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Electric Power Systems Research 35 (1995) 141–148

ELECTRIC POWER SYSTEMS RESEARCH

Analysis of distribution disturbances and arcing faults using the crest factor

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Received 1 May 1995

Abstract

Transient analysis of distribution disturbances for fault discrimination and event identification can be an important tool for the secure protection of power systems. A simple parameter which quantifies wave distortion has been used to analyze many different behaviors. Theoretical perspectives of the transients were studied and their impacts on changes in the crest factor were thoroughly examined. After testing the scheme with real transient data, discrimination and identification guidelines based on the crest factor were developed. The identification method may not be complete, but it successfully discriminates arcing faults from other disturbances, providing security enhancement for distribution protection.

Keywords: Fault analysis; Arcing faults; Waveform distortion; Crest factor

1. Introduction

Much work has been done over the last two decades to improve the detection of arcing faults on distribution feeders. Many satisfactory detection methods have been developed and, in recent years, research has concentrated on the discrimination of fault events from normal system events on the distribution feeder. Since reliability and service continuity are necessary in distribution systems, discrimination of normal events from faults is most important for a protection system.

It has been shown that the time domain and frequency domain behavior of 'normal' disturbances and arcing faults are similar and, therefore, correct discrimination and identification is most difficult.

Various frequency domain analysis methods have been applied to discriminate faults from normal events and disturbances. Harmonic analysis of arcing faults and disturbances has revealed much information not seen in transient analysis. Through digital signal processing techniques, harmonic analysis has considerably improved our understanding of the nature of arcing faults and has offered assistance in their detection.

However, harmonic analysis cannot satisfactorily identify the disturbances of arcing faults from many switching events [1]. A neural network approach which trains the behavior of the harmonic algorithm still cannot successfully discriminate arcing faults and capacitor bank switching events [2]. Many advanced analysis techniques using frequency domain information have been applied, but the results are only partially successful [3,4].

The reason for only partial success in discrimination is that when there is a disturbance, except in a few cases, the frequency domain information of the disturbance contains almost all harmonic components. Thus, it is not easy to find one or two essential harmonic components which will discriminate one disturbance from another. In some cases, the only difference is the magnitude of the frequency components. However, if we only concentrate on the magnitudes of frequency components, we may be fooled.

In this research, we will analyze the disturbances by quantifying time domain waveform distortions. Transient phenomena, such as arcing faults or capacitor bank operations, cause distortion of the current and, sometimes, the voltage waveforms. If we quantify the distortions of the waveforms and find the unique features of the transients, we may identify and discriminate most transient events.

2. Crest factor

The amount of distortion in a waveform may be expressed in several different ways. One way to quantify

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0378-7796/95/$09.50
SSDI 0378-7796(95)00988-W

distortion is to use the difference in consecutive cycles of a waveform which will show the deviation at each instant [5]. The 'difference' method has been used for periodicity elimination from time series data. This method is simple to apply and easily arrives at a distortion value. But the result has no firm mathematical result and the characteristics of AC loads do not easily relate to this analysis [6].

Another method of distortion quantification is to relate the basic parameters of a sine wave to the distorted wave. A pure sine wave has a certain ratio between the effective (r.m.s.) value and the crest (peak) value. Also, there is a fixed ratio between the crest (peak) value and the average value of each half cycle. The first ratio is called the crest factor and the second one is the form factor [6].

In the literature, the two factors are defined as follows [7]. The crest factor is "the ratio of the maximum or crest value (peak value) to the effective value (r.m.s.)". The crest factor for a sine wave is $\sqrt{2} = 1.414$. The form factor is "the ratio of the effective value to the half-period mean value". The form factor for a sine wave is $\pi/(2\sqrt{2}) = 1.111$.

The crest factor indicates the 'peakness' of a waveform. However, if we compare the ratio of the peak value and the mean value of a cycle instead of the effective value, the 'peakness' of a waveform will be more sensitively defined. The data preparation for calculation of the average value, in real-time application, takes less time than for calculation of the effective value. We combined the above two factors together to create a revised crest factor. In this paper, this revised factor will be referred as the RCF.

