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BEHAVIOUR OF LOW FREQUENCY SPECTRA DURING ARCING FAULT AND SWITCHING EVENTS

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ABSTRACT - Distribution feeder faults modulate primary current and generate noise through arcing phenomena. The variation and behaviour of selected low frequencies during fault conditions are herein presented. These are contrasted to normal events such as feeder switching and capacitor bank operations. Recorded field data has been analyzed and is statistically presented in the paper. Specific behaviour characteristics such as arc duration, arc repetition rate, and magnitude of low frequency spectra are presented. Comparisions are made for different soil types and conditions.

INTRODUCTION

High impedance faults can be described as those distribution feeder faults that do not draw sufficient fault current to be detected by conventional protective devices such as phase overcurrent and/or ground relays. Such faults may be caused by a downed conductor on a poorly conducting surface. Often, arcing is associated with these faults which poses a potential hazard to public safety. It is therefore important that these faults be detected quickly and the faulted feeder isolated. There has been considerable interest in solving this problem resulting in several major research efforts.

Phadke [1] has suggested a microprocessor based digital relaying scheme in which changes in the positive, negative and zero sequence components of the fundamental power frequency are monitored continuously in real time. The presence of a high impedance fault is detected based on changes in the ratio of the symmetrical components. Balser [2] suggested a technique which monitors the imbalance in the fundamental, third and fifth harmonic feeder currents and performs a statistical evaluation of the present imbalance relative to the past imbalance. Using hypothesis testing, the presence of a fault is detected if the chi-square test statistic exceeds a pre-determined threshold value. Graham [3] suggests monitoring the distribution feeder input impedance at high frequencies in the range 50 KHz to 100 KHz. Russell [4,5] suggested monitoring the energy of high frequency components in the range 2 KHz to 10 KHz to detect arcing faults. There are other significant schemes including the ratio ground relay resulting from research at Westinghouse and PP&L. [6,7]

This paper presents the behaviour of several low frequency spectra during arcing fault and normal switching conditions. It has been observed that the arcing phenomena associated with high impedance faults causes certain low frequency spectra to change in magnitude and phase from pre-fault conditions. The frequency spectra selected for investigation were :

1. 30 Hz
2. 90 Hz
3. 150 Hz
4. 210 Hz
5. 270 Hz
6. 330 Hz
7. 60 Hz
8. 120 Hz
9. 180 Hz
10. 240 Hz
11. 300 Hz
12. 360 Hz

Of these spectra, the first six comprise the 'in-between' harmonic frequencies and the last six, the harmonics of the power frequency. The different events that were investigated to characterize the behaviour of the above spectra included :

1. Arcing faults on different soil conditions.
2. Arcing faults with capacitor bank switched off.
3. Arcing faults with capacitor bank switched on.
4. Arcing faults with air switch operations.
5. Air switch operations.
6. Capacitor bank operations.
7. Load tap changer operations.

The first four events are fault conditions on distribution feeders and the last three are normal switching events. The behaviour of the magnitude of the low frequency spectra for the events listed above is the primary subject of this paper.

DATA ACQUISITION AND PROCESSING

A frequency domain analysis was performed for each event investigated using certain digital signal processing techniques. Analog recordings of waveforms were first converted to digital domain by sampling them at a suitable rate. The sampling rate chosen must take into consideration the maximum frequency of interest and also satisfy the Nyquist sampling rate in order to avoid aliasing effects. The maximum frequency of interest being 360 Hz, the analog signal was first bandlimited to 360 Hz by an analog bandpass filter of passband range 0~360 Hz. The bandlimited signal was then sampled at a rate of 960 Hz using a 12 bit A/D converter.

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In order to extract the specific frequency of interest, the sampled data was further processed by filtering with two separate multi-bandpass linear phase Finite Impulse Response (FIR) digital filters - one for filtering the 'in-between' harmonics and the other for filtering the harmonic frequencies. The Parks - McClellan design of linear phase FIR digital filters was adopted to design the two digital filters. A linear phase filter is necessary to preserve the phase characteristics of the analog signals. The frequency response of these filters is shown in Figure 1a for the 'in-between' harmonics and Figure 1b for the harmonic frequencies. A passband width of 10 Hz about the center frequency was used for each passband in the digital filter design.

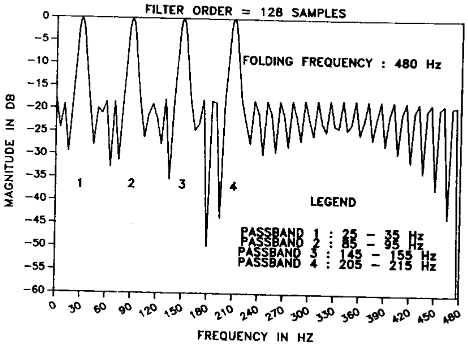

Figure 1a. Frequency response of in-between harmonic digital filter.

