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Harmonic Behavior during Arcing Faults on Power Distribution Feeders

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SUMMARY

The waveforms of normal and arcing fault currents on power distribution feeders are investigated and compared in terms of the percentage amplitude with respect to the amplitude of the normal fundamental. The purpose of the study is to find better parameters to indicate arcing faults. The effect of capacitor banks on distribution feeder harmonics is discussed briefly.

1. INTRODUCTION

The behavior of arcs has been studied by many scientists and, for power systems, can be summarized as follows. If two conductors separated by a small gap have a small potential difference between them, the air acts as an insulator. As the potential difference is increased, the resistance of the air gap decreases and current flows between the two conductors. The rapid ionization accounts for the sudden ability of the air to conduct current. Typically, a stable arc can be formed after several strikes and restrikes occur within a short period of time. In general, for the case of arcing in an AC system, stable arcs will form and be extinguished every half-cycle [1].

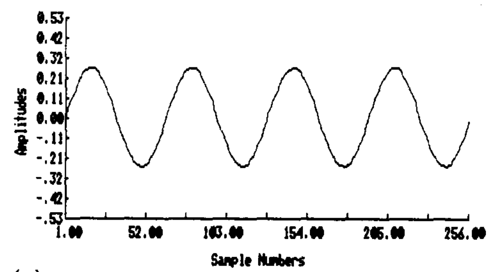
Current harmonics have their origin in the nonlinear voltage–current characteristics of the arc voltage. This effect results in typical wave shapes and thus in harmonics. The harmonic current characterized by an arc is variable and, although odd harmonic frequencies dominate, all harmonic frequencies are produced at times and even harmonics can persist.

Capacitor bank sizes and locations are important factors in determining the harmonics of a distribution system. Capacitor banks sometimes increase harmonic voltages with resonance and decrease some harmonic voltages at other times by acting as a shunt attenuator.

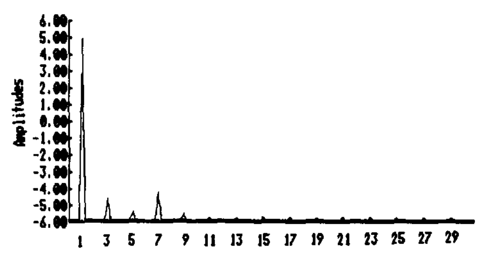
2. BASIC ANALYSIS

Here, the waveforms of normal and arcing fault currents are investigated and compared in terms of the percentage amplitude with respect to the amplitude of the normal fundamental. The purpose of this study is to find better parameters to indicate arcing faults. The effect of capacitor banks on distribution feeder harmonics is discussed briefly.

Firstly, Fig. 1(a) shows the current waveform of a 12 kV feeder system. The scale of the Figure is relative. This shows fundamental



(a)



(b)

Fig. 1. (a) Normal current waveform. (b) Periodogram of the normal current waveform.

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60 Hz current waveforms. Occasionally, deviations occur in the fundamental, but the amount of deviation is negligible (namely 59.95 - 60.05 Hz). Figure 1(b) shows the periodogram (i.e., squared amplitude of each frequency) of the normal current waveform. Here, the TIMESLAB software package was used to get the periodogram of each waveform [2]. From Figs. 1(a) and (b), it can be seen that a normal waveform has harmonic content. As expected, the odd harmonics, even though their absolute values are small, are predominant. Even harmonics are marginally present.

Secondly, an arcing fault waveform is studied. As is explained in the above section, arc current starts to flow at the quarter-point of a cycle. This results in harmonics, as discussed earlier. Figure 2(a) shows a typical arcing fault current waveform. There are distortions around the peaks of every half-cycle. Possible phase shift is not considered here. As can be seen, the waveform is not symmetric but variable and transient. Figure 2(b) shows a third waveform, called the differenced waveform, which is obtained from the fault current waveform after subtracting the normal waveform. Theoretically, this differenced waveform starts at every quarter-point of a cycle and remains for a quarter-cycle; it is zero at the other portions of the