The relationship for the revised crest factor RCF is obtained by multiplying the original crest factor and the form factor. For the mean value, we use the average of absolute sample values for one cycle instead of half a cycle. In our experience, having data for one cycle is enough to identify most disturbances. The RCF is defined as

$$\mathrm{RCF} = y_{\max}/y_{\mathrm{av}} \tag{1}$$

The RCF for a sine wave is $\pi/2 = 1.571$.

This value of the RCF can be used to decide the amount of distortion of a sine wave of current and voltage. A noisy feeder will have somewhat higher RCF values, even in normal situations. If there is any distortion in the wave, one or both of the values of peak and average will change the ratio. This relationship is mathematically meaningful. The advantage of using this factor is that we do not have to compare the values for a sudden change with the previous values as in the 'difference' waveform method. With the RCF, we have a mathematically meaningful reference to compare.

The crest factor has not previously been used for power system transient analysis, but it has been used in the analysis of tonal complexes in speech [8]. The crest factor is very sensitive compared with the r.m.s. value, because a high spike at an instant will directly increase the peak with the value of the spike. The r.m.s. or average, however, will absorb the effect throughout a whole wave cycle.

Even though the crest factor is sensitive, it is not sensitive, or does not change at all, if the sine waveform is changed in magnitude without distortion. In other words, the crest factor will be the same when the levels of current and voltage are changed gradually without any distortion in the waveforms. The crest factor is very sensitive to the instant of distortion, but the change in magnitude which usually follows switching or equipment operation cannot be seen in the crest factor before and after that instant. The change in magnitude can be seen in the denominator of the crest factor formula, which is the average, AV. This average will be used with the RCF for the examination of disturbance events. So, the four parameters of identification and discrimination of disturbances are the revised crest factors of current and voltage, I_{cf} and V_{cf}, and the averages of current and voltage, I_{av} and V_{av}.

In the next section, we will theoretically analyze the distribution disturbances and arcing faults. Interpretation of the transients in term of the RCFs and AVs of current and voltage will follow.

3. Distribution transients: theoretical perspectives

The majority of transient conditions in distribution electrical circuits can be divided into three categories of disturbance: faults including arcing faults, action of closing or opening a switching device or circuit breaker, and other events such as the transients from an arc furnace. In this section, we will analyze these transient behaviors from a theoretical perspective. This is necessary for a complete understanding of the event discrimination methods which follow.

3.1. Arcing faults

The behavior of arcing faults and schemes for detecting them have been thoroughly examined during the last decade [9–14]. However, discrimination of arcing faults is not yet complete. This is because such faults draw very low fault currents which are very similar to loads. Their frequency domain harmonic behavior is very dependent on the electrical environment and is somewhat similar to that of switching events [1].

The behavior of an arc in a power system can be summarized as follows. If two conductors are separated by a small gap and have a small potential difference between them, the air acts as an insulator. As the potential difference is increased, the resistance of the air

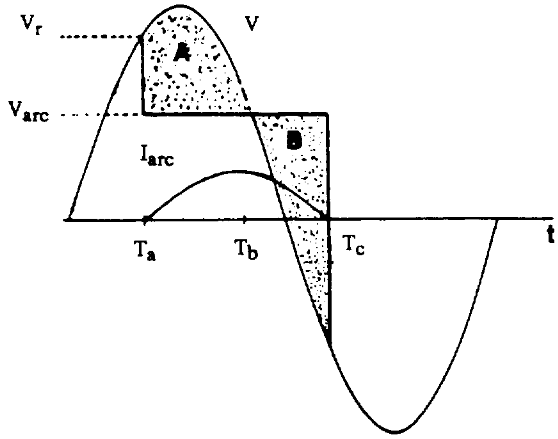

Fig. 1. Arc voltage–current relationship.

gap decreases and the current flows between the conductors [15].