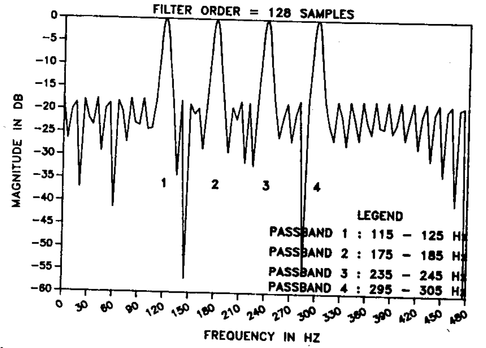

Figure 1b. Frequency response of harmonic digital filter.

Next, the frequency spectra of the filtered data was obtained by performing a Fast Fourier Transform of the filter output. The time domain signal (sample amplitude vs. sample number) was reconstructed from the sampled data and plotted as shown in Figure 2. The frequency spectra of interest were also plotted as a function of time in order to determine their magnitude variation. Examples are shown in Figure 3a for 90 Hz component and Figure 3b for the 180 Hz component. The start and end of an arcing 'burst' can be determined from the frequency plots by comparing them with the corresponding time domain waveform. This procedure was repeated in order to obtain the variation of each frequency spectrum for all of the seven events that were investigated.

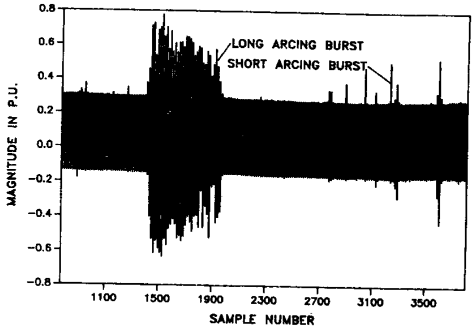

Figure 2. Arcing fault waveform.

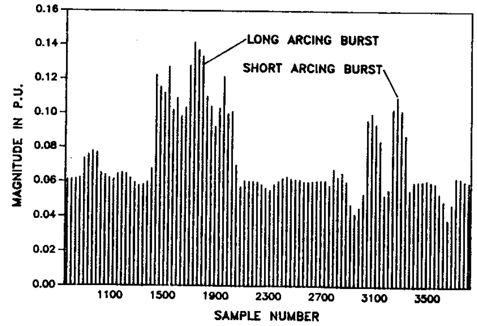

Figure 3a. Variation of 90 Hz spectrum during arcing fault.

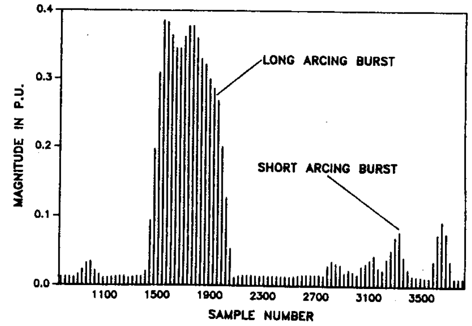

Figure 3b. Variation of 180 Hz spectrum during arcing fault.

DATA ANALYSIS

In order to analyze the data, bar plots were created for each event indicating the change in magnitude of the spectra from pre-event to an event condition. These were contrasted to the maximum values attained by the spectra during pre-event and event conditions. The magnitudes shown reflect the average of the values attained by the spectra during several identical tests conducted for each event.

Figure 4 shows the relative change in average magnitude of several 'in-between' harmonic and harmonic frequencies for arcing tests performed during switching operations. The plot indicates that all the frequencies show an increase of

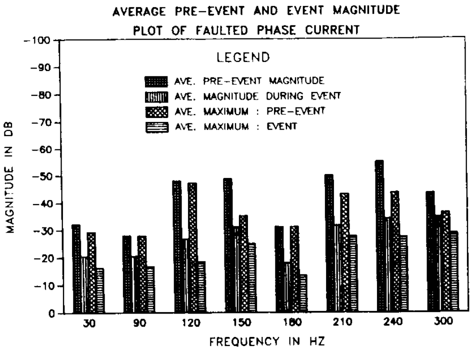

Figure 4. Change in spectral magnitude during switching conditions.

