Discrimination of Arcing Faults from Normal Distribution Disturbances by Wave form Distortion Analysis

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Abstract

Detection of arcing high impedance faults has been a perplexing problem in the power distribution protection. Transient analysis of distribution disturbances for fault discrimination from other normal events is important for a secure protection of the power system. A simple parameter of wave form distortion quantification is used to analyze the behaviors of arcing faults and normal distribution disturbances. Theoretical perspectives of the transients were studied and actual disturbances were examined. From this investigation, a discrimination guideline based on the revised crest factor is developed. The discrimination method has a high potential to enhance the reliability and security for the distribution system protection.

I. 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 emphasized discrimination of faults from normal events. Since reliability and service continuity are essential 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" transients and arcing faults are similar and, therefore, correct discrimination and identification is most difficult.

Various frequency domain analysis methods have been applied to identify arcing faults. 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 can not satisfactorily identify 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 from capacitor bank switching events [2]. Many advanced analysis techniques using frequency domain information have been applied, however, the results are only partially successful [3]-[5].

The reason for the partial success in discrimination is that most transient contains almost all the harmonic components. In some case, the only difference is the magnitude variation in the frequency components. Hence, if we concentrate on a specific frequency component as a discriminant, we may be fooled.

In this research, we will analyze some arcing faults and switching events 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 wave forms. If we quantify the distortions of the wave forms and find the unique features of the transients, we may be able to discriminate arcing faults from other events.

II. Wave Form Distortion and Crest Factor

The amount of distortion in a wave form may be expressed in several different ways. One way to quantify distortion is to use the difference of the consecutive cycles of a waveform. The "difference" of the a waveform will observe the deviation at each instant [6]. The "difference" method has been used for periodicity elimination from time-series data. This method is simple to apply and easily

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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 [7].

Another method of distortion quantification is to relate the basic parameters of a sine wave to a distorted wave. A pure sine wave has a certain ratio between the effective (rms) value and the crest (peak) value. Also there is a fixed ratio between the crest (peak) value and an average value of each half cycle. The first ratio is called the *crest factor* and the second one, the *form factor* [8].

The crest factor is defined as "the ratio of the peak value to the effective value." Thus, 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 has not been used for power system transient analysis, however, it has been applied in the analysis of tonal complexes in speech [9]. The crest factor is very sensitive to find the changes in a wave form, because a high spike at an instant will directly increase the peak value. However, if we devise a new ratio, the peak value to the mean value of a cycle, it will more sensitively detect the "peakness" of a wave form. In addition, the calculation of mean value, in real time application, takes less time for data preparation than of the effective value.

By multiplying the original crest factor and the form factor, we have the following relationship of the revised crest factor (RCF).

$$\text{RCF}= (\text{Peak Value}) / (\text{Mean Value}) \qquad (1)$$

The value of RCF for a sine wave is $\pi/2 = 1.571$. This value of RCF can be used to decide the amount of distortion in the wave form of current and voltage. A noisy feeder will have somewhat higher RCF values even in normal situation. If there is any distortion in the wave, one or both of the values of peak and average will change the ratio. For the "mean" value, we use the mean of absolute sample values for one-cycle instead of half-cycle. In our experience, having data per one cycle is enough to measure the magnitude variation in transients.

The advantage of using this factor is that we do not have to compare the values for a sudden change with previous values as in the "difference" wave form method. With the RCF, we have a mathematically meaningful reference to compare.

However, RCF only is not enough to quantify the changes in a wave form. RCF does not change if the levels of current and voltage are gradually changed without any distortion in the wave forms. In other words, if there is no distortion, RCF is immune to the magnitude change before and after the moment of switching or equipment operation.

The magnitude change can be obtained from the denominator of the RCF formula, the mean or *average*. The average, with symbol AV, will be used along with RCF to examine the disturbances. Then, four parameters for discrimination of the disturbances are: the RCFs of current and voltage, I_{cf}, V_{cf}, and the AVs of current and voltage, I_{av}, V_{av}.

The values of RCF and AV can be obtained through the following steps. First, the analog data monitored or collected are digitized. In this paper, with sampling rate of 1920 Hz, we sample 32 data points per 60 Hz cycle. Second, in each cycle, we find the peak value from the digitized data. This "peak" value coincides to the numerator of the RCF equation (1). Third, using the same 32 samples, find an absolute mean value, and this value corresponds to the denominator of the equation (1). This absolute mean value also functions as the AV value. Therefore, in each cycle, we generate one value of RCF and AV. This process applies to the current and voltage.

