Analysis of complex faults in distribution systems

N. Solís, J. A. Gutiérrez, J. L. Naredo, V. H. Ortiz

Abstract—**Distribution systems are exposed to natural events like storms, fall of tree branches, lightning strokes, etc. These events often cause evolutionary faults involving arc phenomena. This paper focuses in the analysis of these complex faults and it explores the possibility of identifying and locating high impedance faults by conventional distance relays. A considerable number of records have been collected from actual faults on a distribution system belonging to the Mexican Federal Power Commission. These records have also been complemented with measurements from faults staged in the actual system, as well as from lab measurements.**

Keywords: Arcing faults, high impedance faults, evolving faults, covered conductors, distance protection, over-current protection.

I. Introduction

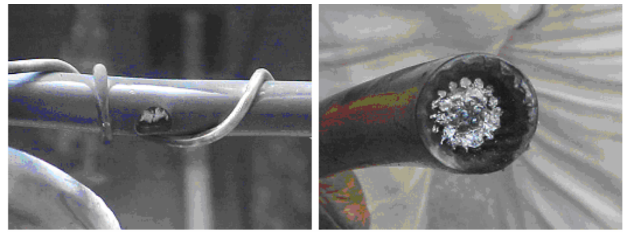
NATURAL phenomena, like storms, winds, lightning strokes, falling or growing of tree branches, etc., are among the most important factors for the interruption of power supply in distribution systems [1, 2]. Recently, insulation clad conductors (or covered conductors) have been used to reduce the effects of these phenomena [3, 4]. This measure certainly has reduced these effects; nevertheless, lightning induced surges tend to produce small perforations in the insulation cover. Currents circulating along covered conductors, both at nominal and at fault levels, tend to produce overheating at perforation points and eventually the melting and the falling of the aerial conductor involved. This overheating apparently is caused by an arc originating at the perforation. Figure 1a shows the picture of a covered conductor with a perforation. Figure 1b shows a picture illustrating the eventual rupture. Downed conductors usually end up producing a high impedance fault (HIF) which is undetected by conventional relays; still, it represents a serious hazard, included the possibility of a fire break up.

The research reported in this paper focuses in the analysis of the above mentioned complex faults, as well as on the reasons as why the conventional relaying equipment fails at detecting them. A long term aim of this research is to find out small modifications for standard relay software to add the capability of detecting such faults too.

In this paper we classify complex faults in three groups: 1) arcing faults, 2) high impedance faults (HIFs), and 3) atypical faults. For each one of these faults we provide measurement examples. Some of the measurements were obtained in laboratory, some others were obtained from staged faults on actual distribution lines, and the rest came from records of faults occurring at a distribution system in the Center-West Region of the Mexican Federal Power Commission (CFE). This is near the city of Patzcuaro, Michoacán.

Most of the records presented here were taken at 32 samples per 60 Hz cycle. Recorded signals usually are contaminated with undesirable noise. Two methods are applied here for its elimination. The first one is a low pass filtering process which is applied in the frequency domain through the FFT algorithm. The second one consists in the averaging of several cycles of the signal, taking as fundamental period 1/60 s. The two methods are applied in combination, unless it is stated otherwise. Filtered signals are then used to produce *v-i* trajectories which come up very clean and resemble hysteretic curves. Two cases of trajectories are then detected: 1) simple curves (*i.e.*, with no crossings of trajectories) and 2) curves with two crossings. It is proposed in this paper that the former case be used to declare a fault as a high impedance one (HIF), and the latter to declare it as an arcing one.

Arcing faults are difficult to detect and locate with conventional relays. This is due to the complex nature of the arc impedance, which has time and random varying features. High impedance faults usually are not detected by conventional relays because the current drained by the fault is too low if compared with the line nominal current. Finally, atypical faults are related to induced arcs or to trees, branches and other objects that get close or in contact with phase conductors. These often are evolving faults and, for this reason, they are difficult to classify. Due to normal growth, a tree branch may get close enough to a line conductor; this then often produces a one-phase-to-ground fault that standard relays can detect correctly. However, if a tree branch falls on a distribution line, this may start as a two-phase-without-ground fault, and then to evolve into a three-phase fault. Other instances of evolving faults are lightning induced arcs that may start as one-phase-to-ground faults and evolve into two- and three-phase faults as the air ionization increases.