In other words, it takes an instantaneous value of the 'restrike' voltage, V_r, before the spark gap begins to conduct so arc current flows. This takes place at time T_a (Fig. 1). Once the spark gap conducts, the voltage across the gap reduces to a level called the 'arc' voltage, V_{arc}, which is the voltage drop between two gaps when fault current flows [11,12].

Beyond this point, the build-up of arc current is proportional to the voltage–time area by which the driving voltage V exceeds the arc voltage. The arc current–voltage relationship from time T_a to T_b is defined by [12]

$$I_{arc} = \int_{T_a}^{T_b} (V_m \sin t - V_{arc})\, dt \tag{2}$$

At time T_b, the circuit driving voltage has dropped to a value equal to the arc voltage. This corresponds to the point of maximum arc current. Beyond this point the arc voltage exceeds the circuit driving voltage and creates a current flow decrease. Since the arc current is proportional to the voltage–time area, current ceases to flow when the negative voltage–time area (area B) is equal to the positive voltage–time area (area A) at time T_c. The arc voltage maintains the same polarity out to T_c because current flow is in the same direction throughout this interval [10–13].

3.2. Switching (breaker) events

A switch connection or disconnection can cause distorted voltage and current waveforms. The amount of distortion largely depends on the amount of current being interrupted. As the contacts of a breaker separate, an arc is drawn between them. The arc only continues until the current between the contacts is insufficient to maintain it [16]. At this instant, the arc is extinguished and the transient recovery voltage appears across the contacts. If the current zero is not met, the arc will be reestablished and current interruption will be delayed until a subsequent current zero.

When the current stops flowing, the arc voltage between the contacts changes from virtually zero to the instantaneous value of the supply voltage. Such a change causes overshoot and the voltage approaches its steady-state value by means of a transient oscillation.

3.3. Capacitor bank operations

During energization, the capacitor on the supply side has negligible capacitance in comparison with that of the bank being energized. The capacitor is initially discharged so that, at the instant of energization, the voltage on the supply side of the switch drops to zero because instantaneously the capacitor appears as a short-circuit. The supply side and capacitor voltages are now equal and increase towards the peak V_m of the supply voltage. Hence, the capacitor voltage can attain a value of $2V_m$ [17,18].

However, a restrike of the capacitor switch during an opening operation can result in substantially higher transient voltages than in normal capacitor energizing. Significant transient overvoltages occur both at the substation and at remote capacitor banks for this case. Switching of smaller feeder capacitor banks should result in lower transient voltages when compared with the switching of larger substation capacitor banks [19].

3.4. Arc process

When the arc is unstable during a meltdown period, sudden changes in arc length cause sudden changes in current magnitude, which in turn cause voltage flicker [20,21]. The general relationship between arc voltage and current and the length of the arc is very nonlinear. To provide arc stability, external reactance is usually installed. When the arc is stable during the refining period, the nonlinear resistance characteristics of the arc tend to cause a peak current waveform and a flat-topped voltage [6].

4. Distribution transients: crest factor perspectives

In this discussion, we will analyze each of these disturbances in terms of the RCF and AV. Also, we will show an example disturbance for each of the three categories.

4.1. Arcing faults

The arcing fault current, which discontinues every half cycle, will distort the current waveform. Thus it

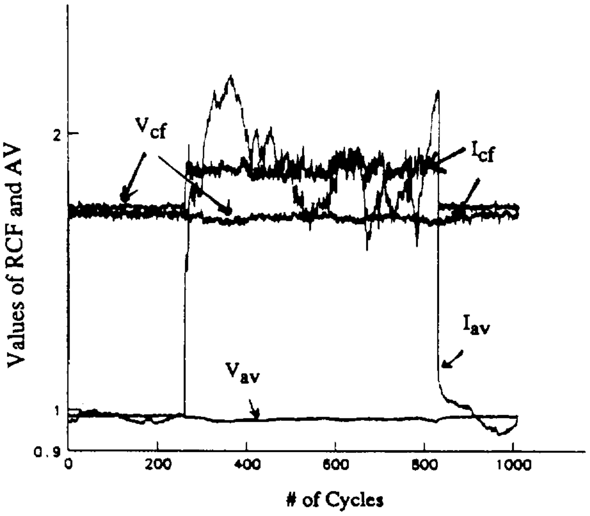

Fig. 2. RCF and AV values of an arcing fault.

