans called for using overlapping data segments and Welch analysis due to the assumption concerning zero crossing maintained previously. However, since up to 200 periodograms can be generated from the data provided, little statistical significance could be added due to reduced variance of the spectral estimate. This is particularly true due to the round-off error and aliasing error inherent in the computation and digitizing of the data. So the spectral estimates which follow are modified Welch estimates in that they may overlap slightly, but are windowed by a rectangular window.

RESULTS AND DISCUSSION

It should be remembered that below 2 kHz, the data has been rather severely filtered to insure recorder compatibility with data levels.

Figure 13 is one typical cycle of filtered noise burst caused by arcing. Figure 14 is the FFT produced spectral analysis produced by that cycle of data. Figure 15 is an average of 200 such typical cycles. It can be stated with reasonable certainty that Figure 15 is a true representation of the high frequency portion of the frequency spectrum produced on Feeder 3551 at White Substation on 2-2-79. The spectrum estimate continues beyond the graph in a rather homogenous manner and was not plotted due to array space limitations of the minicomputer. The spectrum is non-zero at frequencies well above 30 kHz. It may or may not be representative of other feeders on TESCO system or on other distribution systems.

These results are presented in an effort to quantify the conducted frequency domain characteristics of high impedance arcing faults.

Figure 16 shows that at the substation at least, the arc current was nearly in phase with phase voltage. The lower trace resembles in form that predicted by Kaufman and Page [5] however, it corresponds more closely with the representation used by Beasley. [6]

As can easily be seen from Figures 18, the arcing produced considerable strike bursts at arc onset which corresponds to the beginning of 60 Hz current flow at the fault. However, noise continues to be produced in the current flow at the arc even after the arc is

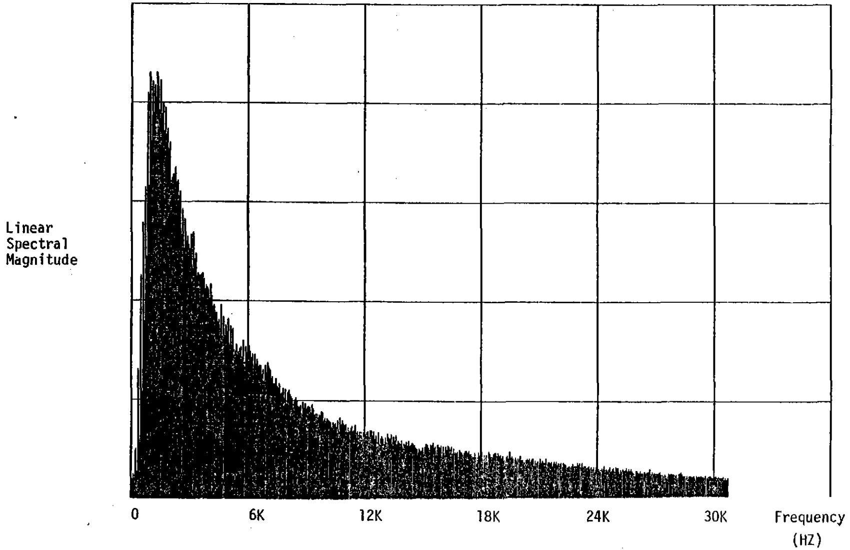


Figure 15 Average Arcing FFT (No Load / TESCO)

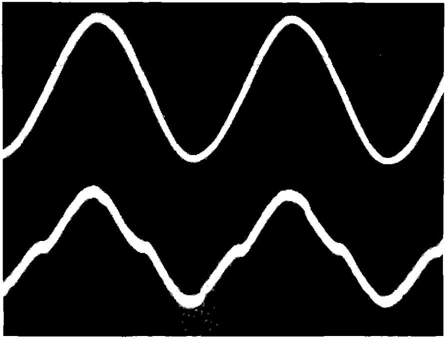


Figure 16a TESCO Arcing Test 2-2-79
Top: Phase voltage; bottom: unfiltered phase current

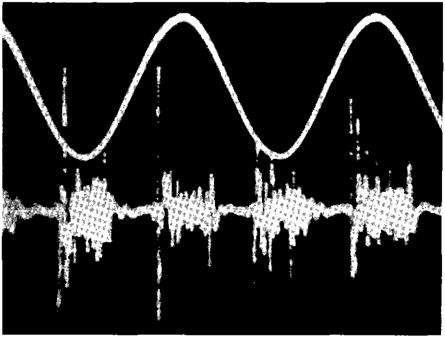


Figure 16b TESCO Field Tests 2-2-79
Top: Phase voltage; bottom: Phase current filtered

established.