(a) (b)

Fig. 1. a) Perforation on a clad conductor cover. **b)** Eventual melt and rupture caused by the perforation.

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Presented at the International Conference on Power Systems Transients (IPST'07) in Lyon, France on June 4-7, 2007

II. Complex Fault Classification

For the purposes of this paper it has been found very convenient to classify complex faults in the following three classes: 1) arcing faults, 2) high impedance faults (HIFs), and 3) atypical faults. The main features for each type of fault are described as follows. It should be pointed out that real life faults will usually present combined features; nevertheless, usually those from one class will dominate.

2.1 *Arcing faults.*

Electric arcs are not yet fully understood and characterized. Some arc models have been proposed and are used to match the voltage versus current curves, or *v-i* curves, of measured arcs [6]. An arc being drawn at a circuit breaker operation is a case where length variations have to be accounted for. It usually has short arc properties [7, 8, 9]. In overhead lines one can find long arcs. Most faults in power lines, such as short circuits, are followed by an arc. In these cases, impedance evaluation and fault location is complicated by the arc voltage arising at the fault point. This represents a major complication for the task of relay setting [10, 11]. Arcs have a highly complex nonlinear *v-i* characteristic [6, 7, 12]. The analysis of an arc *v-i* trajectory is the first step to establish whether all arcs have common features.

2.2 *High-impedance faults* (HIF)

When a conductor falls on the ground it may not establish a solid contact with it or the ground might have a very poor conductivity. An HIF is thus produced, resulting in a low fault current level that conventional over-current relays do not detect. This phenomenon involves arcing and a nonlinear behavior for the fault impedance. By this, voltage and current waveforms become distorted. HIFs can go on undetected for long periods of time; nevertheless they represent major hazards including the possibility of a fire break up. HIFs involve arcs; nevertheless, their *v-i* trajectories differ substantially from those of a long arc or an arcing fault.

2.3 *Atypical faults.*

When a tree branch gets close enough to a line it normally provokes a typical single phase fault. If, however, a tree branch falls on a line, it may first touch one conductor, and after that it may end up involving a second one or the three conductors. This evolution might complicate the determination of the fault by a protection device. For this reason it is risky to have a single trip pole configuration in high speed protection arrangements. In distribution systems it is more common to have a three phase trip configuration.

Lightning induces traveling surges on line conductors and their wave fronts could produce the ionization of the air around an insulator string. This establishes a trajectory to the tower structure for the line current line and a one-phase-to-ground fault is produced. Depending on several factors, the ionization could evolve to other phases thus producing another kind of fault.

III. Electric Arc Measurements

Three sets of experiments are presented as follows. The first one is carried out in a laboratory and is aimed at characterizing the arc originated by the perforation on the insulation of a covered conductor. The second set is conducted on a similar set up as the first one, the difference being its purpose which is to determine conductor rupture times. The third set of experiments involved two cases of downed conductors on an actual 13.8 kV distribution line. In one case the downed conductor was laid on wet grass and in the other it was near to a buried grounding rod. In both cases, because of the low soil resistivity, the faults presented dominant arcing features.

3.1 First set of experiments (laboratory).

The experiments consisted in circulating over-currents along covered conductors until their rupture. The tests were made on 1/0 and 3/0 AWG conductors positioned as shown in figure 2. The conductors had their covers perforated with a small puncture; then, an over-current with magnitude similar to the one from a short circuit was injected.

Figure 3 shows the measured current and voltage waveforms corresponding to the 1/0 AWG conductor. Only few cycles are shown here; however, the measurements were taken until the conductor rupture. The two sets of measurements, voltage and current, are used to produce the *v-i* trajectory for the arc at the piercing point. Figure 4 corresponds to this trajectory. The current waveform had a high frequency noise which was removed passing the signal to the frequency domain with an FFT. After this, an average was made with all the cycles.

In the same manner as with the clad 1/0 AWG conductor, the experiment is repeated for a 3/0 AWG conductor. Figure 5 shows the measured current and voltage waveforms. These signals are also used to produce the *v-i* trajectory for the arc in the 3/0 AWG conductor. In this case the current signal was

Fig. 2. Layout for experiment involving a pierced clad conductor.