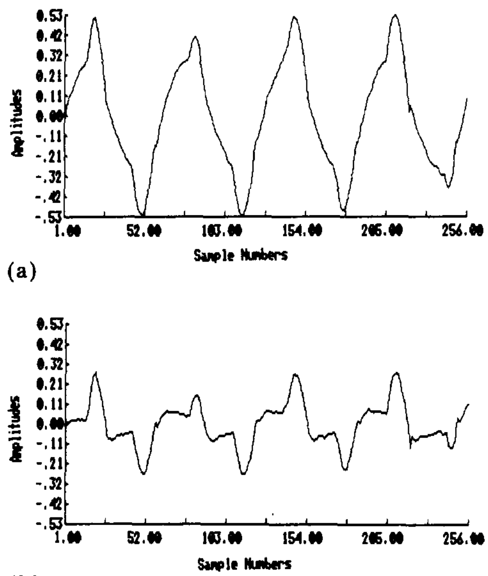

Fig. 2. (a) Arcing fault current waveform. (b) Differenced waveform.

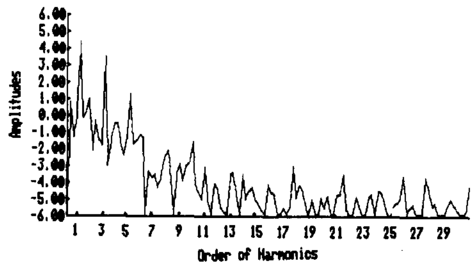

Fig. 3. Periodogram of the differenced waveform.

cycle. This differenced waveform exhibits a peak amplitude at every quarter-point of a cycle as high as that of a normal current waveform. In other words, the amplitude of the arcing fault current waveform is about twice as high as that of the normal current waveform. This, however, is not enough for an overcurrent relay to detect and isolate this type of arcing fault current.

Now, the frequency domain is investigated. A periodogram is also used to see which harmonics are present and which one or more harmonics are predominant. Figure 3 shows the periodogram of a differenced waveform on a logarithmic scale. Here, odd harmonics (3rd, 5th) are still predominant, but some even harmonics (e.g. 2nd, 4th, 6th, 8th, and 10th) have significant amplitudes; the 8th harmonic is higher than the 7th harmonic, and the 10th harmonic is higher than the 9th harmonic.

In addition, up to the 16th harmonic, each harmonic shows its frequency component, even though it is not as high. Above the 16th harmonic, all harmonics are present at the same or a similar level. It can be said that higher frequencies exhibit the characteristics of white noise.

To use harmonics to discriminate arcing fault current from normal current, several possibilities exist. Three are used in this paper:

(1) the relative amplitude increases of the odd harmonics (e.g. 3rd, 5th) with respect to the normal amplitude;

(2) the relative amplitude increases of the even harmonics (e.g. 2nd, 4th, 6th, 8th, 10th);

(3) comparison of the relative amplitude increases of the even harmonics with the relative increases of the odd harmonics.

When a capacitor bank is present on a distribution feeder, some harmonics are increased in some cases and eliminated in other cases. Moreover, the resonance is shifted to higher frequencies. All these are quite depen-

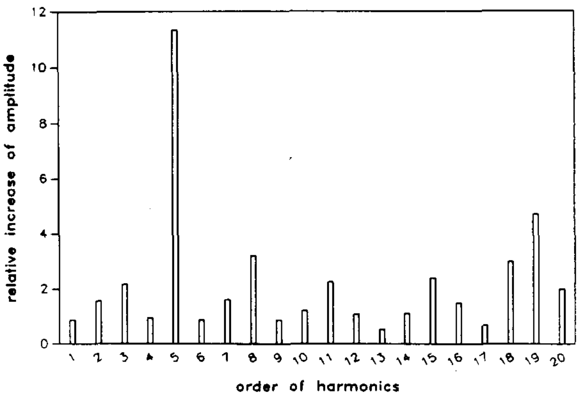

Fig. 4. Frequency component of each harmonic of the normal current waveform with a capacitor bank.

dent on the size and location of the capacitor bank.

A normal current waveform of a distribution feeder, when a capacitor bank is present, shows no significant change in phase current in the amplitude and wave shape. Figure 4 shows the frequency component of each harmonic of the normal current waveform when a 1200 kVAR capacitor bank is about 3 miles away on a 12.5 kV feeder on wet soil. Odd harmonics, especially the 5th harmonic, show big relative increases, and the 8th harmonic shows a significant relative increase.