For arcing fault discrimination, transients in distribution system are divided into two categories: arcing faults and switching events. In the following chapters, we will analyze two categories of the transients in theoretical and RCF perspectives.

III. Arcing Faults

1. *Theoretical Perspective*

The behavior of arcing faults and schemes for detecting them have been examined during last two decades [10]-[14]. However, the discrimination of arcing faults is not yet complete. This is because such faults draw very low fault currents, and their harmonic behaviors are very dependent on the distribution system and somewhat similar to those 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 gap decreases and the current flows between the conductors [15].

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

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

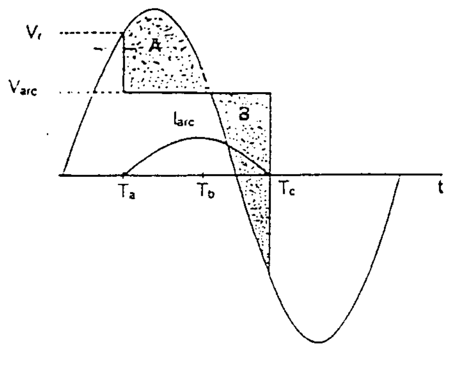

Fig. 1. Arc Voltage-Current Relationship.

At time T_b, the circuit driving voltage has dropped to a value equal to the arc voltage. This makes 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 volt-time area, current ceases to flow when the negative volt-time area (area B) is equal to the positive volt-time area (area A) at time T_c. The arc voltage has maintained the same polarity out to T_c because current flow has been in the same direction throughout this interval [10]-[13].

2. *RCF Perspective*

As we see above, the arcing fault current discontinues every half-cycle and, thus, distorts the current waveform. Therefore, it will increase the I_{cf} and the I_{av}. The increase amount of I_{cf} is much larger than that of I_{av}.

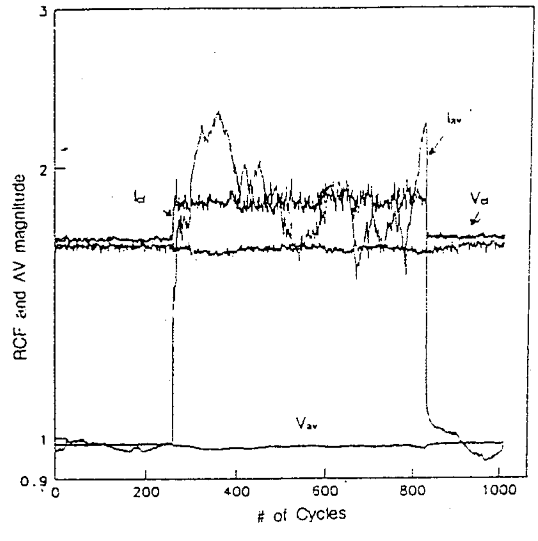

Fig. 2. RCF and AV values of and Arcing Fault.

During arcing fault, voltage distortion has been assumed to be negligible. However, when arc current flows between two contacts, there is a voltage drop, though the amount is small. The RCF responds to even the small amount of change in the peak voltage, therefore, this small drop can be detected. If the "restrike" voltage is well below the peak level of 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. This fault sample was obtained from the data base of the Texas A&M University which is one of the largest data collection in its kind. Texas A&M holds a vast amount of transient data which had been collected since early 1970's. The recorded data were digitized by high-speed signal analyzer. The sampling rate for digitization of the recorded analog signal was 1920 Hz, that is, 32 samples per cycle. Average (AV) was obtained by calculating relative value to the normal sine wave.

This arcing fault was staged at the DCTF (Downed Conductor Test Facility at the Riverside Campus of Texas A&M University) in July 10, 1993 and the test was recorded in the Bryan utilities substation, about 1.6 km away from the test site. The fault started at the 250th cycle of the time and ended at the 820th cycle when a fuse blew. As we see, I_{cf} and I_{av} increased much during arcing faults. V_{cf} decreased much and V_{av} decreased in a less amount.