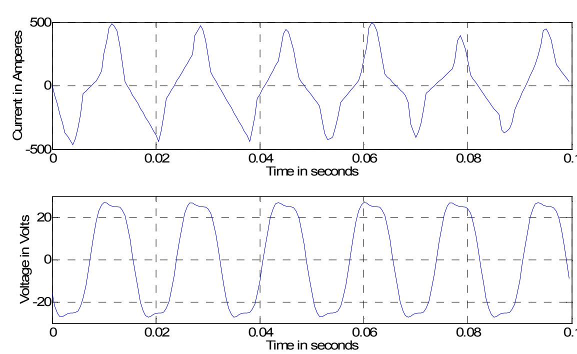

Fig. 3. Current and voltage for 1/0 AWG electric arc.

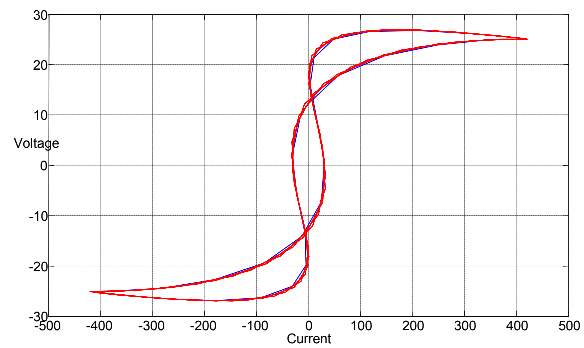

Fig. 4. Current-Voltage curve to 1/0 AWG electric arc characterization.

filtered in two different ways obtaining similar results. In the first one, the Fast Fourier Transform was applied to the entire waveform and the obtained spectrum was filtered by preserving only those components with the major part of the signal. The second method consisted in identifying each cycle and in applying the FFT to each one. Then, the high frequency components were removed from each one of the spectra. Finally, the resulting time domain cycles were averaged. Figure 6 shows the obtained *v-i* trajectories.

3.2 Second set of experiments (laboratory).

The second set of experiments consists in the rupture of various covered conductors provoked by an over-current. The experimental set up is as shown in figure 2. In this case also nominal voltage levels were applied. The tests were made on 1/0, 3/0, 266 and 336 AWG conductors. The obtained rupture times are plotted in Figure 7 [5].

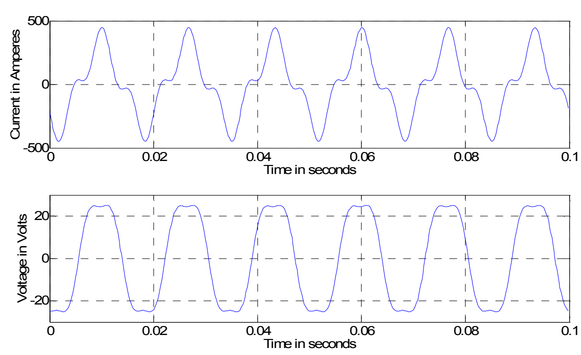

Fig. 5. Current and voltage for 3/0 AWG electric arc.

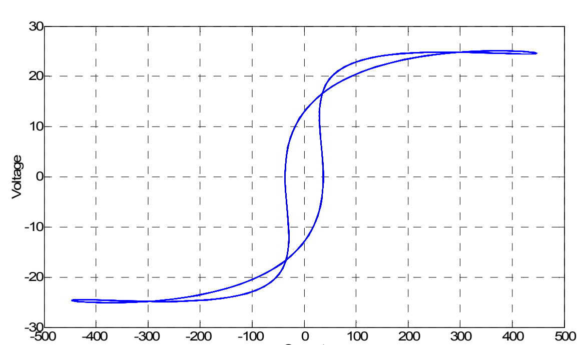

Fig. 6. Current-Voltage curve to 3/0 AWG electric arc characterization.