It was observed that the arcs produced by the negative half cycle of voltage and those produced during the positive half cycle, tended to be independent. That is, an arc might form and produce considerable noise in the negative half cycle and not in the positive half cycle of voltage. It was further observed that the arc tended to last over several seconds exhibiting noise generation characteristics not unlike those exhibited by transformer in rush. That is, the first strike produced a significant transient, next strike was always lower, the next lower still. Further study of this phenomena might prove very interesting.

CONTINUING RESEARCH

Several arcing high impedance fault tests have been performed since the analysis of the February TESCO tests was begun. One of the more interesting ones was a series of tests run on a 23 mile long feeder serving a rather remote gold mine near Sante Fe, New Mexico. Fault currents 15-18 miles from the fault site were recorded and observed using the same techniques employed at TESCO. The noise observed at the substation was on the same order of magnitude as that produced by the arcs at TESCO. The noise propagated very well to the substation as long as no capacitor banks were on the line.

CONCLUSIONS

Based upon the preliminary testing at Rochester Gas and Electric, and subsequent testing at Texas Electric Service Company, this researcher has come to the following conclusions.

1. High impedance arcing faults produce high frequency noise in the fault current in the 2-40 kHz range.
2. The high frequency noise appears to be from 40-60 db below the predominately 60 Hz current level of the arc.
3. The high frequency noise bursts caused by the arcing fault propagated 0.6 miles at the TESCO test. In subsequent testing at New Mexico Public Service Company, the same phenomena was observed at a distance of 18 miles.
4. Grounded capacitor banks perform as expected in that they provide a path to ground for those high frequency currents produced by high impedance arcing faults.
5. The frequency spectrum shown in Figure 17 is representative of that which will be seen through substation CT's and distributed line parameters during an arcing fault.

Obviously, more work is required in this area. For instance, no effort was made to study in great detail other phenomena which also cause high frequency currents on distribution systems. In addition, there should be some thought given in the future to determine the extent of superposition of load and fault noise.

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APPENDIX

Filter/Amplifier Transfer Characteristics

Two identical filter amplifier systems were designed and constructed for this project. Both contained a 60 Hz notch filer, and analyptical high pass filter. In addition the gain of each system was variable from 0 to approximately 60 db.

At maximum gain setting, a measurement of the input noise was made. A 20 kHz square wave was attenuated by 96 db and introduced into the filter input. The output of the square wave generator was adjusted so that a 1 to 1 signal to noise ratio was achieved at the output of the filter. The output of the generator was measured to be 0.1 v pk to pk. The noise value at the input of the filter was then 1.0 vpp/6250(-96 db) = 16 uvpp.

The output of the signal generator was increased until distortion of a sinusoidal waveform was observed. The maximum signal input level was measured as 9 v pp/1250(-61 db) = 7.2 mvpp.

Thus the dynamic range for the system is

$$r(db) = 20 \log (\text{max in}/\text{min in}) = 20 \log (7.2\ mv/16\mu v) = 53\ db$$

Figure 16 is a plot of the frequency response for the notch filter. Figure 17 is the total frequency response of the filter system where 0 db is the system gain variable.

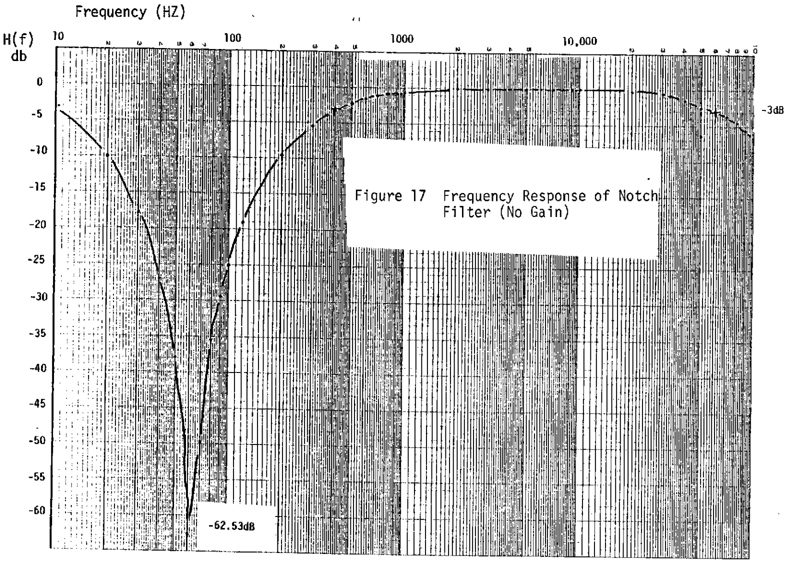

Figure 17 Frequency Response of Notch Filter (No Gain)