3. STATISTICAL ANALYSIS

A statistical study has been done on two different types of soil condition at two different sites. Using recorded data at the two sites, over 80 different arcing fault waveforms were sampled at the rate of 3840 Hz, that is, 64 sample points per cycle, and studied in the frequency domain. The relative increases of in-between harmonics and the distribution of duration and off-duration of arcing on different soil types has been presented in an earlier paper [3]. Here, three kinds of scenario are investigated: arcing fault without capacitor banks, the effect of capacitor banks under normal conditions, and arcing fault with capacitor banks.

Arcing fault without capacitor banks

In this case, it is easy to see the harmonic distortion of the normal current wave. The contents of each harmonic at two different sites are given in Table 1.

From Table 1, the odd harmonics are predominant, as expected, at both sites, but site 2 has more harmonic content than site 1. Figure 5(a) shows the amplitude of each harmonic at site 1 (wet soil), and Fig. 5(b) shows the relative increase of each harmonic with respect to the fundamental at site 1 (wet soil). In Fig. 5(a), the odd harmonics are still predominant, but even harmonics can be seen to be present to some extent. Thus, in Fig. 5(b), though the relative increase of the 6th harmonic is less than that of the 5th harmonic, up to the 16th harmonic the relative increases of the even harmonics are much higher than those of the odd harmonics.

Figures 6(a) and (b) show the same graphs as Figs. 5(a) and (b) at site 2 (dry soil). In Fig. 6(a), the odd harmonics are still predominant, but the relative increases of the even harmonics are more marked than before. Based on the graphs of Figs. 5 and 6, it is

TABLE 1

Relative increases of the odd and even harmonics (the unit is the percentage of the fundamental 60 Hz) during an arcing fault without capacitor banks

Odd harmonics			Even harmonics		
Order	Site 1	Site 2	Order	Site 1	Site 2
1	100	100	2	0.14	0.85
3	0.83	2.90	4	0.16	0.87
5	0.35	4.50	6	0.24	0.75
7	1.00	2.30	8	0.06	0.51
9	0.50	1.10	10	0.10	0.31
11	0.38	0.73	12	0.11	0.37
13	0.19	0.37	14	0.07	0.34
15	0.10	0.31	16	0.11	0.26
17	0.09	0.35	18	0.07	0.34
19	0.09	0.25	20	0.06	0.24

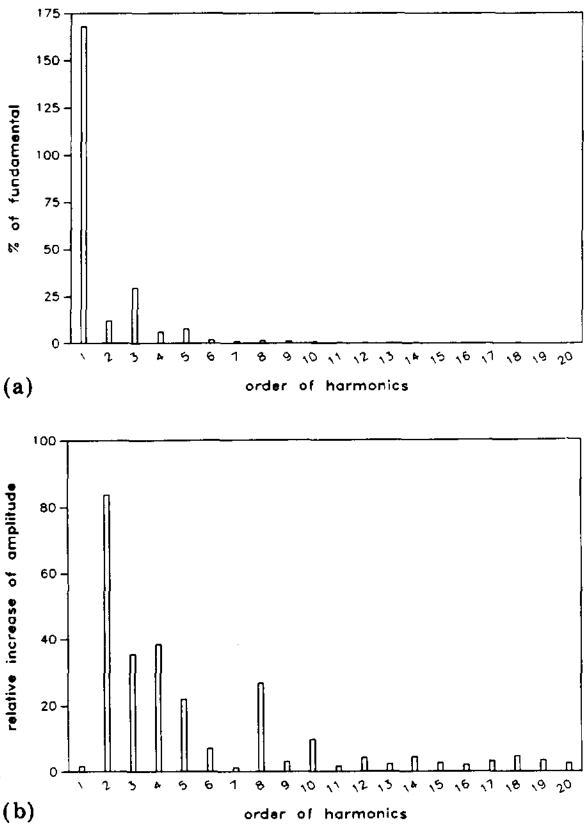

Fig. 5. (a) Amplitude of each harmonic of the arcing fault current waveform without capacitor banks at site 1. (b) Relative increase of each harmonic of the arcing fault current without capacitor banks at site 1.