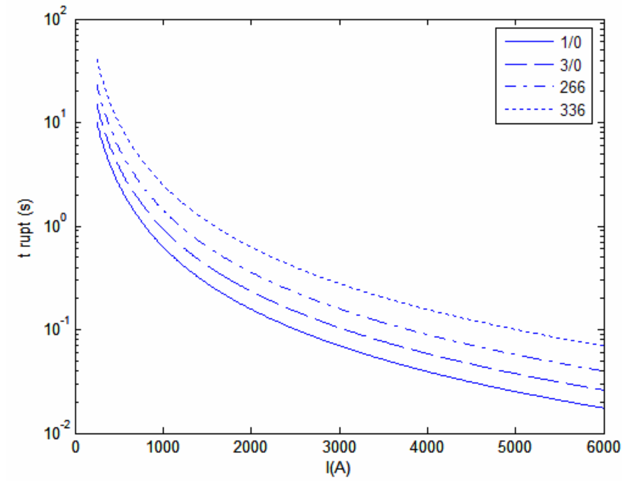

Fig. 7. Relation of rupture time – current for semi isolated cable under arc circuit.

3.3 Third set of experiments (13.8 kV line).

Two experiments were performed on a rural distribution line operated at 13.8 kV. The first experiment consisted in laying one of the energized conductors on a wet grass surface. This is shown in figure 8. The equipment for recording voltage and current waveforms was located at the nearest pole.

Figure 9 shows the voltage and current waveforms obtained from figure 8 experiment. This figure shows only a 0.1 s segment of the measured waveforms. Figure 10 shows the *v-i* characteristic curve for the arc at the tip of the downed conductor. This curve was obtained using the full set of waveform data.

Fig. 8. 13.8 kV conductor laid on wet grass.

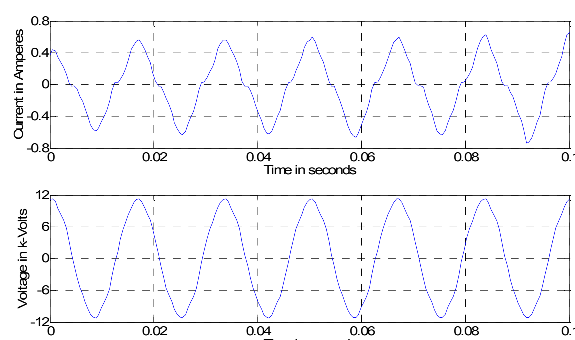

Fig. 9. Current and voltage for the 13.8 kV line with electric arc.

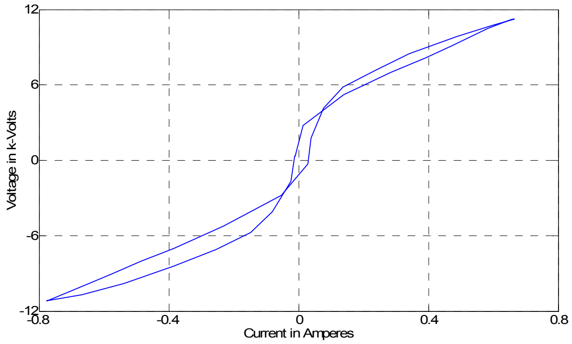

Fig. 10. Current-Voltage curve for the 13.8 kV line with electric arc.

The second experiment on the 13.8 kV line consisted in placing the downed and energized conductor on the ground near a buried grounding copper rod. Figure 11 shows a picture of this experiment. Notice in this figure the rod tip sticking out of the ground, as well as the arc that is produced. Figure 12 shows the measured voltage and current waveforms for this experiment. Same as before, only 0.1 s segments of these waveforms are shown for illustration purposes. The corresponding *v-i* curve is shown in figure 13. In the case of figure 12 waveforms no filtering was applied as the signals didn't seem to be affected by noise. In addition, the cycle averaging process is a natural filter for random noise.

IV. High Impedance Faults

Typical values of currents for HIFs are between 10 and 50 A. This is for ground surfaces like concrete, grass and wet floors in general [9, 10]. To characterize high impedance fault behavior some experiments were performed on a 13.8 kV line. The measurements were obtained from a nearby over-current protection relay 51. A distance relay 21 that was also present did not operate. Both relays were in series, so the distance relay saw the same signals as the over-current relay.

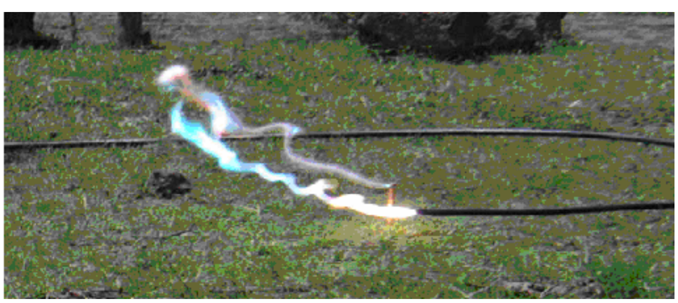

Fig. 11. Photo of the provoked arc for a 13.8 kV line.