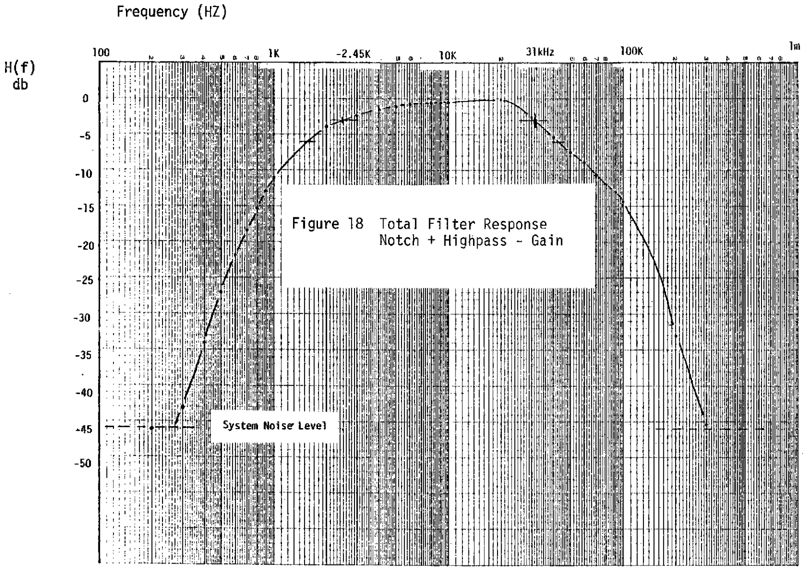

Figure 18 Total Filter Response
Notch + Highpass - Gain

Ampex PR-2200 Portable Instrumentation Recorder

General Description

The PR-2200 is versatile, light weight portable instrumentation recorder/reproducer. It is IRIG compatible, 1/2" and 1", and capable of up to 32 tracks. Signal electronics cover bandwidths up to 80 kHz FM, 300 kHz or 1 MHz Direct. Operator-oriented features include front-loaded electronics modules, front-operated controls, built-in FM calibration, and a self-monitoring diagnostic system that pinpoints location of a malfunction.

Tape Transport

Tape Speeds: Discrete by switch selection (or continuously) variable with external variable frequency oscillator in tach model). Direct activation between any of seven discrete speeds: 60, 30, 15, 7-1/2, 3-3/4, 1-7/8 and 15/16 inches per second. Tape speeds and forward and reverse drive directions are electrically selectable.

Tape Speed Accuracy: 0.15% maximum error, long term, with input power variations from 90-250 volts AC, 47-420 hz.

Fast Wind Time: Fast forward and reverse for 10 1/2 inch reel with 3000 feet of tape is less than 5 minutes. Tape is continuously under capstan control.

Time Base Error:

Tape Speed (ips)	Error in Microseconds
60	±0.8
30	±0.8
15	±1.0
7-1/2	±2.0
3-3/4	±4.0
1-7/8	±6.0
15/16	±12.0

Dynamic Skew: The relative time displacement of an event recorded simultaneously on any two adjacent tracks within the same head stack as observed on playback is less than:

Tape Speed (ips)	ΔTMicroseconds (Zero-to-Peak)
60	.4
30	.8
15	1.6
7-1/2	3.2
3-3/4	6.4
1-7/8	12.8
15/16	25.6

Flutter: Percent measured per IRIG 118-73 (2-Sigma)

Tape Speed (ips)	Flutter Bandwidth	Flutter
60	0.2Hz to 10kHz	.2
30	0.2Hz to 5kHz	.2

Tape Speed (ips)	Flutter Bandwidth	Flutter
15	0.2Hz to 2.5kHz	.3
7-1/2	0.2Hz to 1.25kHz	.32
3-3/4	0.2Hz to 625Hz	.45
1-7/8	0.2Hz to 312Hz	.50
15/16	0.2Hz to 312Hz	.65

Start Time: The start time required to meet flutter specifications at 60 ips is less than 3.0 seconds.

Stop Time: One second maximum to 60 ips.

Servo Reference Frequency: The servo reference frequency is 100 kHz ±0.01% at 60 ips and proportionately lower at the lower tape speeds. An external reference frequency can be supplied to the recorder for taken advantage of continuously variable speeds.