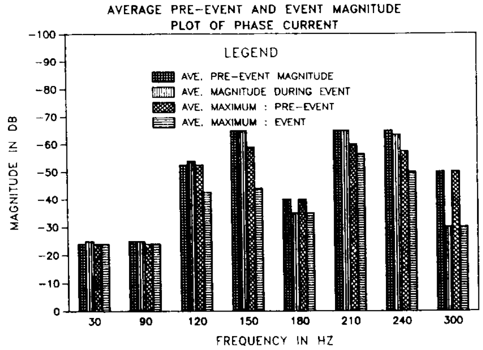

Figure 5. Change in spectral magnitude during capacitor bank operation.

at least 10 db in magnitude under arcing fault conditions. The 150 Hz and 210 Hz components indicate the maximum change for the 'in-between' harmonics (~ 20 db). All the harmonic frequencies show an increase of at least 15 db under fault conditions. The 120 Hz and 240 Hz components indicate the maximum change for harmonic frequencies (~ 25 db).

Figure 5 shows the behaviour of the low frequency spectra for a capacitor bank operation. It is observed that the 'in-between' harmonic frequencies remain fairly constant during the switching operation whereas the harmonic frequencies show a greater change in magnitude. This is especially true in the case of 180 Hz and the 300 Hz component. Figure 6a shows the variation of the third harmonic during a capacitor bank operation. Figure 6b shows the variation of the fifth harmonic for the same operation. It is observed from these figures that both the 180 Hz and the 300 Hz spectra show a step increase in magnitude which persists the entire duration the capacitor bank is switched on. On the other hand, the 'in-between' harmonics do not indicate such phenomena. Their magnitude change is more of an impulse nature lasting for a short duration of time due to the transients of the switching operation itself. In the case of other switching operations such as an air switch or a load tap changer, such anomolies were not observed. Figure 7 shows the behaviour of the low frequency spectra for a load tap changer operation and Figure 8 for an air switch operation.

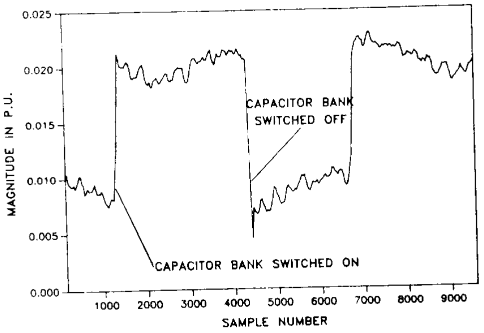

Figure 6a. Variation of 180 Hz spectrum for capacitor bank operation.

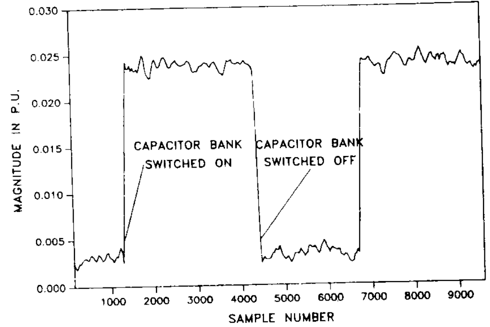

Figure 6b. Variation of 300 Hz spectrum for capacitor bank operation.

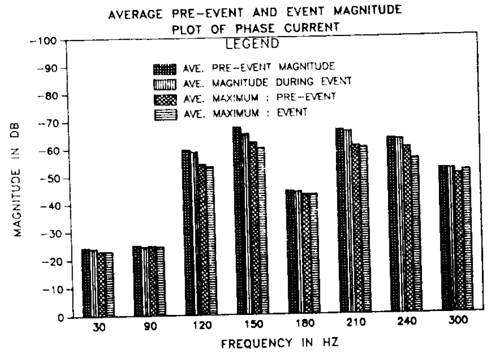

Figure 7. Behavior of low frequency spectra for load tap changer operation.

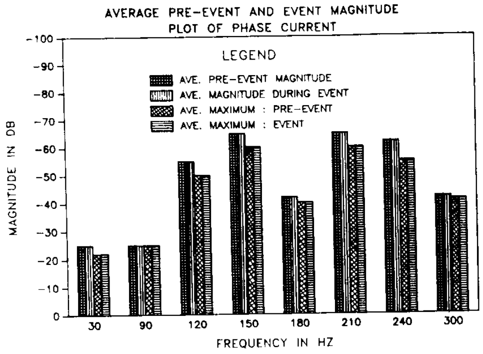

Figure 8. Behavior of low frequency spectra for air switch operation.

STATISTICAL ANALYSIS

A statistical analysis was performed to investigate the dependency of the low frequency spectra magnitude upon arcing burst duration and soil conditions. Arcing fault data was obtained from three separate test locations representing different soil conditions. In test site 1 the arcing tests were conducted on wet soil, in site 2 they were conducted on dry soil and on sandy soil in site 3. Each site data record was then subdivided into at least three different clusters, each cluster comprising arcing bursts of approximately the same burst duration. The different arcing burst durations typically considered comprised 'short' duration bursts (1 ~ 3 cycles), 'medium' duration bursts (5 ~ 20 cycles) and 'long' duration bursts (> 20 cycles). At least 50 different arcing events were considered to comprise a single cluster making a total of at least 150 events investigated at each site location.