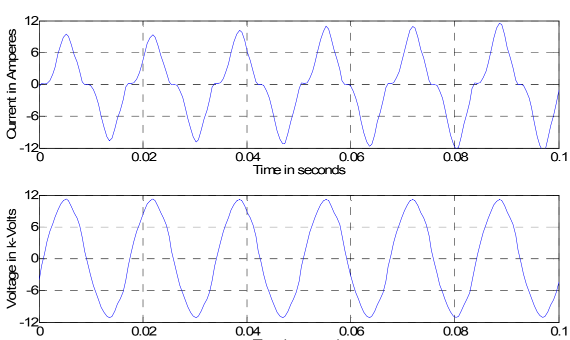

Fig. 12. Current and voltage for the 13.8 kV line provoked electric arc.

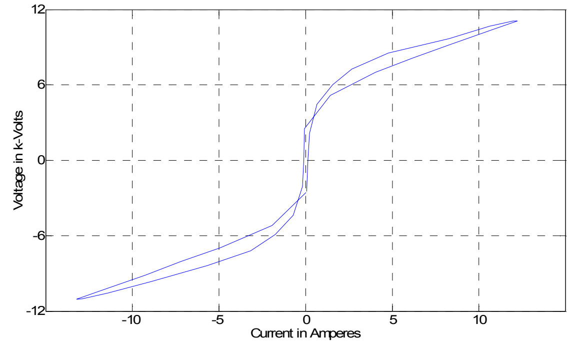

Fig. 13. Current-Voltage curve for the 13.8 kV line provoked electric arc.

4.1 Experiments on a 13.8 kV line.

One of the 13.8 kV conductors is placed on dry grass as it is shown in figure 14. Figure 15 provides the voltage and current waveforms obtained from the over-current relay, while figure 16 shows the corresponding *v-i* trajectory. Note from this figure that this is a simple curve without trajectory crossings, as opposed to those in figures 4, 6, 10 and 13.

Fig. 14. 13.8 kV conductor in touch with the wet grass.

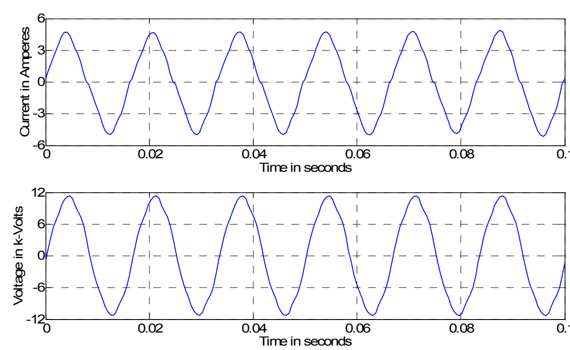

Fig. 15. Current and voltage for the 13.8 kV line with high impedance fault.

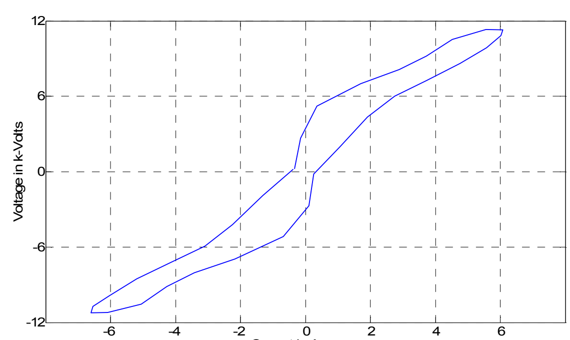

Fig. 16. Current-Voltage curve for the 13.8 kV line high impedance fault.

4.2 Fault measurement on a 69 kV circuit

A fault occurring on a 69 kV distribution system and recorded by an over-current relay had to be analyzed to determine why the associated distance relay did not operate. Figure 17 shows the layout for the distribution system and the fault was on L2.

