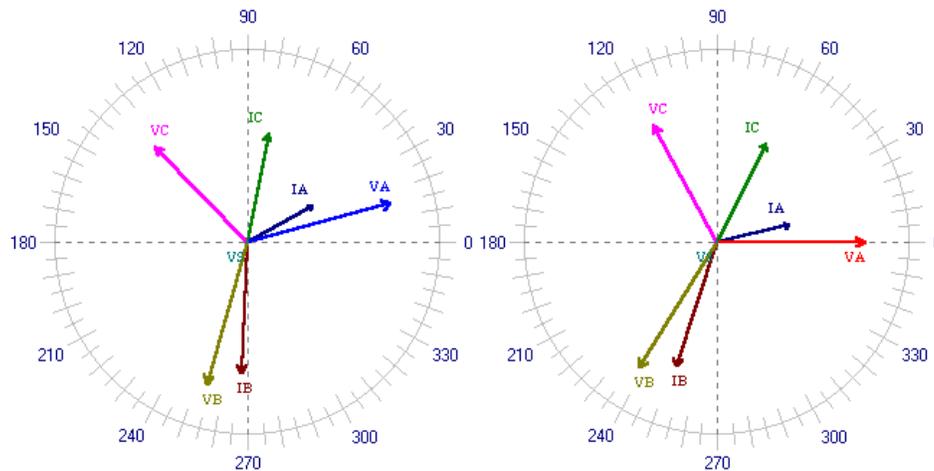


Double Ended Fault Location Application using IEEE Standard C37.114



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I – Abstract

The paper describes the double ended fault location method of IEEE Standard C37.114-2004 and its proper application under real life fault conditions. The method is based on sequence components and there are conflicting recommendations on which components to use and under which fault conditions to use them. The paper addresses these conflicting recommendations and addresses the complexities of calculating sequence components from multiple fault records including synchronization, missing phases, reversed polarities, calibration (RMS or peak), scale (primary or secondary), rates, and filtering. Special emphasis is placed on understanding and quantifying what causes errors in the calculation.

The paper provides a number of case studies showing performance of the method in real life including with single and multiphase faults. The method is benchmarked against single ended locators including reactance and radial line methods. The intent of the authors is for the paper to serve as a tutorial on the double ended method and its proper application in the field. The authors strongly recommended getting the C37.114 Standard from the IEEE web site. It is an excellent read.

II – Background (the Double Ended Equation)

Figure-1 shows the equivalent circuit model used in C37.114 for a fault on a transmission line with two sources. The model is used to calculate fault location based on the availability of fault data records from

both ends of the line. The near and far side bus terminals are designated NS and FS respectively. The fault is located on the transmission line at a unit distance “ m ” from Bus NS and a distance “ $(1 - m)$ ” from Bus FS.

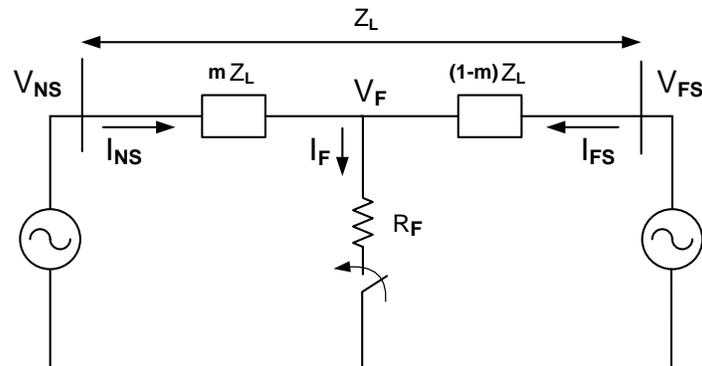


Figure-1; Fault on a Transmission Line with Near and Far Sources

The terms used in Figure-1 for the three phase equivalent circuit model are:

- V_{NS} = near side bus voltages,
- V_{FS} = far side bus voltages,
- I_{NS} = near side line currents,
- I_{FS} = far side line currents,
- V_F = fault voltages,
- I_F = fault currents,
- R_F = fault resistances, and
- Z_L = line impedance between terminals NS and FS.

The values for the near and far side voltages and currents are known because they can be calculated from the available fault data records from both ends of the line. The line impedance value is also known because it is a measured and well documented quantity. The only unknowns are fault location “ m ” and the corresponding voltages and currents which means that the above model reduces, using Kirchoff’s voltage law, to a simple system of two equations with two unknowns “ m ” and “ V_F ”:

$$V_{NS} = m Z_L I_{NS} + V_F \quad (1)$$

$$V_{FS} = (1 - m) Z_L I_{FS} + V_F \quad (2)$$

The fault location “ m ” can thus be calculated by subtracting the above equations to eliminate “ V_F ” which yields:

$$m = (V_{NS} - V_{FS} + Z_L I_{FS}) / Z_L (I_{NS} + I_{FS}) \quad (3)$$

At first glance, equation 3 seems simple and easy to automate because it does not depend on load, fault type, or fault resistance, and it also works for temporary or intermittent faults where neither end opens which makes it a valuable tool for maintenance. The only question left is which sequence components

should we use to represent the equivalent circuit model. C37.114 does not explicitly state which components to use and in which cases to use them. It states that “positive sequence components are used rather than zero sequence”. The standard also states that the equation “has been tested in the field with accurate results” and provides a number of good references.