Magnitude Evaluation

A frequency domain analysis was performed for the individual events in a cluster to determine the relative change in magnitude of the various spectra from pre-fault to fault conditions. Next, the mean and standard deviation of the magnitude change was determined for each frequency spectrum by averaging over all the 50 odd events in the cluster and determining the variation about the mean. This procedure was repeated for each of the clusters at the three test site locations and the statistics indicated by bar plots. Figure 9a shows the average relative increase in magnitude of the spectra due to short duration arcing bursts on wet soil conditions. The standard deviation indicates the dispersion of the magnitude about the mean for short arcing bursts. It is seen that the 'in-between' harmonic frequencies indicate a large dynamic change in magnitude (20 ~ 50 times greater) under arcing fault conditions. However, this change is very random as indicated by the large standard deviation. This means that even though the 'in-between' harmonics show a large percentage increase in magnitude, the dispersion about the mean is also large thereby indicating that the precise amount of increase is unpredictable. The harmonic frequencies however show a reliable change in average magnitude as indicated by their smaller value of standard deviation. This suggests that the relative change in magnitude is consistent for the different events comprising the cluster.

Figure 9b shows the relative change in magnitude of spectra for medium duration bursts on wet soil conditions. In this case, it is seen that the change in magnitude of the 'in-between' harmonics is more reliable as indicated by their low value of standard deviation. Figures 10a & b show similar plots for arcing faults on dry soil conditions. Again, the 'in-between' harmonics show randomness for short arcing bursts as compared to medium duration bursts. Figures 11a &b show the relative changes in spectra magnitude when arcing tests were conducted on sandy soil.

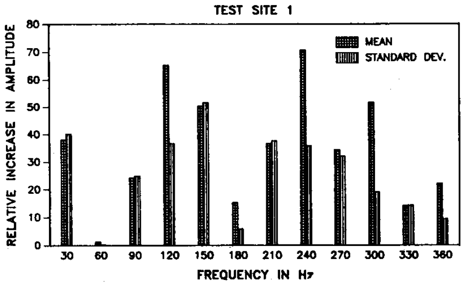

Figure 9a. Statistics of short duration bursts on wet soil.

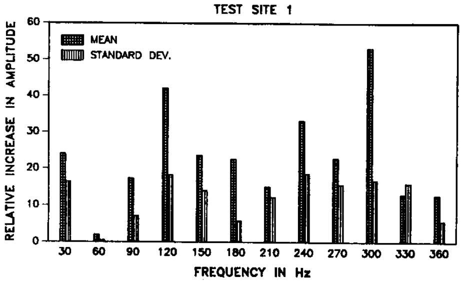

Figure 9b. Statistics of medium duration bursts on wet soil.

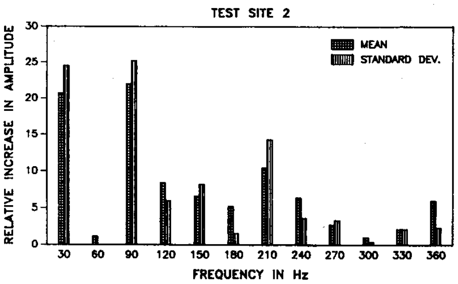

Figure 10a. Statistics of short duration bursts on dry soil.

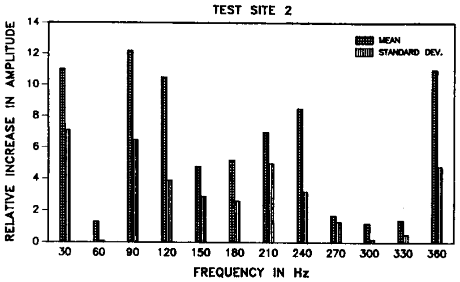

Figure 10b. Statistics of medium duration bursts on dry soil.

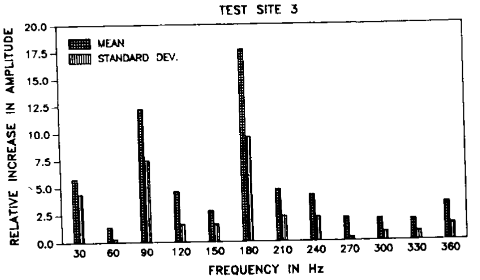

Figure 11a. Statistics of medium duration bursts on sandy soil.

