Detection of Incipient Faults in Underground Medium Voltage Cables

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1. Introduction

Medium voltage underground cables may exhibit incipient, self-clearing arcing faults prior to failing permanently. These events typically last one half- cycle and extinguish at the first natural zero crossing of the current. The magnitude of the half-cycle event is primarily dependent on the location of the fault on the feeder, but is also dependent on the point on the voltage waveform that the fault starts.

Operational experience, at least in urban areas, suggests that it is beneficial to trip a feeder suspected of incipient cable faults automatically very early after detecting first symptoms of an incipient fault. Because it limits the overall energy at the point of fault, it also limits the often-repeated voltage transient seen by the system. However, the relatively short duration of an incipient fault and the inability to achieve selectivity via time coordination, make the design of an incipient fault protection function challenging. A simple instantaneous overcurrent element is not sufficient.

Along with presenting operational experience of these half-cycle events at a large urban utility, this paper details a simple and robust method for detecting incipient faults in cable and combined overhead and cable feeders. A number of security measures are implemented to make the method fast, secure and selective.

The method is based on current signals only (no voltage signal required) and, therefore, can be applied in simple feeder overcurrent relays. The logic is simple enough to be programmed via user-programmable math and logic available on some modern microprocessor-based relays.

Test results are presented and explained, including playback of field events and transient simulation using a digital power system simulator.

2. Operational Experience with Underground Cables

With the increased installation of system power quality monitoring devices at the substation level, it was noticed that prior to approximately 10 to 15% of feeder trips the feeder exhibited earlier signs of breakdown in the form of the half-cycle events described above.

Because the monitoring devices were at the substation level, typically installed on one of the supplying transformers, it was not known on which of the 8 to 30 feeders the

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disturbance was occurring. What was known was that anywhere from two cycles to two weeks later, these half-cycle events could manifest into a permanent multi-cycle fault, on the same phase, which would operate traditional overcurrent relay elements. The number of half-cycle events that occur before the “true” fault could be anywhere from one to more than 100.

Very rarely has a half-cycle event occurred in the medium voltage underground network system that has not resulted in a subsequent fault that could be linked to the earlier event by phase and also by magnitude of the neutral current.

The operating implications of these half-cycle faults are as follows:

Fault Energy and Safety

The resulting arc flash energy from these half-cycle events is typically 10 to 20% of a full 3- to 5-cycle fault. Limiting the energy released in a fault obviously has safety benefits for a crew that may be working in the vicinity of the feeder, and also limits the damage to other feeders or equipment. It also has benefits for transformer faults, in that it limits the possibility of a violent failure.

At one extreme, if the relay is enabled to trip after one half-cycle event, with no intentional delay, this would limit the energy of the full fault for almost all cases, except those where the half-cycle event precedes the eventual full fault by less than 3 to 5 cycles.

The other option is to have the relay alarm for these events, if the microprocessor relay is connected to an alarming scheme. This helps identify which feeder the fault is on, and the feeder may be taken out of service, or work in close proximity to the feeder restricted. Of course, this has limited value, because the full fault may occur before operational people can react to the alarm.

The decision as to whether to trip or alarm has the following considerations

- will it eventually fail permanently,
- what are the system conditions at the time of the fault,
- can the fault be located.

Network Reliability

Every time there is a fault on the system, whether it is a full fault or a half-cycle fault, there can be some elevated voltage transients, particularly at the interruption of the fault. This is even more prevalent for ground faults on a large network system supplying delta-connected transformers from a station that is effectively ungrounded (typical source impedances for a Con Edison Area Station are Z_1=0+0.2j ohms, Z_0=0+0.95j ohms).

The problem that half-cycle faults present that are not present in “true” faults, where the feeder breaker opens, is that the half-cycle faults can be occur numerous times in quick succession. On a number of occasions they have been seen to occur multiple times at periods of less than 2 or 3 seconds apart. If, on occasion, a half-cycle fault occurred in a cable joint on a feeder about 40 to 50 times over 90-second period. At the end of the 90-second period, the fault manifested into a true fault, and tripped the breaker, but in the intervening 90 seconds, 2 other faults occurred on separate feeders, almost certainly caused by the voltage transients that occurred on the clearing of each half-cycle event. Within a 90-second period, the network went from all feeders in-service to a 3rd contingency, which was beyond the level designed for.

Fault Location

There is another consideration regarding opening or tripping the feeder that has had these half-cycle faults: whether the fault can now be located using the fault locating techniques presently employed. The thinking being that because the fault self -healed at the first current zero, it will be less likely to break down again under elevated test voltage. This is certainly a consideration and to date there is very little data on this issue, as almost no feeders have ever been taken out of service for a half-cycle event.

However, there have been a few occasions where the fault has been a full-cycle self-clearing event, which operated the traditional relaying protection. Under these circumstances no particular difficulty was observed in locating the fault.

Although rare, another issue that has occurred is where the flash from a half-cycle event is observed by the public or by a crew. The knowledge that it is a primary half-cycle event, and not a low voltage secondary event, is garnered from a corresponding half-cycle disturbance recorded by the substation Power Quality (PQ) device. In this case, where the manhole structure contains only one primary feeder, the issue is simple. Take the feeder out, confirm the location of the fault, and repair. However, when there are multiple primary feeders in the hole, the issue is more complicated because, although the fault is localized to the structure, we may not know which feeder is having the problem, and entry to the manhole for a full inspection of the feeders is not possible for safety reasons. In these cases, having a feeder relay that trips or alarm for such events would be beneficial. In cases such as this that have occurred to date, the feeder with the half-cycle event has failed before any other actions were required. The eventual fault is correlated with the half-cycle fault by phase, approximate magnitude of neutral current, and the fact the half-cycle events cease.

3. Fundamentals of Incipient Faults in Cables

Incipient faults are leading indicators of deteriorating insulation. The aging process of the cable insulating material can be caused by a number of factors, including thermal, electrical, mechanical, and environmental/chemical factors. These mechanisms are relatively well understood. Reference [1] provides good background information. In [1] the aging factors for cables are classified as summarized in Table 1.