The fault occurred when one insulator of phase A broke loose from the tower arm. The loose conductor formed a pronounced sag and became close enough to the tower pole as to produce an arc. A distance relay was located at node 4. The relay report indicated a ground fault in phase A-G, located at 50.11 km. The actual fault, however, was at 18.0 km. The registered signals of voltage and current are shown in figure 18, while the corresponding *v-i* trajectory is shown in figure 19. This trajectory shows that the fault has high impedance features.

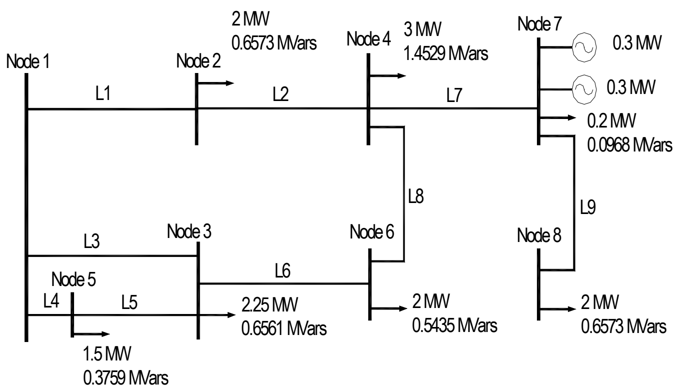

Fig. 17. Lay out of the distribution system Cóbano-Puruarán.

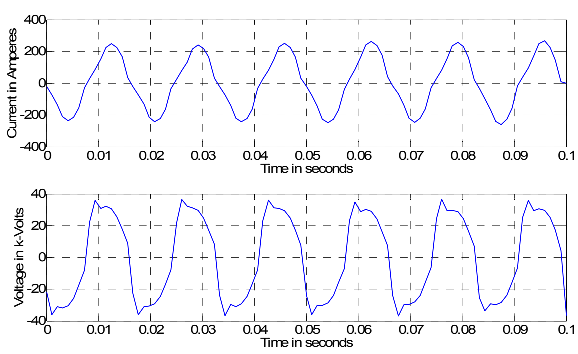

Fig. 18. Voltage and current for the 69 kV line fault occurrence.

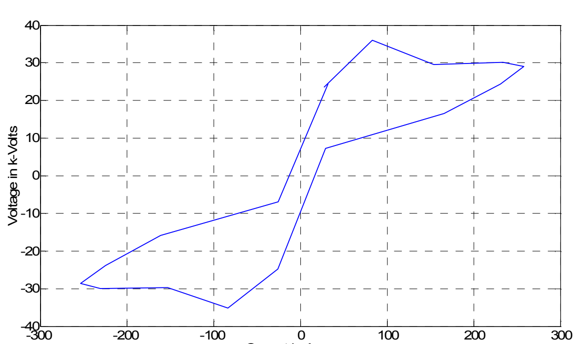

Fig. 19. Current-Voltage curve for the 69 kV line fault occurrence.

V. Evolutionary Faults Caused By Natural Phenomena

Atypical faults are analyzed in this section, all the measurements correspond to real events where distance or over-current relays operated but did not determine correctly the fault; that is, location, type, zone or direction. Full characterization of these faults is extremely difficult and *v-i* trajectories are of no use, especially if the faults are of the evolutionary type. Nevertheless, it is possible to analyze their measured signals and determine some aspects of the faults.

5.1. Evolutionary fault caused by three branches

This fault began with the contact of a three branch with phase A of a 13.8 kV line, after seven and a half cycles it involved phase B; almost five cycles after, the feeder was open. Operating Relay 51 was positioned at about 600 m from the fault location. According to the relay report, the event was a single phase-to-ground fault A-G. Figure 20 shows the waveforms for phase A currents and voltages. These waveforms show how the fault evolves from one to two phases. Healthy phase waveforms are not given here as they do not present meaningful changes.

5.2. Fault caused by a storm

Figure 21 shows a fault caused by strong winds on a transmission line. It initially started as a single phase fault. Two minutes after, a re-close command was executed and distance relay 21 operated under the condition of a three phase fault. The distance relay did not register a fault location and did not operate. However the over-current relay record is shown in Figure 22 and the distance relay record is unavailable.