Heads: Comply with IRIG 106-73 for 7 tracks with 1/2 inch tape of 14 tracks with one-inch tape. Other available configurations include: 8, 14, 16 tracks with 1/2 inch tape and 16, 28, 32 with one-inch tape.

Tape: All specifications are based upon the use of Ampex recommended tape.

Signal Electronics

Direct System: All measurements per IRIG 118-73. Equalizers for all speeds are self-contained and electrically switchable.

Input Level: 0.25 to 10 volts RMS adjustable for 20 K ohm in put impedance and 0.25 to 3.0 volts RMS for 75 ohm input impedance.

Input Impedance-Selectable: 75 of 20,000 ohms unbalanced to ground.

Intermediate Band:

Tape Speed (ips)	Bandwidth (±3 dB)	S/N (RMS Signal to RMS Noise) 14 Ch	28 Ch
60	300Hz to 300kHz	40	37
30	150Hz to 150kHz	40	37
15	100Hz to 75kHz	40	37
7-1/2	100Hz to 38kHz	38	35
3-3/4	100Hz to 19kHz	38	35
1-7/8	100Hz to 10kHz	38	35
15/16	100Hz to 5kHz	38	35

Intermediate Band Output Level: Adjustable to 1.0 volts TMS across 600 ohms.

Wideband:

Tape Speed (ips)	Bandwidth (±3 dB)	S/N (RMS Signal to RMS Noise) (dB) 14Ch	28Ch
60	400Hz to 1Mhz	24	21
30	400Hz to 500kHz	24	21
15	400Hz to 250kHz	24	21
7-1/2	400Hz to 125kHz	24	21
3-3/4	400Hz to 62.5kHz	24	21
1-7/8	400Hz to 31.2kHz	24	21
15/16	400Hz to 15.6kHz	24	21

Wideband Output Level: Adjustable to 1.0 volt RMS across 75 ohms.

FM System: FM electronics contain built-in filters for all nine frequency bands. Any seven contiguous speeds can be electrically switchable.

Input Impedance: Selectable 75 or 20,000 ohms unbalanced to ground.

Input Sensitivity: 0.5 volt peak to 25 volts peak adjustable for 20K ohm input impedance and 0.5 to 5.0 volts peak for 75 ohm input impedance.

DC Drift: Less than ±5% of full deviation over a 20°F temperature change in eight hours, after 15 minute warm-up.

DC Linearity: ±0.5% of total deviation.

Low Band:

Tape Speed (ips)	Center Carrier Freq (kHz)	Bandwidth (within 1 dB)	S/N (RMS) Signal to RMS Noise)(dB) 14Ch	28Ch
60	54	DC to 10kHz	53	51
30	27	DC to 5kHz	53	50
15	13.5	DC to 2.5kHz	51	49
7-1/2	6.75	DC to 1.25kHz	49	47
3-3/4	3.375	DC to 625 Hz	47	45
1-7/8	1.6875	DC to 312 Hz	47	45
15/16	.847	DC to 156 Hz	44	42

*Total Harmonic Distortion for 60 ips no greater than 1.5%.

Immediate Band:

Tape Speed (ips)	Center Carrier Freq (kHz)	Bandwidth (within 1 dB)	*Total Harmonic Distortion	S/N (RMS) Signal to RMS Noise (dB) 14Ch	28Ch
60	108	DC to 20kHz	1.2%	52	50
30	54	DC to 19kHz	1.2%	50	48

Tape Speed (ips)	Center Carrier Freq (kHz)	Bandwidth (within 1 dB)	*Total Harmonic Distortion	S/N (RMS) Signal to RMS Noise (dB) 14Ch	28Ch
15	27	DC to 5kHz	1.2%	50	48
7-1/2	13.5	DC to 2.5kHz	1.2%	48	46
3-3/4	6.75	DC to 1.25kHz	1.5%	46	44
1-7/8	3.375	DC to 625 Hz	1.5%	44	42
15/16	1.6875	DC to 312 Hz	1.5%	42	40

Wideband Group 1:

Tape Speed (ips)	Center Carrier Freq (kHz)	Bandwidth (within 1 dB)	*Total Harmonic Distortion	S/N (RMS) Signal to RMS Noise (dB) 14Ch	28Ch
60	216	DC to 40kHz	1.2%	50	48
30	108	DC to 20kHz	1.2%	48	46
15	54	DC to 10kHz	1.2%	48	46
7-1/2	27	DC to 5kHz	1.2%	47	45
3-3/4	13.5	DC to 2.5kHz	1.5%	45	43
1-7/8	6.75	DC to 1.25kHz	1.5%	43	41
15/16	3.375	DC to 625 Hz	1.5%	40	38

*For 14 Channel Systems.