Most commonly, electrical stress is the predominant factor in causing cable failures. A typical failure mechanism is a partial discharge and treeing. The former mechanism takes place in organic dielectrics such as in the cross-linked polyethylene (XLPE) cables. The latter mechanism is typical in oil/paper-insulated cables and is aggravated by the presence of moisture.

Table 1. Cable aging [1].

Aging Factor		Aging Mechanism
Thermal	High temperature and temperature cycling	• Chemical reaction • Thermal expansion • Diffusion • Insulation melting • Anneal locked-in mechanical stresses
	Low temperature	• Cracking • Thermal contraction
Electrical	Voltage	• Partial discharges • Electrical trees • Water trees • Charge injection • Intrinsic breakdown • Dielectric losses and capacitance
	Current	• Overheating
Mechanical	Cyclic bending, vibration, fatigue, tensile, compressive and shear stress	• Yielding of materials • Cracking • Rupture
Environmental	Water, humidity, contamination, liquids, gases	• Electrical tracking • Water treeing • Corrosion • Dielectric losses and capacitance
	Radiation	• Accelerated chemical reactions

This pre-breakdown phenomenon takes place in the form of either electrical trees or water tress [1]. The cause of treeing in dry dielectrics is partial discharges due to high electric stresses (Fig.1), and moisture at lower electric stresses (Fig.2).

<u>Electrical Trees</u>

The presence of high and divergent electric stresses is the primary contributing factor to initiate and propagate electrical trees [1]. An electrical tree may consist of many discharge paths including a “trunk” and “branches.”

Electrical trees initiate at about 150kV/mm field strength. When initiated, an electrical tree will propagate through the insulation as a series of random bursts, and when the branches of the tree span the entire insulator layer, a breakdown occurs.

<u>Water Trees</u>

Water trees are caused in the presence of moisture typically at the semiconductor-insulation interface of a cable. Water trees typically start at lower electric fields and propagate slower compared with electric trees [1].

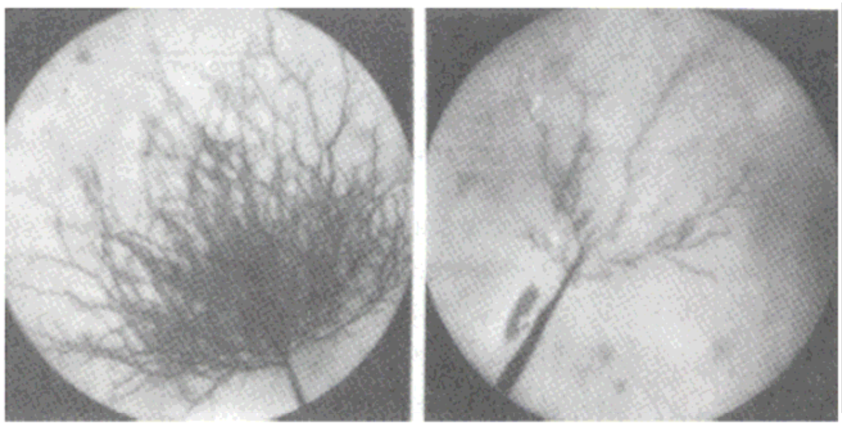

Fig.1. Sample electrical trees [1].

Fig.2. Sample water trees [1].

Water trees convert to electrical trees and result in a catastrophic failure. Typically the conversion is associated with a sustained discharge activity in cavities that are created in the water tree channels. Large water trees can convert at normal operating voltages, and small water trees convert at higher voltage levels during over-voltages caused by switching transients or lightning. As the discharge takes place in the water cavities, only water trees are not associated with detectable partial discharge patterns before converting to the electrical trees.

Incipient Faults

The process of converting a water tree into an electrical tree through a localized partial discharge is relatively complicated and can occur at various rates, including temporary regression of the degradation process due to evaporation of the moisture.

During such period of partial discharge high frequency components are present in the currents. The frequency spectrum spans into few or few tens of kHz, and the nature of such current spikes is random. This situation can last days or months or even years. This paper is not concerned with detecting incipient faults at this stage.

Eventually when the insulating layer is broken, a high fault current of a fundamental frequency is created. However, at this stage considerable damage is done to the cable, and the phenomenon will repeat at an accelerated rate leading very quickly to a permanent fault.

Fig.3 shows an example of an incipient fault. The phase B current is affected showing a typical half-cycle fault pattern. When the current is self-extinguished considerable transients are created in voltages due to interactions between the cables inductances and capacitance.

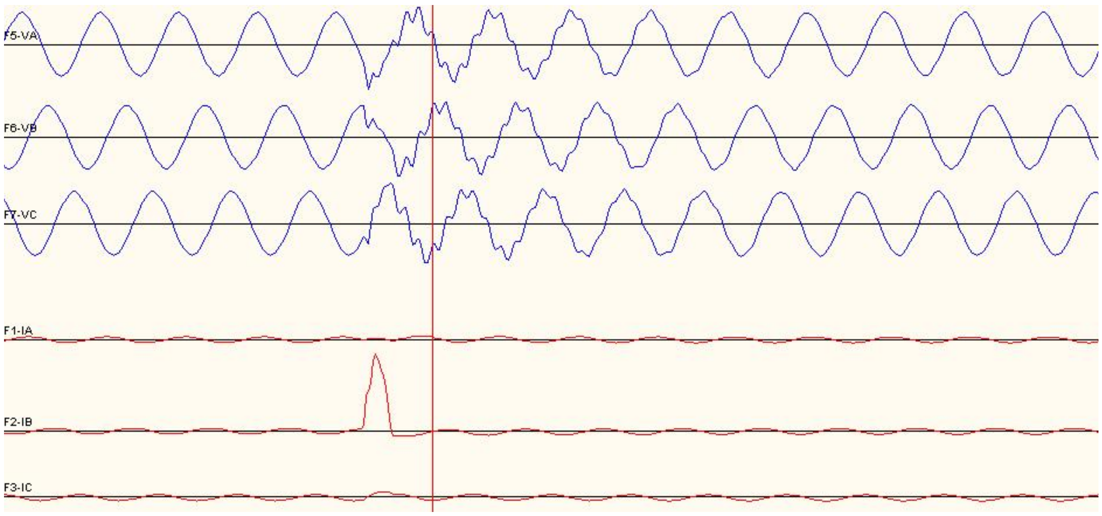

Fig.3. Sample incipient fault: voltages (top) and currents (bottom).