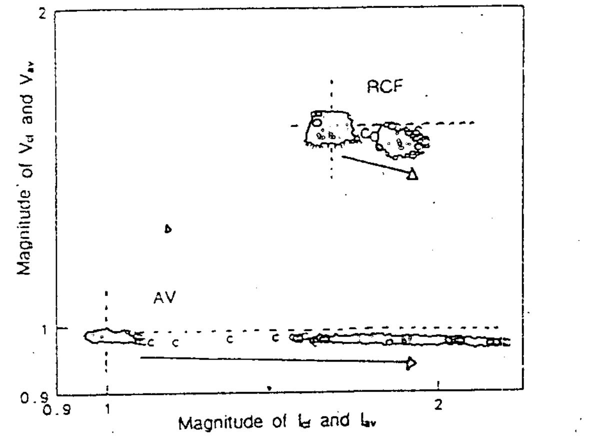

Fig. 3. X-Y Scatter Plot for Arcing Fault.

However, it is easier to see the variation of RCF and AV values if we indicate them in a scatter X-Y plot of all 3-phases. We will indicate the RCF or AV values of the current in X-axis, and those of the voltage in Y-axis. This effectively conveys the changes in the RCFs and AVs of voltage and current at the same time.

To describe the shape of the scatter plots, we define some shapes of the scatter plot. 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 directed toward the lower right corner, which is a "negative slope" change. In this X-Y plot, there are also "vertical" change and "horizontal" changes based on the RCFs and AVs of current and voltage variations. The alphabetical marks in the graph indicate the phases of A, B, and C. The capital letters indicate RCF values, and the lower cases, AV values.

Fig. 3 is an X-Y plot of the arcing fault. This shows "negative slope" change in RCF and AV values.

IV. Normal Switching Events

Feeder line tie switching and and capacitor bank switching are the main object of this discussion.

1. Theoretical Perspective

A switch connection or a disconnection can cause distorted voltages and currents. 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 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 re-established 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.

In the operation of capacitor bank, the capacitor on the supply side is negligible in comparison with the capacitance of the bank being energized during energization. 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 normal capacitor energizing. Significant transient overvoltages occur both at the substation and at remote capacitor banks for this case. Switching the smaller feeder capacitor banks should result in lower transient voltages when compared with the switching of larger substation capacitor banks [19].

2. RCF Perspective

In a switching transient, there is 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 distortions of current and voltage usually occur at the same time, therefore, when I_{cf} is high, V_{cf} is always high, or, at least, V_{cf} will not be lowered. This disturbance usually is a 3-phase event.

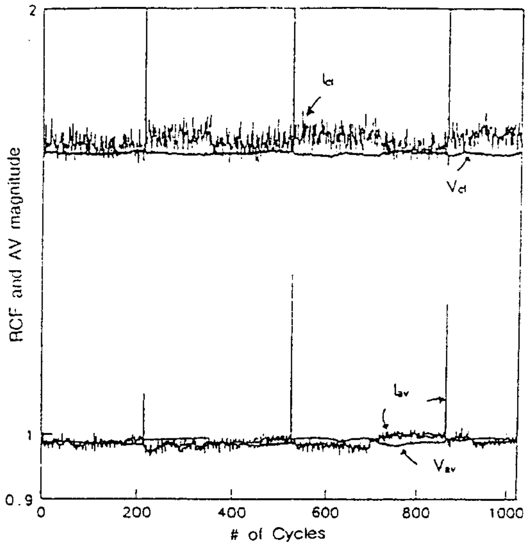

Fig. 4. RCF and AV values of a Bus Tie Switch Operation.

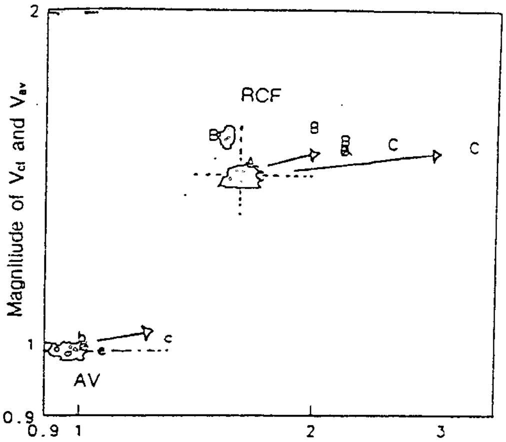

Fig. 5. X-Y Scatter Plot of a Bus Tie Switch Operation.

Fig. 4 is a 12.4 kV bus tie switch open/close operation. The data was collected in 1993 from a substation of the Philadelphia Electric Company. At the instant of opening the contacts, I_{cf} increased, however, the V_{cf} did not change. While I_{av} increased after opening, V_{av} unchanged. After closing, I_{av} went back to the original level, but no changes are seen in V_{av} and V_{cf}. However, a slight change is seen in I_{cf}. The opening operation shows more severe distortion.