2X Wideband Group 1:

Tape Speed (ips)	Center Carrier Freq (kHz)	Bandwidth (within 1.5 dB)	*Total Harmonic Distortion	S/N (RMS) Signal to RMS Noise (dB) 14Ch	28Ch
60	432	DC to 80kHz	1.5	47	45
30	216	DC to 40kHz	1.5	46	44
15	108	DC to 20kHz	1.5	45	43

Tape Speed (ips)	Center Carrier Freq (kHz)	Bandwidth (within 1.5 dB)	*Total Harmonic Distortion	S/N (RMS) Signal to RMS Noise (dB) 14Ch	28Ch
7-1/2	54	DC to 10kHz	1.5	44	42
3-3/4	27	DC to 5kHz	1.5	42	40
1-7/8	13.5	DC to 2.5kHz	1.8	40	38
15/16	6.75	DC to 1.25kHz	1.8	-	-

Output Level: Adjustable to 1 volt RMS across 75 ohms (±40% deviation.

Power Requirements

Voltage: 90-135 VAC or 185-250 VAC, switch selectable.

Frequency: 47 to 63Hz single phase, convertible with fan change to 380-420Hz single phase.

Power Consumption: No more than 400 watts for a complete 14 track FM record/reproduce system, excluding monitor accessories and non-standard options.

Environment

Temperature: Operating: 5°C to +52°C; Non-operating: -20°C to +71°C.

Altitude: Operating: to 20,000 feet (6096 meters); non-operating: to 50,000 feet (15,000 meters).

Relative Humidity: The system, excluding tape limitations, will operate from 5% to 90% without condensation. For tape limitations see appropriate tape manufacturer's specification limits.

Physical Characteristics

Size: In portable case: 10" deep (25.4 cm), x 17-3/4" wide (45.1 cm) x 26-1/4" high (66.7 cm).

Weight: In portable case: 86 lbs (39kg) for full 7 track record/reproduce system; 95 lbs (43kb) for full 14 track record/reporduce system.

Pearson Current Transformers

Wideband and Pulse Current Transformer
Pearson Electronics, Inc.

Model 411-Specifications:

1. Output Voltage/Ampere - 0.1 (+1%, -0%, initial pulse response).
2. Rise Time - 10 nonoseconds for a step-function current pulse.
3. Droop - 0.5% per milli-second for top of a square wave or pulse.
4. Pulse $I\tau$ = 0.19 ampere second max. (Small bias current in secondary needed for values approaching this max.
5. Frequency Response - 1Hz to 35MHz at 3dB points.
6. Sine Wave I/f - 0.59 amps peak per Hz.
7. Current - 5,000 amps peak, 50 amps rms maximum.
8. Insertion Resistance - 0.0002 ohm.
9. Output Connection - BNC receptable (UG-290A/U.
10. Cable - 50 ohm cable such as RG-58C/U.
11. Cable Termination - typical oscilloscope input (e.g.,

1 megohm and 20pF in parallel).

12. Overall Dimensions - 2" OD x 1" thick, 1/2" ID.

A photograph of the Pearson Current Transformers in field use is shown in Figure 7a.

Computer

The Digital Equipment Corporation PDP-11/34 minicomputer provides the capability for analysis of recoeded data. The specifications of the system are as follows:

Operating System: RT-11 (Single user)

Available Memory: 28K words

Fixed Disks (2): RK05-J (2.5 Mbytes/disk)

Removeable Disk: RK05 (Decpak - 1.25 Mbytes/disk)

Software: FORTRAN Assembler-compiler

MACRO (Machine lanuage)

Text Editor

Disk Handlers

VITA

Thomas James Talley was born in Fort Worth, Texas on October 30, 1945, the son of Dr. and Mrs. Paul J. Talley of College Station. After attending high school in Pine Bluff, Arkansas, Mr. Talley served 4 years in the United States Air Force as a radar and electronics counter measures warefare techniques instructor. He then attended Texas A&M University majoring in Electrical Engineering where he was awarded the B.S. Degree in December 1971.

Mr. Talley was employed by Texas Electric Service Company, an electric utility company in Fort Worth, Texas until he returned to Texas A&M in the spring of 1977 to work towards a Master of Science degree in Electrical Engineering.

Mr. Talley's permanent home address is 5713 Wharton, Fort Worth, Texas 76133.

③ 478 w/white
1204