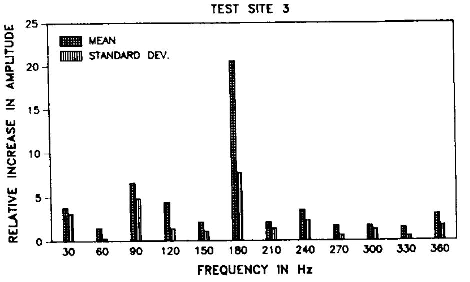

Figure 11b. Statistics of long duration bursts on sandy soil.

Summarizing, it can be said that the 'in-between' harmonic frequencies are random noise spectra which show a large relative change in magnitude under arcing fault conditions. The change in magnitude is more predictable for medium and long duration arcing bursts as compared to short bursts. The harmonic frequencies show a more consistent change in magnitude without respect to burst duration.

Results of Correlation by soil type

The dependency of arcing burst duration on soil conditions was also investigated. Figure 12a shows the distribution of arcing burst duration on wet soil conditions. It is seen that a large percentage of the events comprised short arcing bursts typically 2 or 3 cycles in duration. Figure 12b shows the distribution of arcing burst duration on dry soil conditions. On

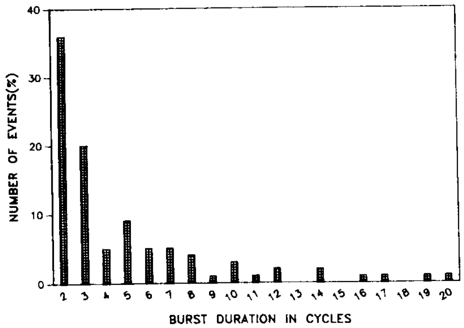

Figure 12a. Distribution of burst duration on wet soil.

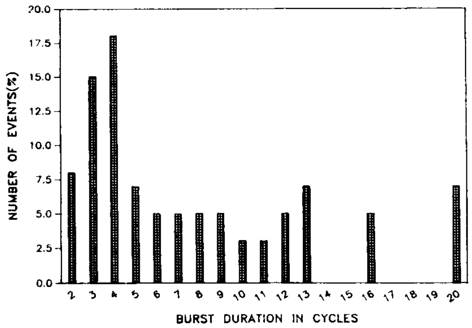

Figure 12b. Distribution of burst duration on dry soil.

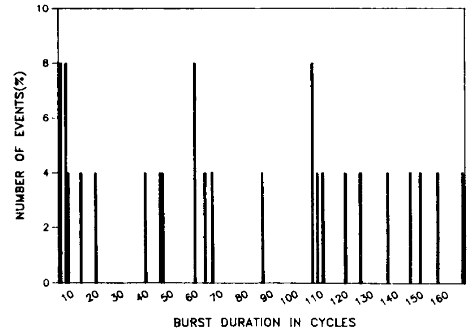

Figure 12c. Distribution of burst duration on sandy soil.

Table 1. Statistics of low frequency spectra.

TEST SITE	Ft.Worth, Texas			Kluge, Texas			Embudo, New Mexico		
SOIL TYPE	wet soil			dry soil			sandy soil		
BURST LENGTH	short			medium			long		
OFF-DURATION	short			medium			long		
MEAN and STANDARD DEVIATION of magnitude st.dev inside ( )									
	2-4 cycles	5-10 cycles	11- cycles	2-6 cycles	7-13 cycles	15- cycles	6-47 cycles	60-120cycles	130- cycles
60 Hz	1.4(0.2)	1.7(0.3)	2.0(0.5)	1.1(0.0)	1.3(0.1)	1.3(0.1)	1.4(0.3)	1.5(0.3)	2.0(0.3)
120 Hz	65.3(36.7)	47.7(29.4)	42.1(18.2)	8.4(6.0)	12.4(12.2)	10.5(3.9)	4.6(1.6)	4.4(1.4)	6.3(1.2)
180 Hz	15.3(5.9)	21.4(7.6)	22.6(5.8)	5.2(1.5)	6.3(1.7)	5.2(2.6)	17.7(9.6)	20.6(7.7)	32.3(7.4)
240 Hz	70.8(35.9)	43.6(25.7)	33.2(18.6)	6.4(3.6)	8.3(3.9)	8.5(3.2)	4.2(2.2)	3.5(2.3)	6.0(1.9)
300 Hz	51.7(19.1)	58.9(20.2)	53.2(16.8)	1.0(1.9)	1.9(2.2)	1.2(0.2)	2.0(0.8)	1.7(1.3)	3.0(1.4)
360 Hz	22.1(9.4)	17.5(8.4)	12.6(5.7)	6.0(2.3)	9.8(5.2)	11.0(4.8)	3.4(1.5)	3.0(1.7)	4.3(1.9)
30 Hz	38.7(40.1)	25.3(29.2)	24.0(16.4)	20.7(24.5)	13.4(11.2)	11.0(7.1)	5.8(4.4)	3.8(3.1)	5.0(4.0)
90 Hz	24.2(24.9)	15.5(18.0)	17.3(7.1)	22.0(25.2)	15.0(12.2)	12.2(6.5)	12.2(7.5)	6.6(4.8)	7.7(6.9)
150 Hz	50.5(51.6)	26.0(27.1)	23.6(14.0)	6.6(8.2)	3.7(4.3)	4.8(2.9)	2.8(1.6)	2.1(1.1)	3.3(1.7)
210 Hz	36.7(37.7)	20.0(23.7)	15.0(12.2)	10.5(14.3)	8.7(5.1)	7.0(5.0)	4.7(2.3)	2.1(1.4)	2.8(1.3)
270 Hz	34.4(32.1)	19.2(16.8)	22.8(15.6)	2.7(3.3)	2.3(2.2)	1.7(1.3)	2.1(0.3)	1.7(0.6)	1.7(1.0)
330 Hz	14.2(8.8)	8.8(9.5)	12.9(15.9)	2.1(2.1)	2.0(1.3)	1.4(0.5)	1.9(0.8)	1.5(0.5)	1.6(0.7)