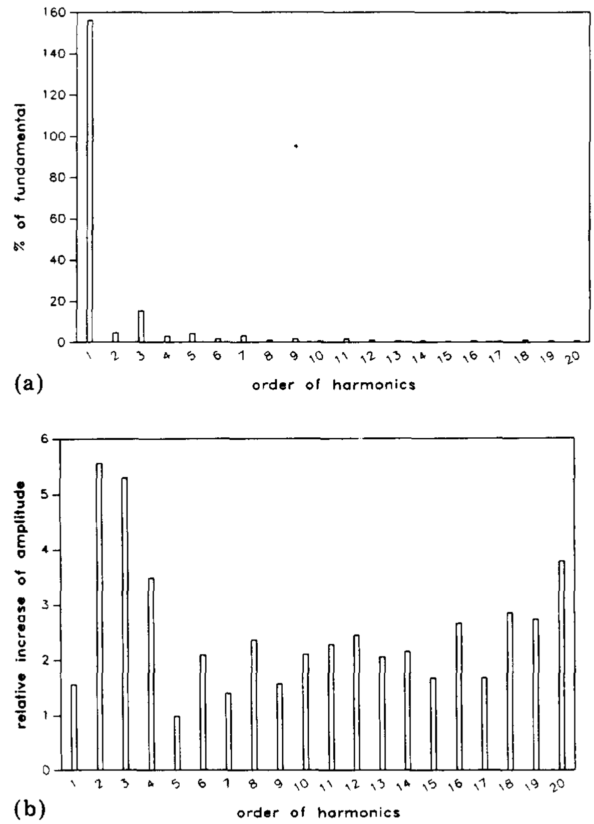

Fig. 6. (a) Amplitude of each harmonic of the arcing fault current waveform without capacitor banks at site 2. (b) Relative increase of each harmonic of the arcing fault current without capacitor banks at site 2.

concluded that, from the 7th to the 14th harmonic, comparison of the relative increases of the even harmonics with those of the odd harmonics, or simply the relative increases of the even harmonics, can be a good candidate to discriminate an arcing fault condition from the normal state. If only one or two harmonics are chosen, the relative increase of the 8th and/or the 10th harmonic can be a good indication of arcing fault at both sites. This is confirmed in Fig. 3.

A comparison of the relative increases of the even and odd harmonics at both sites is shown in Table 2.

Here, site 2 shows a lower ratio of even to odd than site 1. The possible reasons are: the soil type is different (wet) and the harmonic contents of the normal waveform are much higher than those of site 1. Therefore, a possible strategy for finding better parameters to indicate arcing faults is, from the 7th to the 14th harmonic, either to compare the relative increases of the even and odd harmonics, or just to use the relative increases of the even harmonics.

TABLE 2

Comparison of the relative increases of the even and odd harmonics during an arcing fault without a capacitor bank

	Site 1	Site 2
Odd harmonics (7, 9, 11, 13th)	8.28	7.30
Even harmonics (8, 10, 12, 14th)	45.1	9.07
Even:odd	5.40:1	1.24:1

Capacitor bank on unfaulted feeder

Figure 7(a) shows the comparison of frequency components of the normal current waveform with and without a capacitor bank at site 1. Figure 7(b) shows the corresponding plot at site 2. From the above two graphs, it is

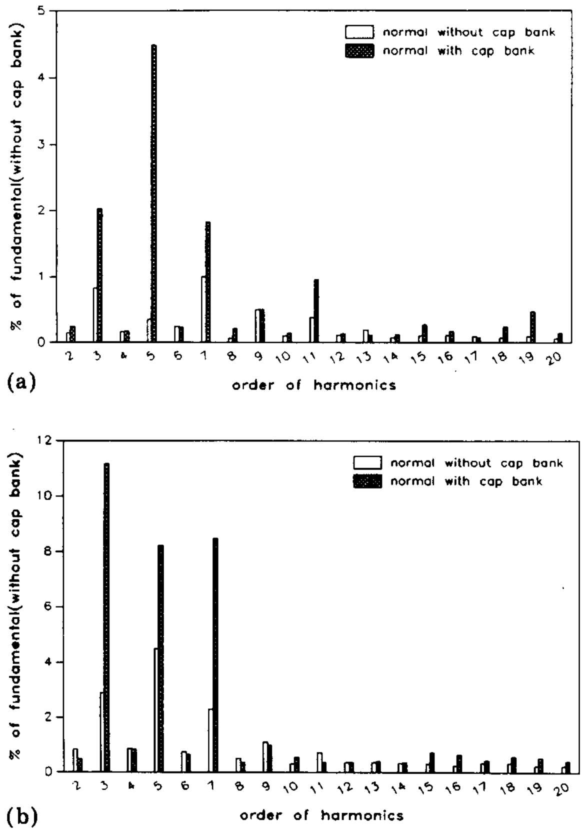

Fig. 7. (a) Comparison of the frequency components of the normal current with and without a capacitor bank at site 1. (b) Comparison of the frequency components of the normal current with and without a capacitor bank at site 2.