4. Tripping of Incipient Faults in Cables

4.1. Fundamentals

This section describes a method for detecting incipient cable faults based on signals available to a feeder protective relay.

The algorithm is a heuristic pattern recognition function defining an incipient cable fault as the following event (compare with Fig.3):

- no load change occurs during an incipient fault; pre- and post-even currents are virtually identical, otherwise the event might be an external fault cleared very fast by a fuse;
- an incipient fault occurs in one phase only; the superimposed fault current in one of the phases matches, therefore, the neutral current;
- an incipient fault lasts for few multiples of a half cycle; a limit of 3 half-cycles is applied (vast majority of incipient faults are half-cycle events, and if lasting more than three half-cycle the incipient faults are detectable by traditional protection functions).

The above pattern is analyzed independently in each phase.

The algorithm described in this section processes samples of currents and half-cycle measurements to detect an incipient fault. This fine temporal resolution is necessary because of the short-lived nature of the incipient fault current. Processing filtered currents and their magnitudes estimated with full-cycle windows or longer would not be appropriate.

The basic algorithm detects a single incipient fault pattern based on the current. This is complemented by the following supplementary functionality:

- An overcurrent pickup setting is provided.
- A pickup operand is provided to flag a single occurrence of an incipient fault and can be used with counters and logic in customized user applications.
- Two hard-coded operating (tripping) modes are provided: trip on N-th count of the event (N is a setting) and, trip on the N-th count occurring in a time window T (both N and T are settings).

In theory more security can be brought into the algorithm by monitoring the voltage signal and specific patterns in it. This algorithm does not use voltages in order to expand its applicability to relays with no voltage measurements. The required security is ensured by monitoring certain features in the current signals.

4.2. Algorithm

Signals and constants

i_A, i_B, i_C	instantaneous values of the current in phases A, B and C; in per unit of CT nominal; raw samples;
i_N	instantaneous values of the neutral current calculated from raw samples of currents in phases A, B and C;
i_{FA}, i_{FB}, i_{FC}	fault components of the current in phases A, B and C calculated from raw samples of currents in phases A, B and C;
S_A, S_B, S_C	measures of match between the fault currents in phases A, B and C, and the neutral current;
I_{FA_MAG}	magnitude of the superimposed current in phase A (similar for B and C); estimated with the half-cycle Fourier;
I_{1MAG}	magnitude of the positive-sequence current;
Δ_{OC}	pickup level of the overcurrent detector in per unit of CT nominal (user setting);
N_1	number of samples per power cycle (64s/c);
N_M	length of the memory operation separating the fault and load components;
C_1 - C_4	factory constants;

Calculations

The neutral current is calculated first as:

$$i_{N(k)} = i_{A(k)} + i_{B(k)} + i_{C(k)} \tag{1}$$

In equation (1) and below, k stands for a sample index and means a present sample, while $k-1$ means the previous sample, and so on.

Incremental (superimposed) current components are calculated next in order to separate the load and fault currents. This is done on samples using a 2-cycle memory:

$$i_{FA(k)} = i_{A(k)} - i_{A(k-N_M)} \tag{2a}$$

$$i_{FB(k)} = i_{B(k)} - i_{B(k-N_M)} \tag{2b}$$

$$i_{FC(k)} = i_{C(k)} - i_{C(k-N_M)} \tag{2c}$$

Under steady state conditions, even with distorted waveforms, the fault components are very small, ideally zero. During faults and other switching events, the above signals will reflect the fault component in the first two cycles of the fault.

During incipient faults the neutral current and the fault component in the affected phase match. Therefore a measure of that match is calculated as follows:

$$S_{A(k)} = \frac{2}{N_1} \cdot \sum_{j=0}^{\frac{N_1}{2}-1} \left| i_{FA(k-j)} - i_{N(k-j)} \right| \tag{3a}$$

$$S_{B(k)} = \frac{2}{N_1} \cdot \sum_{j=0}^{\frac{N_1}{2}-1} \left| i_{FB(k-j)} - i_{N(k-j)} \right| \tag{3b}$$

$$S_{C(k)} = \frac{2}{N_1} \cdot \sum_{j=0}^{\frac{N_1}{2}-1} \left| i_{FC(k-j)} - i_{N(k-j)} \right| \tag{3c}$$

Next, a half-cycle Fourier algorithm is run on the fault current samples:

$$i_{FA(k)} \rightarrow I_{FA\_MAG(p)} \tag{4a}$$

$$i_{FB(k)} \rightarrow I_{FB\_MAG(p)} \tag{4b}$$

$$i_{FC(k)} \rightarrow I_{FC\_MAG(p)} \tag{4c}$$

In equations (4) and below, p stands for a protection processing instant, while $p-1$ means the previous processing instant, and so on.

It is assumed that the magnitude is scaled as the peak value.

Overcurrent conditions are declared based on the following flags:

$$OC_{A(p)} = \left(I_{FA\_MAG(p)} > \sqrt{2} \cdot \Delta_{OC} \right) \tag{5a}$$

$$OC_{B(p)} = \left(I_{FB\_MAG(p)} > \sqrt{2} \cdot \Delta_{OC} \right) \tag{5b}$$

$$OC_{C(p)} = \left(I_{FC\_MAG(p)} > \sqrt{2} \cdot \Delta_{OC} \right) \tag{5c}$$

A match between phase fault currents and the neutral current is established via the following flags:

$$R_{A(p)} = \left(S_{A(p)} < \max\left(C_1 \cdot I_{FA(p)}, C_2\right)\right) \quad (6a)$$

$$R_{B(p)} = \left(S_{B(p)} < \max\left(C_1 \cdot I_{FB(p)}, C_2\right)\right) \quad (6b)$$

$$R_{C(p)} = \left(S_{C(p)} < \max\left(C_1 \cdot I_{FC(p)}, C_2\right)\right) \quad (6c)$$

Next, the following flags are established:

$$E_{A(p)} = OC_{A(p\_)} \;\&\; R_{A(p)} \;\&\; not\left(OC_{B(p)} \; or \; OC_{C(p)} \; or \; R_{B(p)} \; or \; R_{C(p)}\right) \quad (7a)$$

$$E_{B(p)} = OC_{B(p\_)} \;\&\; R_{B(p)} \;\&\; not\left(OC_{A(p)} \; or \; OC_{C(p)} \; or \; R_{A(p)} \; or \; R_{C(p)}\right) \quad (7b)$$

$$E_{C(p)} = OC_{C(p\_)} \;\&\; R_{C(p)} \;\&\; not\left(OC_{A(p)} \; or \; OC_{B(p)} \; or \; R_{A(p)} \; or \; R_{B(p)}\right) \quad (7c)$$

During incipient faults one of the above flags will pickup for a short period of time, depending on the magnitude of the current and duration of the fault.