dry soil, the arcing usually lasted for 4 to 20 cycles and most of the events fell in this category. Figure 12c shows the distribution on sandy soil condition. Here it is observed that the arcing persists longer, usually greater than 20 cycles in duration. These plots indicate that on wet soil conditions, arcing is of very short duration. On dry soil, the arcing persists longer and these type of bursts can be classified as medium duration bursts. On sandy soil, the bursts are of very long duration and can be categorized as long duration bursts. The statistics of the relative magnitude changes on the three soil conditions are indicated in Table 1.

The period duration between successive arcing bursts was also investigated on the three different soil types and their distribution plotted as a function of the soil type. Figure 13a shows the distribution of the interval between successive arcing bursts on wet soil. On comparison with Figure 12a, it is observed that the interval between bursts has a distribution similar to the distribution of the burst duration itself. This indicates that on wet soil, the arcing bursts are mostly of short duration with short intervals between successive bursts. Figure 13b shows the distribution of the 'off-interval' between successive arcing bursts on dry soil. Again, on comparision with Figure 12b, it is observed that the 'off-intervals' have a distribution similar to the burst duration, i.e. on dry soil conditions, the arcing is of medium duration (4 ~ 20 cycles) separated by 'off-intervals' of similar duration. Figure 13c shows the distribution of the 'off-interval' between successive bursts on sandy soil. On comparision with Figure 12c, it is seen that the 'off-intervals' show a distribution similar to the arcing duration on sandy soil.

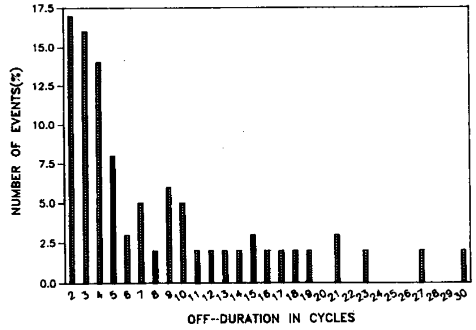

Figure 13a. Distribution of interval between successive bursts on wet soil.

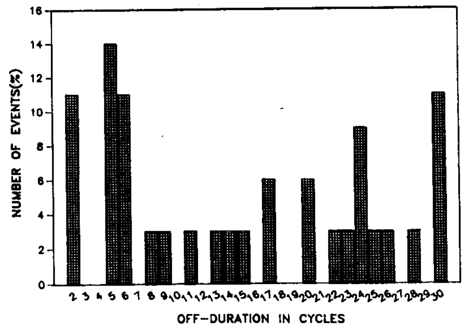

Figure 13b. Distribution of interval between successive bursts on dry soil.

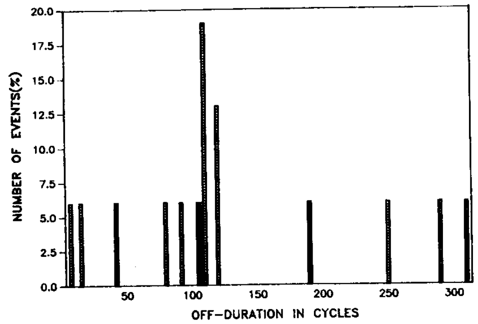

Figure 13c. Distribution of interval between successive bursts on sandy soil.