will increase the I_{cf} and the I_{av}. The increase of I_{cf} is much larger than that of I_{av}.

Voltage distortion has been assumed to be almost negligible. However, when arc current flows between two contacts, there is a voltage small drop. The sensitive parameter RCF will respond to even a small change in the peak voltage. If the 'restrike' voltage is well below the peak level of the supply voltage, then the peak value of the voltage will be significantly reduced. Therefore, V_{cf} and V_{av} will be lowered, with much greater reduction in V_{cf}.

Fig. 2 shows the RCF and AV of voltage and current of phase C of an arcing fault. The fault started at the 250th cycle and ended at the 820th cycle after a fuse blew. This example was collected in 1993 from the Downed Conductor Test Facility at Texas A&M University. The Y-axis is a logarithmic scale. As we see, I_{cf} and I_{av} increased significantly during arcing faults. V_{cf} decreased a lot and V_{av} decreased to a lesser extent.

4.2. Switching (breaker) events

During switching transients, there is a voltage surge phenomenon. This voltage surge occurs at any point of the voltage cycle and it will dramatically increase the peak and the average. However, the duration of the peak increase will be very small, one cycle or less. The current level change after the switching may be dependent upon the power system configuration.

The current and voltage waveform distortions usually occur at the same time; therefore, when I_{cf} is high, V_{cf} is always high, or at least it will not be lowered. This disturbance usually is a three-phase event.

Fig. 3 is a 4 kV bus tie switch open/close operation. The data were collected in 1993 from a substation of the Philadelphia Electric Company. At the instant of opening the contacts, I_{cf} is increased, but V_{cf} does not

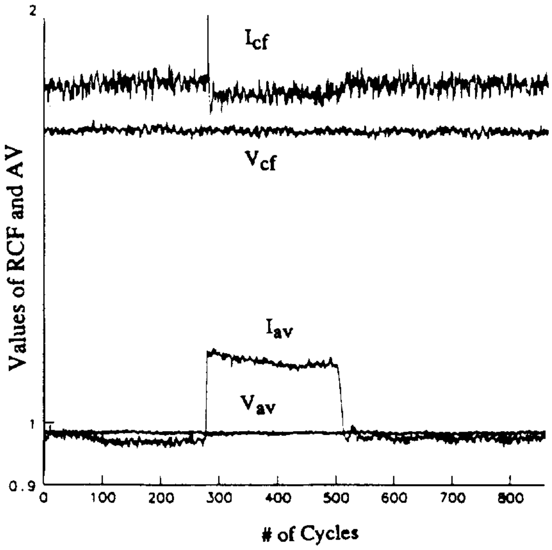

Fig. 3. RCF and AV values of a bus tie switch operation.

change. I_{av} is increased after opening and V_{av} is not affected. After closing, I_{av} goes back to the original level, and no changes are seen in V_{av} and V_{cf}. A slight change is seen in I_{cf}. The opening operation draws a higher distortion.

4.3. Capacitor bank operations

During capacitor bank switching, there may be a voltage peak increase up to twice the supply voltage. This means there will be a short-lived V_{av} and V_{cf} increase. There may also be a voltage or current level change before and after the operation. Therefore, a short-duration I_{cf} and V_{cf} increase is followed by up or down changes in V_{av} and I_{av}. However, there will be no such case that when I_{cf} increases, at the same time, V_{cf} decreases. This operation is most likely a three-phase event.