The last step is to check the lack of loss of load in order to distinguish incipient faults from load changes or external faults.

Upon a rising edge of the *E* flag defined as:

$$E_{(p)} = E_{A(p)} \; or \; E_{B(p)} \; or \; E_{C(p)} \quad (8)$$

the following operations are performed:

- Magnitude of a pre-fault positive-sequence current is captured: I_{1PRE}. This value is a 2-cycle old value proceeding the rising edge of the *E* flag.
- Magnitude of the post-fault positive-sequence current is captured: I_{1POST}. This value is a value that occurs 4 cycles after the rising edge of the *E* flag.

Consistent load is declared if the two values differ less than certain portion of the pre-fault current and the CT nominal current:

$$L = \left(\left|I_{1PRE} - I_{1POST}\right| < \max\left(C_3 \cdot \max\left(I_{1PRE}, I_{1POST}\right), C_4\right)\right) \quad (9)$$

The final event flags are supervised with the consistent load condition as follows:

$$Event_A = E_A \;\&\; L \;\&\; not\left(OC_{A(at\ post-fault)}\right) \quad (10a)$$

$$Event_B = E_B \;\&\; L \;\&\; not\left(OC_{B(at\ post-fault)}\right) \quad (10b)$$

$$Event_C = E_C \;\&\; L \;\&\; not\left(OC_{C(at\ post-fault)}\right) \quad (10c)$$

Fig.4 explains the timing relationship between the event flags and the pre- and post-fault currents.

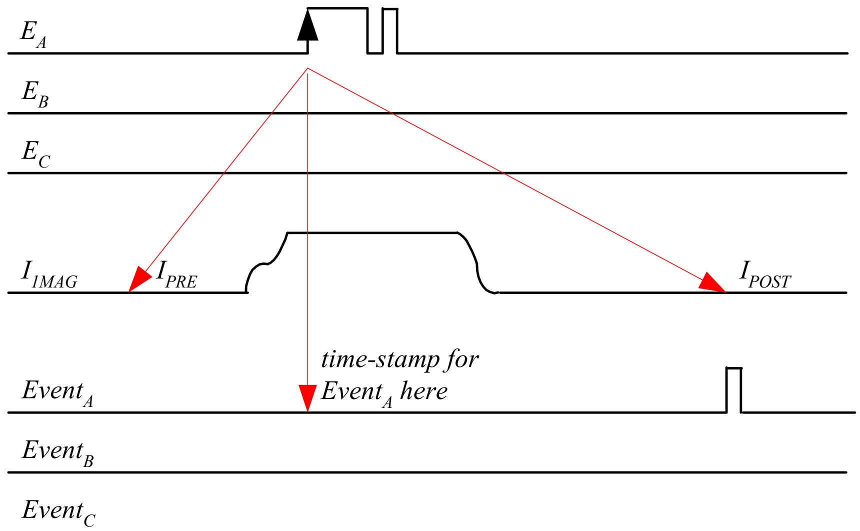

Fig.4. Explanation of capture and application of the pre- and post-fault load check.

4.3. Illustration of the algorithm operation

Fig.5 shows a case of an incipient phase-B fault registered by a feeder relay (top figure shows the raw A, B and C currents). The bottom portion shows the neutral current (blue) clearly revealing the fault period from under the load, and the superimposed phase B current (red). The superimposed current shows the fault current blip twice as the data slides through the 2-cycle memory window. During the actual fault, the neutral current and the superimposed phase B currents match very well, confirming the incipient fault hypothesis and identifying the affected phase.

Fig.6 shows the magnitude of the superimposed currents. Due to half-cycle measurement, the fault current is estimated accurately (full cycle algorithm would see half of the current that last that short). The figure shows a user pickup threshold set at 0.5pu RMS. The bottom portion of the figure shows the S-values. During the actual fault the B-phase value is low indicating a good match between the neutral and phase B current. During the mirror spike in the B-phase, the neutral and B-currents do not match, which will prevent misidentification of this event as a fault.

Fig.7 shows key logic flags of the algorithm. The neutral current is shown to signify the time of actual event. The E-flag is asserted shortly afterwards and stays robustly picked up. The OC-flags behave as expected: only the B-phase seen and overcurrent condition. Two pulses are visible: one for the actual event and the other for the mirror image due to the windowing effect. The match flags (R) are picked up during steady state conditions and reset during transients if the neutral and incremental phase currents do not match.

Fig.8 illustrates the measurement and capture of the positive-sequence current magnitude for the load consistency check.

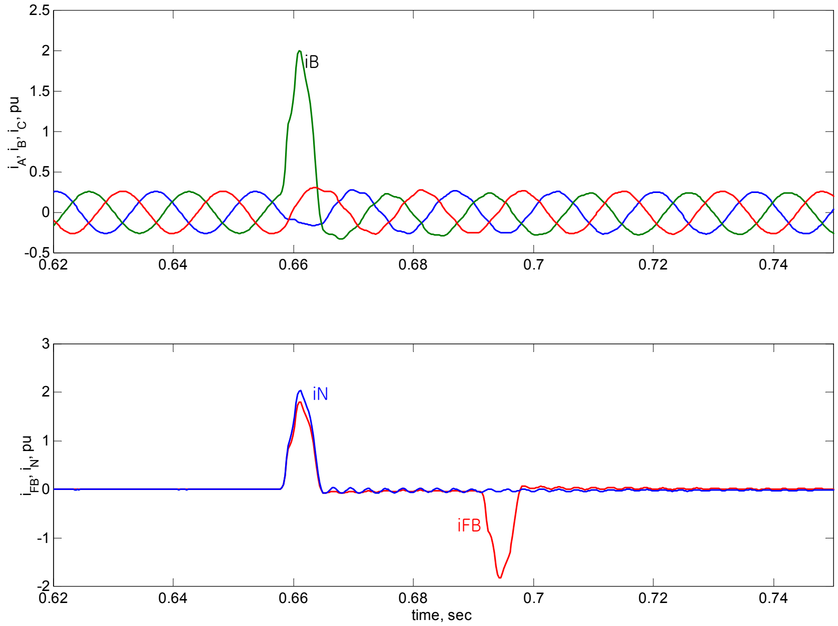

Fig.5. Illustration of the algorithm: phase currents (top), calculated neutral and superimposed phase B current (bottom).