Finally, the dependency of the magnitude of the 'in-between' harmonics on soil conditions was investigated. The relative magnitude change of several 'in-between' spectra at each site was plotted as shown in Figure 14. As seen from the figure, the magnitude of 'in-between' spectra depends on soil type. The change in magnitude is higher on wet soil as compared to dry or sandy soil. This is possibly due to the initial higher conductivity of wet soil. The magnitude dependency of harmonic frequencies on soil type were not investigated because these frequencies were shown to depend and vary as a function of other factors including system impedance and loading.

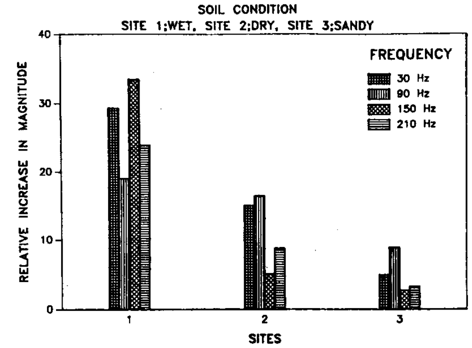

Figure 14. Dependency of spectral magnitude on soil type.

RESULTS QUALIFICATION

The data presented has proved of great value to TAMU researchers investigating high impedance faults. The nature of these faults is more clearly understood from this data analysis. Since several other research teams are studying the problem using magnitude, phase and time domain characteristics at low frequencies, it was felt that the data should be made available. The data comes from the TAMU database, probably the most comprehensive in existence. However, we are constantly concerned that more data and data analysis for different fault scenarios and feeder conditions will result in modified conclusions or results. Those using this data should recognize it is statistical and only absolutely valid for the specific faults that were studied. In spite of this, we believe the results are generally true for many faults and do give an insight into fault behaviour.

CONCLUSION

The behaviour of several low frequency spectra was investigated for arcing faults and normal switching events. It was observed that the 'in-between' harmonic frequencies can be used to discriminate the presence of arcing faults on distribution feeders. More important, these frequencies can be used to distinguish arcing faults from capacitor bank switching operations. The harmonic frequencies indicate reliable increase in magnitude during arcing fault conditions. However, they are not immune to switching and capacitor bank operations.

Statistical analysis was performed to study the behaviour of the low frequency spectra on different soil conditions. It was found that the magnitude of 'in-between' harmonics depend on burst duration and soil condition. The change in magnitude was found to be higher for short duration arcing bursts and on wet soil conditions. Finally, the distribution of arcing burst duration and the interval between successive arcing bursts was determined on different soil conditions. It was observed that the arcing bursts were mostly of short duration seperated by short intervals of inactivity on wet soil, of medium duration separated by similar intervals of inactivity on dry soil and of long duration separated by long intervals of inactivity on sandy soil.

ACKNOWLEDGEMENT

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BIOGRAPHY

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He is presently a research assistant in the Department of Electrical Engineering at Texas A&M University.

Discussion

Kevin A. Pierce (Georgia Power Company, Atlanta, GA): This investigation into the low frequency spectra behavior on distribution circuits during normal switching and during high impedance faults is very revealing. It would be interesting to see similar tests made and statistical data analyses performed on high impedance asphalt, concrete, and tree-staged faults using the three soil types. Possibly this would lead to even stronger conclusions about the behavior of in-between harmonics during high impedance faults.

Perhaps the authors could clarify or add:

1) how the in-between harmonics of 270 Hz and 330 Hz are extracted using the FIR digital filter based on Fig. 1A, and how the harmonics of 60 Hz and 360 Hz are extracted by the FIR filter based on Fig. 1B?
2) how the test faults were staged and if these faults were detected by the protective relays with normal settings applied?

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Adly A. Girgis (Clemson University, Clemson, SC): The authors are to be congratulated for their efforts to establish new concepts in the detection of high impedance faults. We would like to offer the following comments and questions for the authors' consideration.

1) The authors implemented two FIR filters, one for in-between frequencies and the other for harmonic frequencies. The attenuation of both filters is about 20–25 dB. This means that the fundamental frequency is reduced by a factor of about ten in the output of the filters. Considering that the fundamental frequency is the strongest signal in many of the cases studied, in conjunction with the transient response of the filters, the frequency spectra of the filtered signal may incorrectly indicate in-between frequencies and/or even harmonics.

Another factor is the frequency deviation of the fundamental frequency. We have been involved in many field test cases using actual recorded data. In most of these cases the fundamental frequency varies between 59.95–60.05 Hz. Such frequency deviation leads to leakage [A] in the fast Fourier transform results of the outputs when the FFT algorithm assumes the fundamental frequency to be 60 Hz. Have the authors considered these factors?