Fig. 4 depicts a few consecutive capacitor open and close operations in a substation of TU Electric. I_{cf} and V_{cf} both exhibit short-duration increases. V_{av} shows a step change after and before the operation. As the current waveform is affected by the step change, I_{av} shows a step change of small magnitude. Opening operations produce significant voltage distortions both in RCF and AV.

4.4. Arc process

During an unstable arc process, there will be transients in voltage and current. Therefore, I_{cf} and V_{cf} will be high. If the arc process is stabilized, there will be a voltage dip. If the plant process is a continuous melting arc process, continuous changes in voltage dip or increase are expected. The arc process is always a three-phase event.

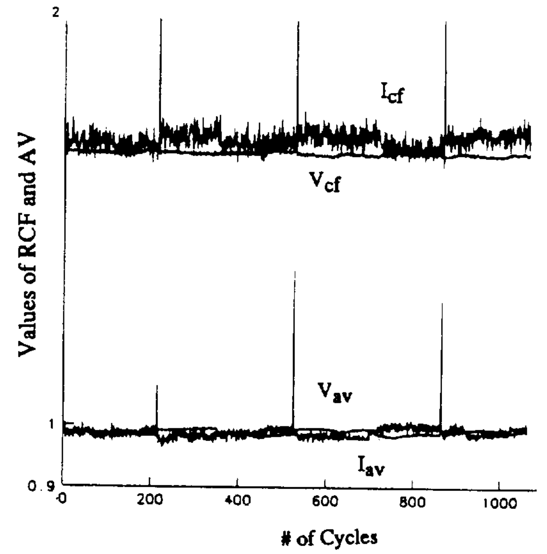

Fig. 4. RCF and AV values of a capacitor bank switching.

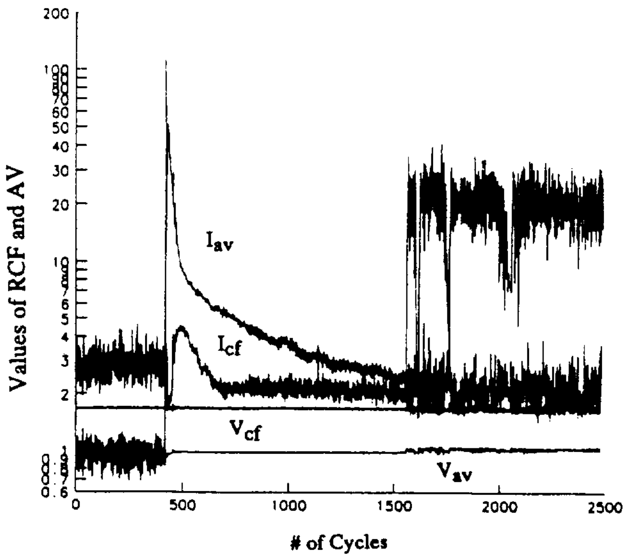

Fig. 5. RCF and AV values of a new melting process.

Fig. 5 shows the start of a new melting process of a steel plant. The data sample was collected from a steel plant substation of the Philadelphia Electric Company in 1993. The new melting process takes a very long time and, after that, a stable arc process starts. During the transition process, I_{cf} and I_{av} exhibit very high increases, but neither V_{cf} nor V_{av} change. During the arc process after the transitional period, I_{cf} shows a very high increase and V_{av} and V_{cf} show random level changes.

5. Crest factor analysis of real transients

In this section, we will examine some real transient data in terms of the RCF and AV and try to draw some discrimination or identification parameters from this examination. It is easier to indicate the variation of the RCF and AV values in a scatter X–Y plot of all three phases. We will indicate the RCF or AV values of the current on the X-axis, and the voltage on the Y-axis. This effectively conveys the RCFs and AVs of voltage and current at the same time. Phases A, B, and C are indicated on the graphs, capital letters for RCF values and lower case for AV values.