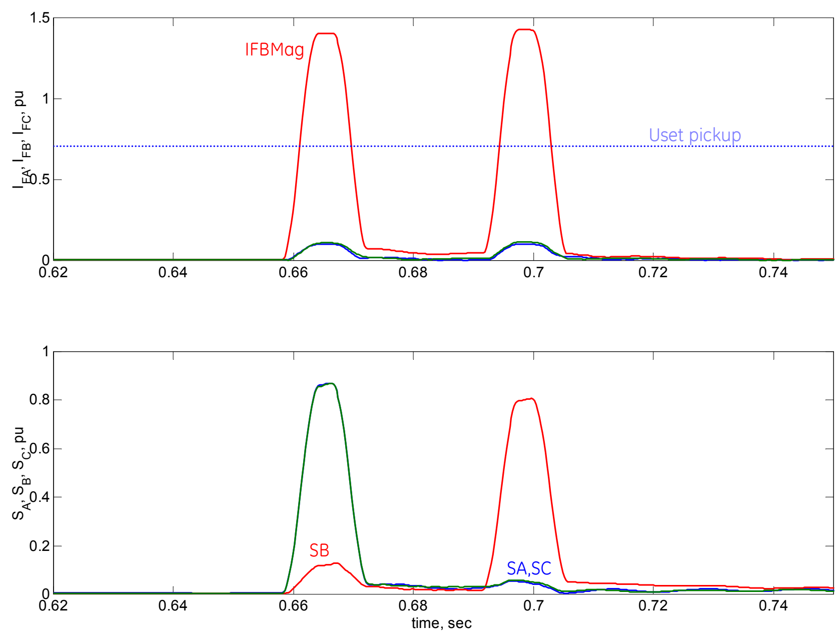

Fig.6. Illustration of the algorithm: fault magnitudes (top) and S-values (bottom).

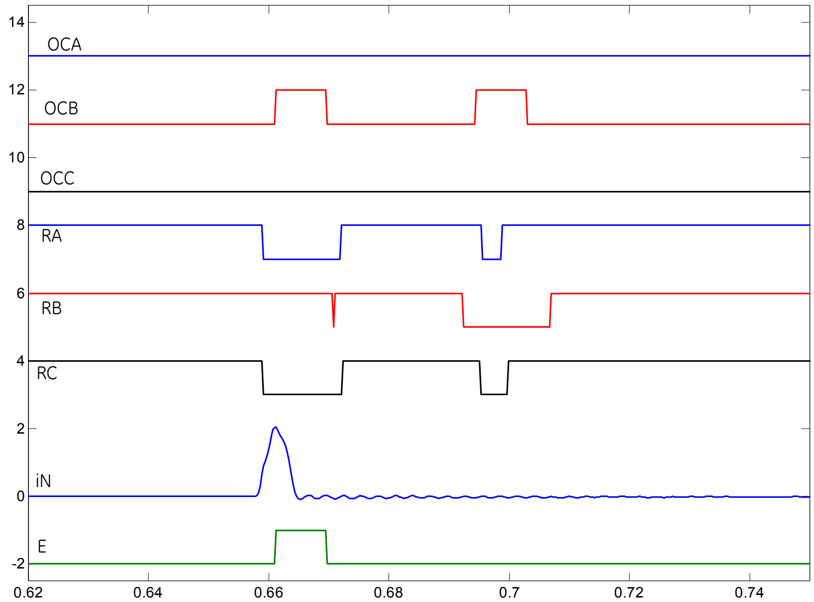

Fig.7. Illustration of the algorithm: major logic flags.

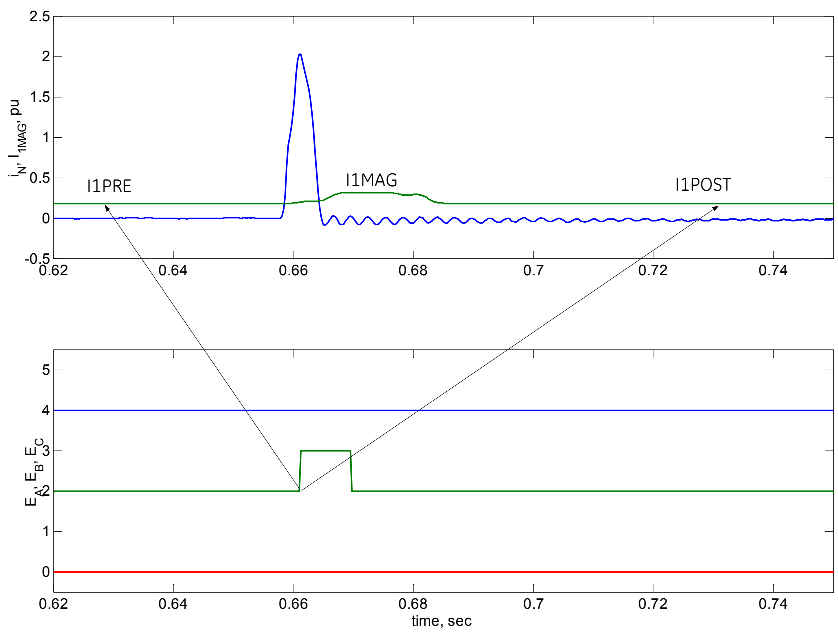

Fig.8. Illustration of the algorithm: positive-sequence magnitude and the pre- and post-fault current points.