2) What is the probable percentage increase of the in-between frequencies that can be contributed by transient response during arcing faults?
3) Would the authors comment on the observation time (how many cycles) used in the fast Fourier transform program?

Once again, we encourage the authors to continue in their interesting investigation.

Reference

[A] A. A. Girgis and F. M. Ham, "A quantitative study of pitfalls in the FFT," *IEEE Trans. Aerosp. Electron. Syst.*, vol. AES-16, no. 4, pp. 434–439, July 1980.

Manuscript received August 12, 1987.

B. D. Russell and **R. Chinchali:** We thank the discussers for the interest they have shown in our paper.

Dr. Girgis shares our belief that the close proximity of some in-between harmonics (especially 30 Hz and 90 Hz spectra) to a strong fundamental signal may result in incorrect evaluation of these frequencies. We feel that monitoring of all frequencies (in-between, even, or odd harmonics) should be done after notching the 60-Hz signal from the input signal. A typical signal conditioning procedure would be to first band-limit the input signal appropriately with a front-end analog band-pass filter and then attenuate the fundamental frequency by at least 40–60 dB. The digital filtering is performed after this stage for extracting the various parameters.

Another point raised by Dr. Girgis concerns the spectral leakage effect inherent in the discrete Fourier transform. This leakage results either from a deviation in the fundamental frequency or from a time-domain truncation of a periodic function at other than a multiple of the fundamental period [1]. To mitigate the leakage effect two procedures have been adopted: first, a zero-crossing detector is used to have a fixed starting point on each fundamental cycle of the input signal whereby a sample set corresponding to a multiple of the fundamental frequency can be derived, and second, by employing a time-domain truncation function of smaller sidelobe characteristic than that of the sin(*f*)/(*f*) response of a rectangular window. One particularly good truncation function is the Hanning window which provides an optimum trade-off between mainlobe width and sidelobe attenuation [2].

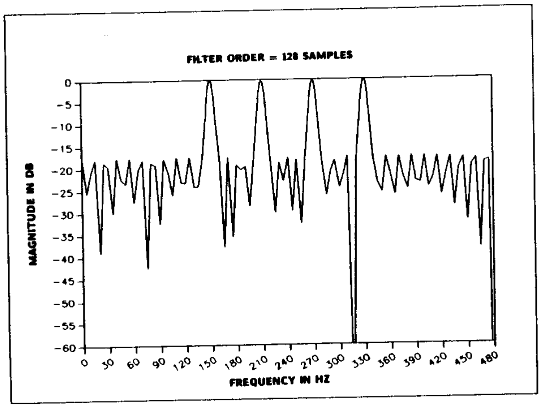

Fig. 1. In-between harmonic digital filter.

Our analysis indicates that the relative increase in magnitude of the in-between harmonics depends on soil type (Fig. 14 in the paper). An average increase of 10–15 dB from the prefault level was observed in most of the cases. In our analysis we sampled each staged fault test recording at 960 Hz for a duration of 20 s. A 32-point FFT was then performed on the sampled data to obtain an FFT resolution of 30 Hz.

We agree with Mr. Pierce that more testing and statistical analysis is necessary to substantiate the use of in-between harmonics as potential fault parameters, especially for those faults involving concrete, asphalt, or macadem.

The digital filter shown in Fig. 1 was used for extracting 270-Hz and 330-Hz components. Figs. 1a and 1b of the paper are typical of that used for various frequencies. The 60-Hz and 360-Hz components were extracted by similar filters.

Several hundred faults were staged with the cooperation of four utilities for these studies. The faults were staged under as normal conditions as possible with no attempt to limit fault current or create abnormal circumstances. The protective relays and fuses in place on the test feeders generally did not detect the staged faults. In fact, 90 percent of the faults staged remained undetected by the protection systems in place. In most cases the staged faults drew substantially less current than the smallest fuse used for lateral protection. Many of the feeders where faults were staged carried normal loads; therefore, protective relaying devices were set at fairly high levels to account for phase currents and load imbalance.

The types of faults staged and particular circumstances have been previously reported [3]. It has been concluded from this staged fault activity that a high probability exists that a downed conductor will not be detected by conventional protection methods.

References

[1] E. O. Brigham, *The Fast Fourier Transform.* New Jersey: Prentice Hall, Inc., 1974, pp. 140–146.
[2] A. V. Oppenheim and R. W. Schafer, *Digital Signal Processing.* New Jersey: Prentice Hall, Inc., 1975, pp. 239–251.
[3] "Detection of arcing faults on distribution feeders," Prepared by Texas A&M Univ., EPRI Rep. EL-2757, Dec. 1982.

Manuscript received September 9, 1987.