To describe the shape of the scatter plots, we define some changes here. If V_{cf} increases as I_{cf} increases, the scattered dots will be in a line toward the upper right corner; we call this a 'positive-slope' change. If V_{cf} decreases as I_{cf} increases, the scatter plot will be located in the lower right corner, which is a 'negative-slope' change. In these X–Y plots, there are also 'vertical' and 'horizontal' changes based on the RCFs and AVs and AVs of current and voltage variations.

Data of staged arcing faults and other switching transients have been collected since the late 1970s. In this paper, we selected six locations at which either or both arcing faults and switching events were tested. The recorded data were analyzed by the MASSCOMP high-speed signal analyzer (Massachusetts computer corporation, Boston, MA). The sampling rate for digitization of the recorded analog signal was 1920 Hz, that is, 32 samples per cycle. AV values were calculated relative to the value of the normal sine wave.

Because of space limitations, we picked two typical tests for arcing faults, a capacitor bank operation, a load tap changing (LTC) transformer operation, a bus tie switch operation, and the arc process at a steel mill plant.

5.1. *Arcing faults*

We present two arcing faults. Fig. 6(a) shows a staged arcing fault in the Enchanted Mesa Substation of the Public Service Company of New Mexico on 31 August 1983. The fault was staged in phase C, 0.8 km away from the substation. Fig. 6(b) depicts a staged arcing fault at the Downed Conductor Test Facility at the Riverside Campus of Texas A&M University on 10 July 1993 and the tests were recorded at the Bryan Utilities Substation, about 1.6 km away from the test site.

As we see from the figures, the faulted phase shows a big increase in I_{cf} and I_{av}, which corresponds to 'negative-slope' changes in RCF and AV values.

5.2. *LTC operations*

One LTC operation case is illustrated in Fig. 7. This test was performed at the Randoll Mill Substation of TU Electric in Fort Worth, TX, on 12 February 1980.

There is no change in either the crest factor or the average in voltage so the change is 'horizontal' in both

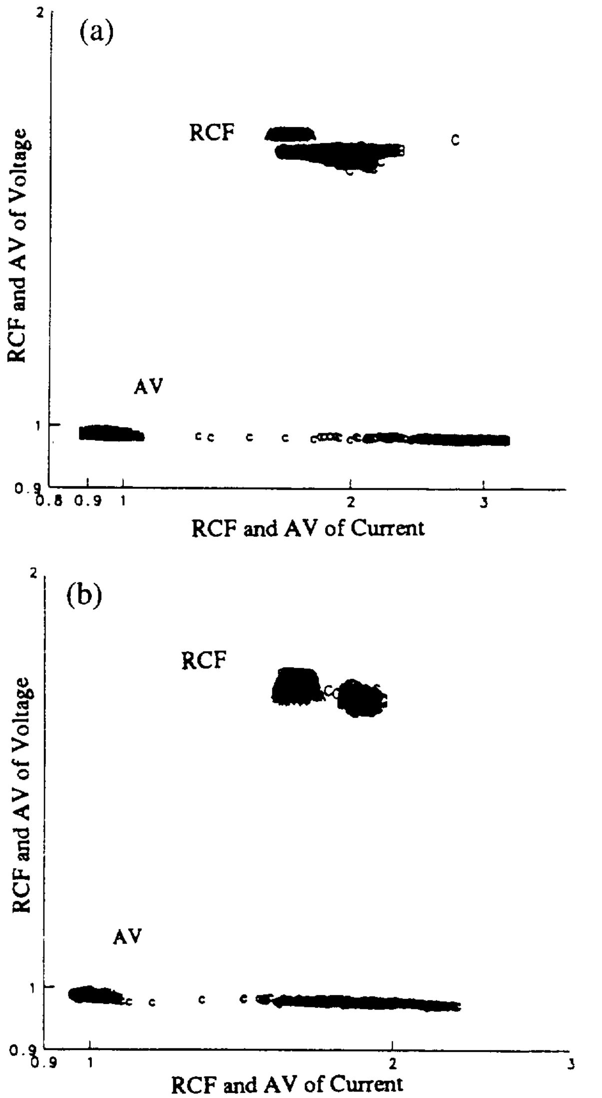

Fig. 6. X–Y scatter plot for an arcing fault from (a) New Mexico and (b) Texas A&M University site.