4.4. Testing recommendations

Simplified test waveforms for positive testing can be created by superimposing a three-phase balanced load current and an incipient fault current ("blip"). The fault current should be combined as a series of 1, 2, or 3 half-cycle waveforms (cosine shapes). The magnitude of the fault component can be varied to test the overcurrent pickup. Fig.9 below illustrates the idea.

Simplified test waveforms for negative testing shall include regular faults (both inception and removal), and other cases that violate definition of the incipient fault as stated in clause 4.1. This includes load pickup and dropout, open phase conditions (down conductor), single-phase load and phase unbalance, etc.

4.5. Operation using transformer currents

The method can be used with the total current supplied from the transformer toward the distribution bus. By subtracting the load current the method retains its sensitivity even though the load current may be significant as compared with the fault current. Of course, when supplied with the total current, the method loses selectivity and may be used for alarming rather than tripping.

The method cannot be directly applied to the high-side transformer currents. For a wye/delta transformer, it is not possible to reconstruct the zero-sequence current on the low-side wye winding from the high-side delta winding currents. Therefore, measuring the high-side delta currents a relay is not able to calculate the true values of the low-side phase currents. However, both the positive- and negative-sequence components on the low-side can be reproduced from the high-side currents, and an expanded method is possible to detect the short lasting incipient faults in the low-side from the currents captured on the high-side of the transformer.

5. Field and Test Examples

Fig.10 presents result of a playback of a sample incipient fault cases recorded by a feeder relay. The event is successfully detected after few cycles of delay in the algorithm provisioned for checking the load change.

Fig.11 presents a sample test case from a real time digital simulator. The incipient fault function was set to operate on the second occurrence of the fault within a pre-defined time window. The element picks up on both incipient faults and operates, as configured, on the second instance. This application can be used to ride through a single incipient fault but operate if the trouble is progressing. The PKP operand may be used for alarming, and the OP operand – for tripping.

Fig.12 illustrates a case of an incipient fault with the magnitude of 3.1pu RMS and duration of one full cycle. The phase IOC function is set at 3.0pu, the neutral IOC function is set at 1.5pu, and the negative-sequence IOC is set at 0.5pu. All three elements are used as instantaneous. Depending on the magnitude of the incipient cable fault, it may or may not be detected by conventional protection elements. In this case, the neutral IOC function operates in addition to the dedicated incipient fault detection function.

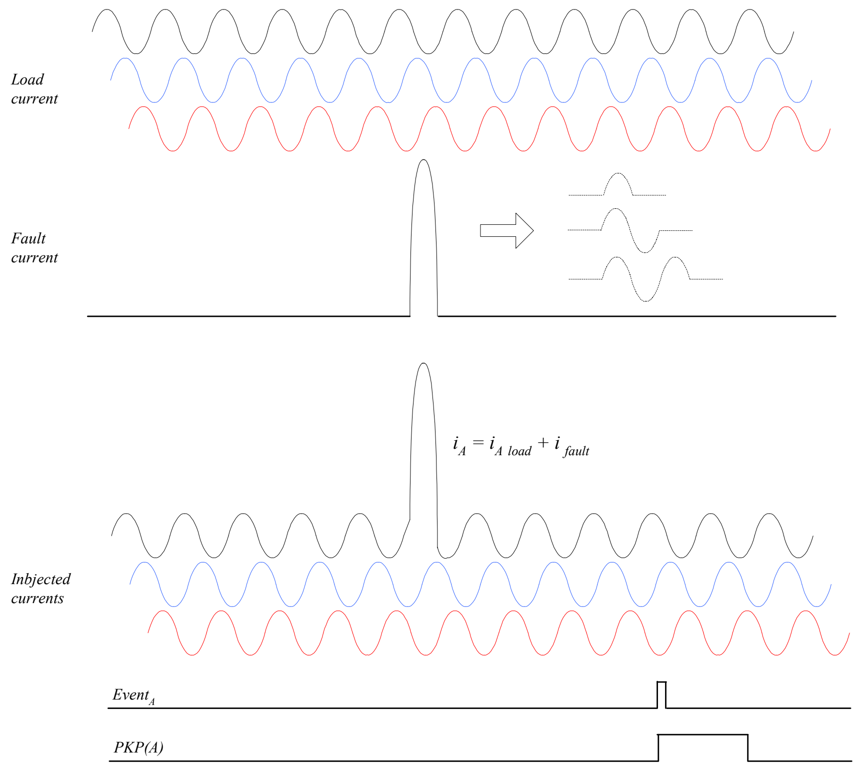

Fig.9. Illustration of a simplified positive test of the algorithm.

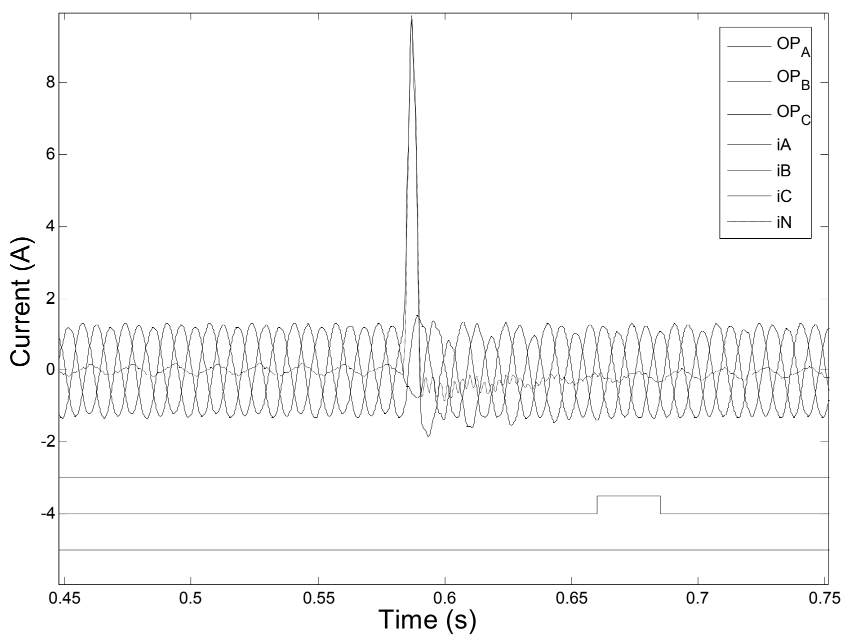

Fig.10. Playback of a sample field case of an incipient fault.