concluded that the odd harmonics (especially 3rd, 5th and/or 7th) dominate and the overall shapes of the frequency components are quite similar to the frequency component shape of the normal current waveform.

The relative increases of the even and odd harmonics at the two different sites are shown in Table 3. At site 2, at higher frequencies the relative increases are higher, but odd harmonics are still predominant. At sites 1 and 2, the shapes of the relative increase of each harmonic are different. The possible reasons are the different sizes and locations of the capacitor banks and the different harmonic contents of the normal current waveforms.

Arcing fault with a capacitor bank

Figures 8(a) and (b) show, respectively, the amplitude and relative increase of each harmonic at site 1. Figures 9(a) and (b) show, respectively, the amplitude and relative increase of each harmonic at site 2. From the graphs of Fig. 8, up to the 10th harmonic, all harmonics are increased except the 7th. The percentage of the fundamental shows that the odd harmonics are predominant, but the relative increases of the even harmonics are much higher than those of the odd harmonics. In Figs. 9(a) and (b), the 3rd harmonic shows a big amplitude decrease. The 3rd harmonic generated by the arcing fault is probably eliminated by the capacitor bank. Up to the 14th harmonic, all harmonics are increased and, up to the 8th harmonic, the even harmonics increase more than the odd harmonics. Here it is concluded that when a capacitor bank is present on the feeder, up to the 8th harmonic a comparison of the relative increases of the even harmonics with those of the odd harmonics, or simply the relative increases of the even harmonics, can discriminate the arcing fault condition from the normal state.

TABLE 3

Relative increases of the even and odd harmonics during an arcing fault with a capacitor bank

Odd harmonics			Even harmonics		
Order	Site 1	Site 2	Order	Site 1	Site 2
1	0.86	0.99	2	1.57	0.58
3	2.16	3.85	4	0.94	0.98
5	11.3	1.82	6	0.88	0.88
7	1.61	3.69	8	3.20	0.71
9	0.88	0.90	10	1.20	1.81
11	2.24	0.49	12	1.09	1.00
13	0.53	1.14	14	1.10	1.09
15	2.40	2.35	16	1.50	2.50
17	0.67	1.26	18	3.00	1.74
19	4.70	2.12	20	2.00	1.71

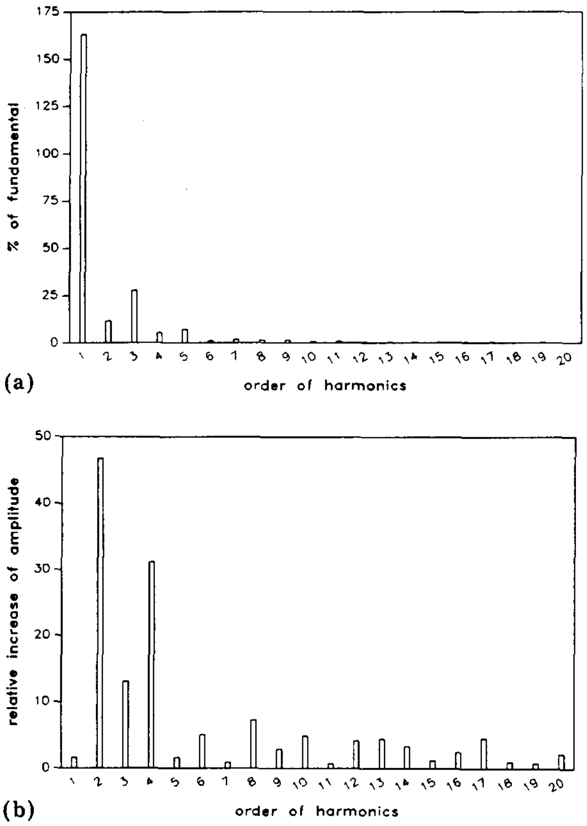

Fig. 8. (a) Amplitude of each harmonic of the arcing fault current waveform with a capacitor bank at site 1. (b) Relative increase of each harmonic of the arcing fault current with a capacitor bank at site 1.