An X-Y scatter plot of RCF and AV of above operation is illustrated in Fig. 5. There are "horizontal "changes in AV and RCF value before and after the switching in all 3 phases.

During capacitor bank switching, there may be a voltage peak increase up to two times of the supply voltage. There may be voltage or current level change before and after the operation. Therefore, a plausible scenario is that a short-duration increase in I_{cf} and V_{cf} is followed by the up or down changes in V_{av} and I_{av}. This operation is most likely a 3-phase event.

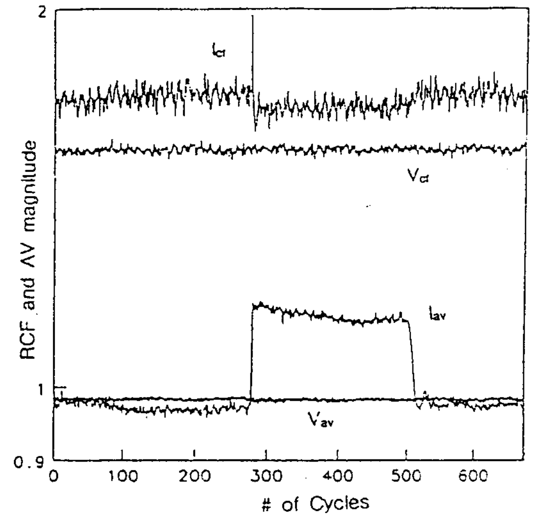

Fig. 6. RCF and AV values of a Capacitor Bank Switching.

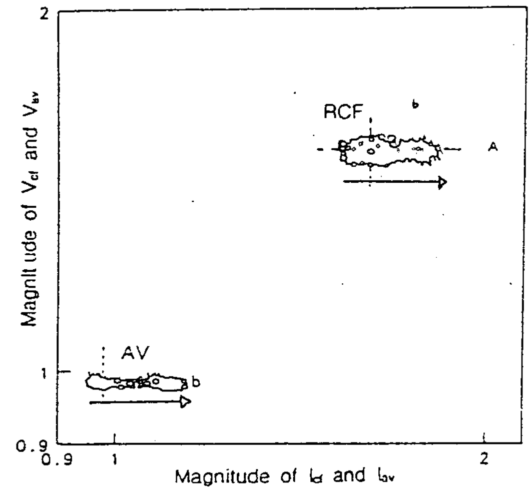

Fig. 7. X-Y Scatter Plot of a Capacitor Bank Switching.

Fig. 6 shows a few consecutive capacitor open and close operations, also from the TAMU data base, in a substation of TU Electric. I_{cf} and V_{cf} both show short duration increase. 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 show significant voltage distortions.

An X-Y scatter plot of RCF and AV of the above capacitor bank operation is illustrated in Fig. 7. We see "positive slope" or "horizontal" changes in both RCF and AV.

V. Discussions and Conclusions

From the previous analysis, we may draw a following identification guideline in terms of the changes in RCF and AV X-Y scatter plots.

Transient Types	RCF slope	AV slope
Arcing Faults	Negative	Negative
Switching Events	Horizontal Vertical Positive	Horizontal Vertical Positive

The above suggested identification guide, using only RCF and AV, may not be accurate enough to be applied in all the situations, because it was drawn from only a few examples from each category and some directional changes are not clear. Also, considering that the collected data represent only the distribution level of 12KV and the RCF behavior in different distribution levels has yet to be explored, the guideline cannot be easily generalized. Nonetheless, the suggested guideline shows revised crest factor's capability as a discriminant for arcing faults and other transients.

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. The guideline suggested here is, unlike the other detection techniques which adopt frequency-domain parameters only, based on the revised crest factor which results from time-domain analysis of the transient. Therefore, this guideline holds a promise for an alternate solution for discriminating fault from normal events.

Research is going on to improve the method with the hope that event identification can be achieved simultaneous to fault discrimination. In addition, the research on the influence of the different distribution voltage level to the behavior of the transients is expected to be launched in the near future.

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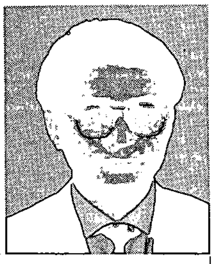

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