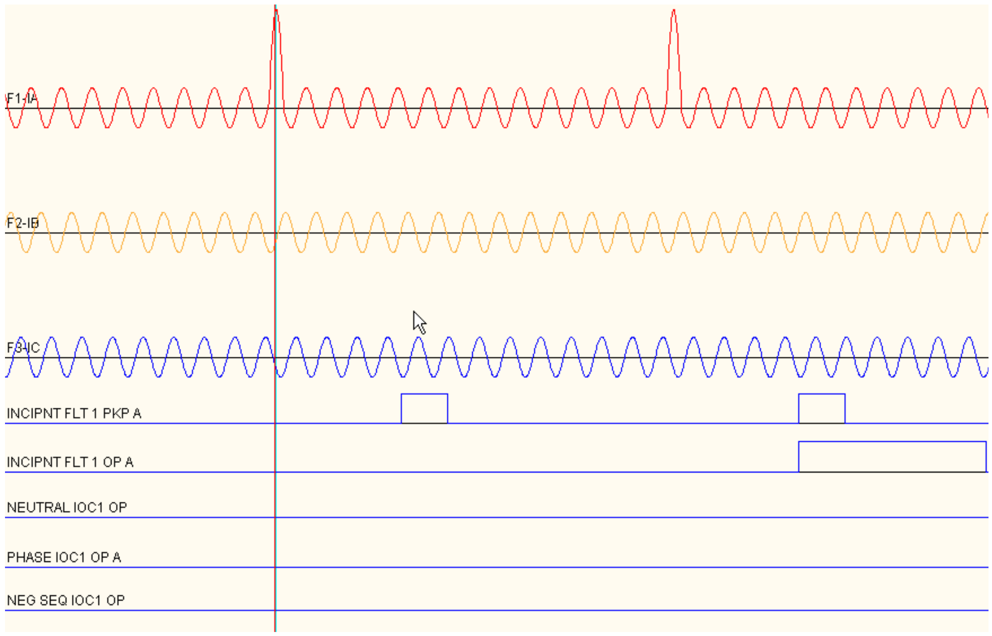

Fig.11. Operation example of the incipient fault element configured to trip in the second incipient fault.

For comparison, Fig.13 shows a case of a fault lasting two cycles. This fault is seen by traditional protection but not by the dedicated incipient fault element. The latter does not respond by design as the event lasts longer than three half-cycles and is very unlikely to be an incipient fault.

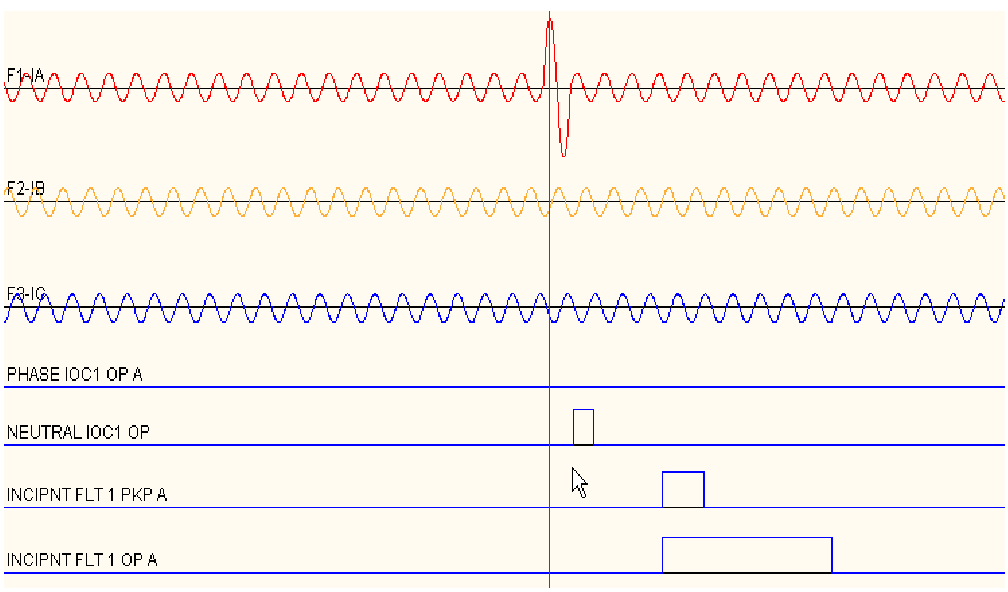

Fig.12. Example of a one-cycle incipient fault detected by the incipient fault function and some traditional short circuit protection functions.

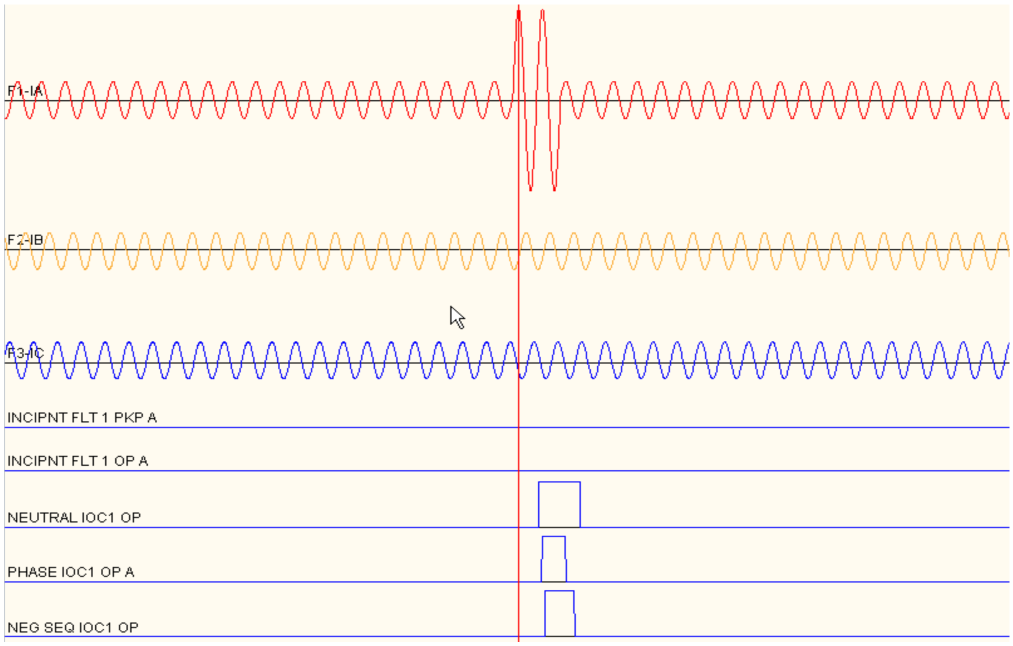

Fig.13. Example of a two-cycle fault detected by the traditional short circuit protection functions, and not signaled (correctly) by the incipient fault detector.