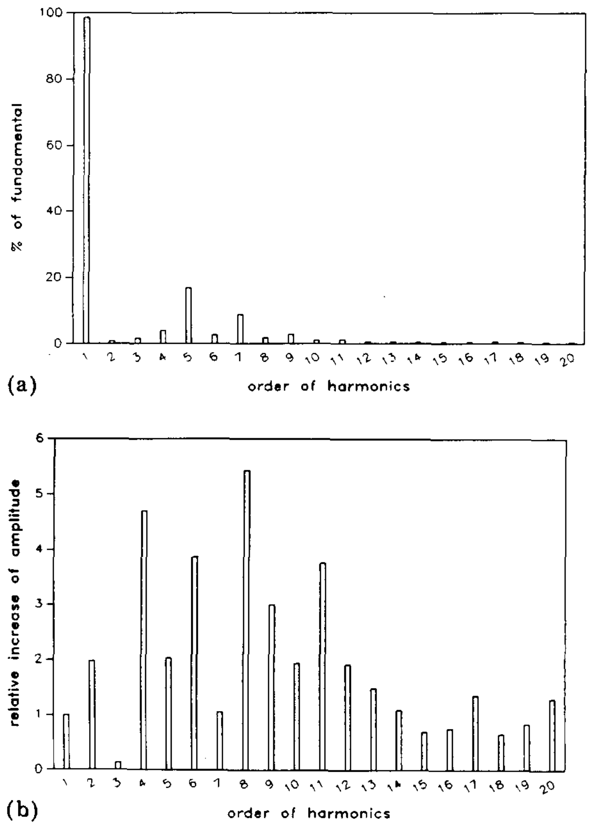

Fig. 9. (a) Amplitude of each harmonic of the arcing fault current waveform with a capacitor bank at site 2. (b) Relative increase of each harmonic of the arcing fault current with a capacitor bank at site 2.

TABLE 4

Comparison of the relative increases of the even and odd harmonics during an arcing fault with a capacitor bank

	Site 1	Site 2
Odd harmonics (7, 9, 11, 13th)	17.3	4.21
Even harmonics (8, 10, 12, 14th)	90.3	16.0
Even:odd	5.21:1	3.79:1

In both cases (arcing fault without capacitor bank and arcing fault with capacitor bank), comparison of the relative increases of the 8th and 7th harmonics, or just the relative increase of the 8th harmonic, can be a good indication of an arcing fault on the distribution feeder. This conclusion is confirmed by the periodogram of the differenced waveform in Fig. 3.

The relative increases of the even and odd harmonics up to the 8th harmonic are shown in Table 4.

Therefore, the strategy here is the same as that for an arcing fault without a capacitor bank.

4. CONCLUSION

A normal current waveform and an arcing fault waveform are studied in both the time and frequency domains. When an arcing fault occurs, the amplitudes of the odd harmonics are predominant but the relative increases of the even harmonics are much higher than those of the odd harmonics. Here, care should be taken that almost all harmonic sources, including solid-state switching devices, generate odd harmonics. Then it would be better to use even harmonics than odd harmonics to indicate an arcing fault.

Faults without capacitor banks, capacitor banks present without fault, and faults with a capacitor bank were studied on two different sites (wet and dry soil types). Without a capacitor bank, at both sites, from the 7th to the 14th harmonic, a comparison of the relative amplitude increases of the even and odd harmonics, or the relative increases of the even harmonics, can be a good indication of an arcing fault.

When a capacitor bank is present on a distribution system, the odd harmonics predominate and the overall frequency component shape is very similar to that of the normal current waveform.

With a capacitor bank, from the fundamental to the 8th harmonic, a comparison of the relative amplitude increases of the even harmonics with those of the odd harmonics, or just the relative increases of the even harmonics, can indicate the presence of an arcing fault.

For both arcing fault cases, comparison of the relative increase of the 8th harmonic with that of the 7th harmonic, or simply the relative increase of the 8th harmonic, can discriminate an arcing fault from a normal state.

The effect of the size and location of the capacitor bank when arcing faults occur remains to be studied.

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