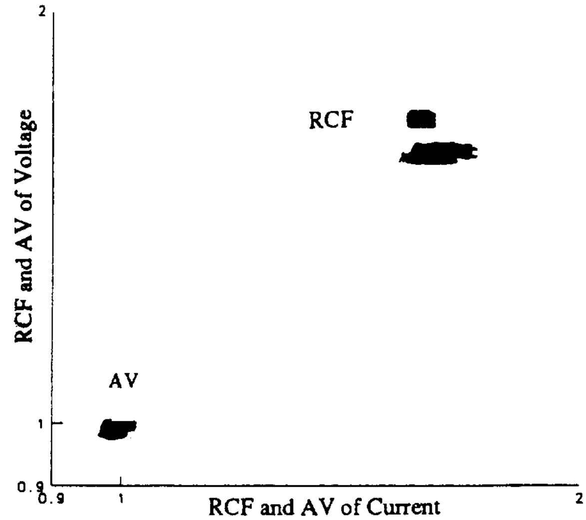

Fig. 7. X–Y scatter plot of an LTC operation.

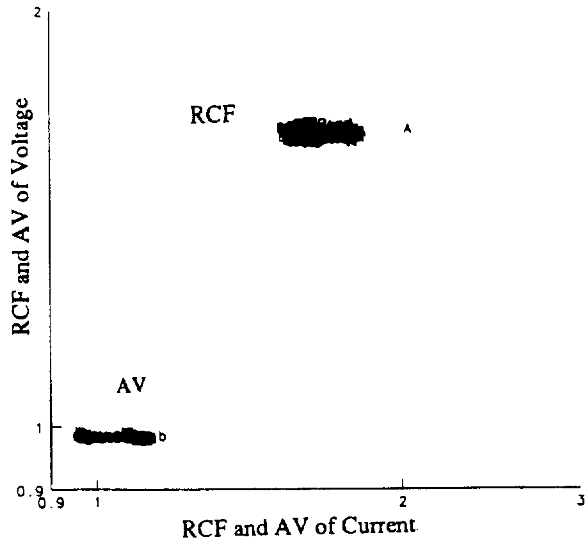

Fig. 8. X–Y scatter plot of a bus tie switch operation.

RCF and AV. With a sharp eye, AV changes can be seen, so we may say that there is a slight 'positive-slope' change in AV.

5.3. *Bus tie switch operations*

A bus tie switch operation is illustrated in Fig. 8. This test was performed on 21 March 1993 at the Bradford Substation of the Philadelphia Electric Company in Downington. There are 'horizontal' changes in the AV and RCF values before and after the switching in all three phases.

5.4. *Capacitor bank operations*

A capacitor bank operation was tested at the Kluge Substation of the Houston Lighting and Power Co. on 16 November 1983. The size of the capacitor bank was 600 kvar. We see 'positive-slope' or 'horizontal' changes in both RCF and AV (Fig. 9).

5.5. *Steel plant arc processes*

We collected arc processes at a steel mill plant from a steel plant load at the Lukens Steel Substation of the Philadelphia Electric Co. in Coatsville on 18 May 1993. Fig. 10 shows the operation of both the main arc furnace and the ladle furnace.

The RCF does not change or it changes in a random manner. If we risk proposing any changes in the RCF, we may say the change is 'positive-slope'. AV shows 'horizontal', 'positive-slope', and 'negative-slope' changes, alternately or cumulatively.