When testing the incipient fault function it is recommended to apply cases of traditional (permanent) faults, unequal pole closing/opening, external ground faults including very fast clearing via fuses, capacitor bank switching, transformer energization and similar events that may cases patterns of elevated current lasting between half a cycle and few cycles.

6. Application Guidelines for Tripping Incipient Cable Faults

The issues that come into the decision to deploy the logic in the first place is how often does the phenomena occur before each genuine fault. As discussed previously, it is estimated that approximately 10% to 15% of faults on the underground system that operate traditional relaying are preceded by at least one half-cycle event.

So, even with full deployment of this system, there will be no impact on the arc flash energy for 85 to 90% of all faults. That being said, there is some evidence to suggest that the number of half-cycle events is on the increase and this may be because they are more prevalent in the newer mechanical type joints that are making up an increasing percentage of the system.

Having decided to implement the logic, the decision really comes down to whether to alarm or to trip. If deciding to trip, the decision comes down to whether to trip after the detection of the first half-cycle event or whether to wait until two or three events occur (possibly even in a certain time period). What influences this decision is the number of events that are typically seen before the full fault and the time difference between the first event and the final fault.

The first issue to consider is that on a fully underground system, where there are no downstream HV switching devices (breakers, fuses) to co-ordinate with, if a half-cycle event has occurred, then the cable will almost certainly fail leading to a fault that will operate traditional overcurrent elements.

The problem faced by the relay engineer is really one caused by the fact he now has a choice as to whether to trip the breaker or wait until the full fault.

Ideally, if one has communication with the relay then one might be more inclined trip at periods of low load or low system risk, and more inclined to see if the feeder will hold in during a summer heat wave. However, if the half-cycle event becomes more frequent with subsequent over-voltages produced by the events, the best thing for reliability purposes (to prevent damage to components on other feeders) may be to take the feeder out of service irrespective of loading and system conditions.

7. Summary

This paper presents an operational experience with incipient faults: it has been observed that 10 to 15% of cable faults are preceded by incipient faults. Practically all incipient faults become permanent faults in the period between a few seconds to few weeks. Incipient faults occurring in fast successions create considerable over-voltages and induce faults on other feeders.

A method has been presented to detect incipient faults in a secure and reliable way. The method is secure by checking consistency of the load before and after the event, checking if the event is a single phase event, and checking for duration and consistency between the superimposed fault component and the ground current.

The presented method has been implemented [2] and tested using recorded field cases and on a digital simulator. Simplified variants of the method can be implemented by using programmability and flexibility of modern microprocessor based relays.

Recommendations are given as to the trip vs alarm applications of the incipient cable fault detection functions. In many cases tripping on the first incipient fault is a prudent application.

8. References

[1] N.H.Malik, A.A.Al-Arainy, M.I.Qureshi, *Electrical Insulation in Power Systems*, Marcel Dekker, 1998.

[2] *F60 Feeder Management Relay*, Instruction Manual, General Electric. Available at www.multilin.com.

Biographies

Bogdan Kasztenny holds the position of Protection and System Engineering Manager for the Digital Energy business of General Electric. Prior to joining GE in 1999, Dr.Kasztenny worked as an Assistant Professor conducting research and teaching power system courses at the Wroclaw University of Technology, Texas A&M University, and Southern Illinois University. His full time academic career culminated with a Senior Fulbright Fellowship in 1997. Between 2000 and 2004 Bogdan was heavily involved in the development of the globally recognized Universal Relay™ product line, for which in 2004 he received GE's Thomas Edison Award for innovation. Bogdan remains hands on and instrumental in new product development at General Electric. He acts as an R&D liaison with several universities and Corporate Research. Bogdan authored more than 160 papers, conceived numerous protection and control products, is an inventor of several patents. Bogdan is an IEEE Fellow class of 2008, and a member of the Main Committee of the IEEE PES Power System Relaying Committee, where he chairs or co-chairs several working groups. Dr.Kasztenny is a registered Professional Engineer in the province of Ontario, an Adjunct Professor at the University of Western Ontario, and a Member of the Canadian National Committee of CIGRE, Study Committee B5 – Protection and Automation.

Ilia Voloh received his Electrical Engineer degree from Ivanovo State Power University, Russia. He then was for many years with Moldova Power Company in various progressive roles in Protection and Control field. Currently he is an Application Engineer with GE Multilin. His areas of interest are current differential relaying, phase comparison, distance relaying and advanced communications for protective relaying. Ilia authored and co-authored more than 10 papers presented at major North America Protective Relaying conferences. He is a member of the PSRC, and a senior member of the IEEE.

Christopher G. Jones holds a degree in Electrical Engineering from the University of Newcastle, Australia. Chris held Engineering positions with Australian utilities TransGrid and Energy Australia from 1991 to 2001 concentrating mostly on substation, protection and metering issues at the transmission and sub-transmission level. Since 2001 Chris has worked for the Consolidate Edison Co. of New York holding various positions involved with transmission and distribution protection as well as distribution equipment and system analysis. He is presently the Department Manager of the Bronx/Westchester Engineering group. Chris is a registered Professional Engineer in the state of New York.

George Baroudi holds a degree in Electrical Engineering from Manhattan College, New York. He's been working at Con Edison since 2001, and has completed Con Edison's Leadership Program. He has worked in Distribution Network Systems department, analyzing load, system conditions, and reviewing distribution specifications. George now works with the Power Quality group at Con Edison. He responds to customers load problems, and supports Con Edison's Control Center with Feeder Fault Locating process using the method of Reactance to Fault.