Clearly from figure 22, the current and voltage waveforms maintain their phase angles. There is thus nonsolid connection between the phases. Phase B has solid connection with the tower crossbeam, and phase C with the tower cross-arm. Phase A seems healthy. Zone 1 relaying time is 0.083 s (5 cycles). This is the reason why the over-current relay did not operate.

VI. Conclusions

In this paper the authors have presented preliminary results of a project dealing with complex faults in distribution systems. By complex faults it is meant to include those ones caused by natural phenomena, such as storms, winds, lightning stroke

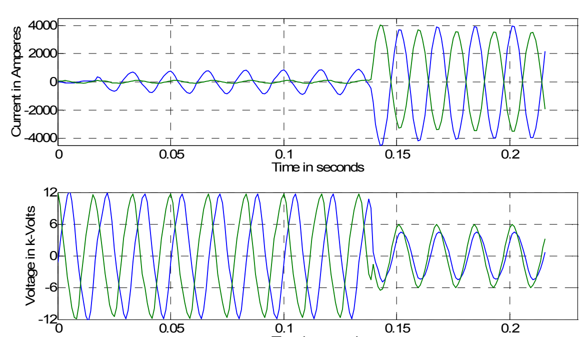

Fig. 20. Current and voltage waveforms of the faulted phases.

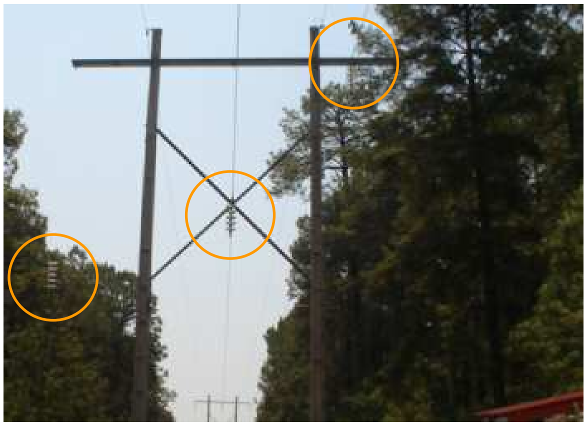

Fig. 21. Set up of the tree phase fault condition.

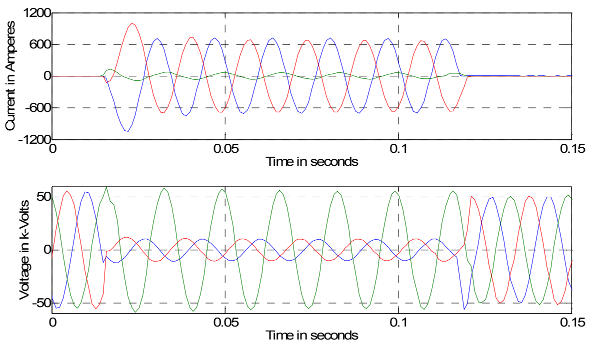

Fig. 22. Current and voltage waveforms of the faulted phases.

induction, falling of tree branches, etc. A classification for these faults has been proposed as follows: 1) arcing faults, 2) high impedance faults and 3) atypical faults. It has been further stated here that real life faults will usually present features from more than one of these classes and that, nevertheless this classification is very convenient.

Measurements corresponding to the above mentioned classes of complex faults have been presented here. Some of these have been obtained from laboratory, some others are from staged faults on actual distribution lines, and the rest are from records of actual faults occurring in a distribution system of the Center-West area of Mexican CFE.

Measured signals of voltages and of currents usually come up contaminated with undesirable noise. A technique to filter this out has been described and applied here to the provided signals. This process has permitted the authors to produce very clean *v-i* trajectories and to distinguish the following two cases: 1) simple trajectories, and 2) trajectories with two crossings. It has been further proposed here that the single trajectory feature can be taken as the criterion to declare a fault as a high impedance one, while the double crossing trajectory-feature to declare it as a fault with dominant arcing effect.

It has been stated here also that atypical faults often end up becoming evolving faults. In these cases it has been pointed out that high speed protection schemes are not recommendable.

The research reported here is at a very preliminary stage. This should be a long term project. Nevertheless, the authors consider that the results provided here are very encouraging and hint at the possibility for detecting correctly most complex faults through conventional relays, only with minor modifications in their software. To accomplish this, however, there is still much additional research work that must be done at both, the experimental and the theoretical levels.

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VIII. Biographies

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