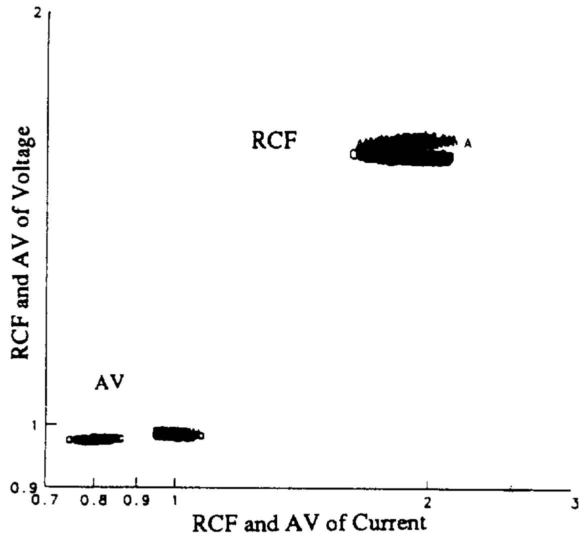

Fig. 9. X–Y scatter plot of a capacitor bank switching.

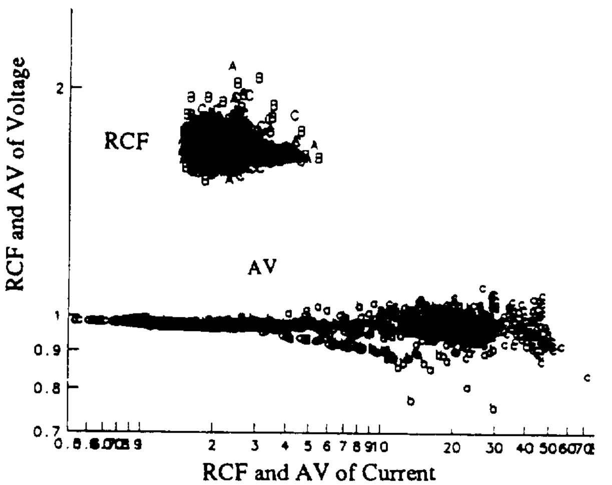

Fig. 10. X–Y scatter plot of an arc process.

6. Discussion

From the previous analysis, we may draw up identification guidelines (Table 1) in terms of the changes in RCF and AV of scatter X–Y plots. These guidelines, using only the revised crest factor, may not be accurate enough because they were drawn from only a few examples from each category and some directional changes are not clear. Nonetheless, the suggested guidelines will successfully discriminate arcing faults from other disturbance categories and will also provide a meaningful identification characteristic for the rest of the disturbances.

To improve and tune the above method, extensive monitoring and testing will be necessary. Comprehensive data processing with crest factor analysis for better discrimination and identification will be the next stage of this research.

Table 1
Identification of transients in terms of RCF and AV changes

Transients	RCF change	AV change
Arcing faults	negative [a]	negative slope [a]
LTC operation	horizontal	horizontal, vertical [a], or positive slope
Tie switch operation	horizontal vertical [a]	horizontal slope vertical [a] slope
Capacitor switching	horizontal positive	horizontal slope positive slope
Arc process	no change postive	horizontal slope positive or negative slope

[a] Single phase only (otherwise, three-phase operation).

7. Conclusions

It is absolutely necessary that any distribution protection system based on arcing fault detection be secure in its decision of the presence of an arcing fault before tripping the feeder. Sensitive arcing fault detection algorithms are, in some cases, not secure and prone to identify normal system events as arcing faults. This paper has analyzed the transient behavior of various distribution feeder events and presents a theoretical analysis of the disturbances. A new parameter, the revised crest factor, has been applied to analyze the disturbances as an alternative identification and discrimination variable.

Various actual disturbance and fault waveforms were analyzed with the revised crest factor and the average. Identification guidelines are presented. This identification or discrimination method may not be completely satisfactory in all cases. However, the guidelines using the RCF will discriminate arcing faults from most normal system events and provide an alternative method for improving the security of the fault/no-fault decision.

Research is ongoing to improve the method with the hope that event identification can be performed simultaneously with fault discrimination.

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