However, a paper by Steve Turner “Simple Techniques for Fault Location” presented at the 2002 Georgia Tech Protective Relaying Conference recommends using negative sequence components which conflicts with the C37.114 recommendation to use positive components. Accordingly, the aim of this paper is to apply and benchmark performance of the double ended equation in a number of real life cases using both positive and negative sequence components. Zero sequence components are also tested. The results of this work are aimed to help guide the next revision of the standard.

III – Sequence Components and Fault Types

Fault types are categorized as either unbalanced or balanced. Unbalanced faults are ground faults such as single phase to ground, double phase to ground, and triple phase to ground faults. Balanced faults on the other hand are phase faults such as phase to phase and three phase faults. In general, fault conditions produce negative and zero sequence components while positive components are produced by the source. In a balanced system, positive components are present in both balanced and unbalanced fault types, zero components are only present in unbalanced types, and negative components are present in both types except for balanced three phase faults as shown in Table-1.

Fault Type	Positive Sequence	Negative Sequence	Zero Sequence
Balanced Three Phase	Yes	No	No
Balanced Phase to Phase	Yes	Yes	No
Unbalanced Faults	Yes	Yes	Yes

Table-1; Fault Types and Presence of Sequence Components

System imbalances such as unbalanced loads and mutual coupling may cause both zero and negative sequence components to be present in all cases. Depending on their magnitudes such imbalances may cause errors in the location calculation. Selecting which components to use and when to use them is a major factor in automating the double ended equation. If system imbalances are properly mitigated then for unbalanced faults all three components should produce the same fault location. For balanced phase to phase faults both positive and negative components should produce the same fault location. However, for balanced three phase faults only positive components are present. Thus positive components seem to be the most logical ones to use for automating the equation because they are present in all cases and are also recommended in C37.114.

To put these logical discussions to the test, the paper provides two case studies where all three components are used and the results are compared to the actual fault locations. The first case is an unbalanced fault and the second one is a balanced phase to phase fault. A critical factor in these studies is the process of reading fault data records from both ends of the line and then calculating the needed sequence components with sufficient engineering accuracy. This type of process requires an array of advanced software tools for validating and conditioning fault data records. The next section provides a flavor of what the process actually entails.

IV – Dealing with Fault Data Records

Calculating a double ended fault location for a particular line requires dealing with fault data from both ends of the line. There are many types of devices that provide fault data. At one end we may have a digital fault recorder but at the other end we may have, amongst other types of devices, a digital relay or a digital meter or a phasor measurement unit. The problem here is that we may end up with fault data from various types of devices which means various types of storage and naming formats as well as various types of calibration, sampling, synchronization, filtering, and triggering techniques all of which affect accuracy. This is especially true with fault data from legacy devices (commonly called proprietary devices). To deal with this problem engineers use and maintain a collection of programs, typically one from each type of device being used which considerably slows down the analysis process and increases the potential of inaccuracies in the calculation.

A number of IEEE standards have been developed to help address this problem. For example COMTRADE (C37.111) provides a common format for exchanging data files, and COMNAME (C37.232) provides a common format for naming them. Fault data from modern devices are mostly compliant with these standards and are therefore easier to work with because a common program can be used to read data from various types of devices which in turn speeds up the analysis process. However, we have plenty of room left for improvement. A number of new standard development activities are underway to further address the problem by standardizing on the contents of fault data. For example many of the fields defined in COMTRADE are free formatted fields such as device names and channel titles which are assigned based on user preference and not based on a common format. Such fields hinder the process of interpretation and automation so COMDEV is being developed to standardize them. COMTAG is another standard being developed to define requirements for time tagging and for stating the resulting time accuracy which enhances the process of aligning data from both ends of the line.

The future of providing double ended locations automatically and accurately is promising but the present process remains highly complex requiring advanced tools for validating fault data records. The typical process involved in calculating a double ended location includes the following steps:

- Collect the fault data records from the devices at each end of the line
- Check and correct for missing phases
- Check and correct for reversed polarities
- Check and correct for calibration mismatches (peak or RMS)
- Check and correct for scaling mismatches (primary or secondary)
- Check sampling rates and align both data records
- Calculate sequence components at the faulted voltages and currents from both records
- Lookup line impedance and match its scale with both records (primary or secondary)
- Run the double ended equation

The above process may take hours to complete especially if done manually but with the proper tools the process takes just a few minutes. An example of a good tool set is the Wavewin program. The program automatically collects fault data records from various types of devices. It provides software channels for calculating missing phases and correcting polarities. It provides options for switching between primary

and secondary values and for recalibrating to peak or RMS. It also provides features for automatically calculating sequence components and for aligning data records including merging and appending. A good paper to read on this subject is "Combining Digital Fault Records from Various Types of Devices (Virtual-DFR)" which was presented at the 2006 Georgia Tech Fault Conference.

All of these features are necessary for validating and conditioning fault records prior to running a double ended calculation. For example consider the fault record shown in Figure-2.

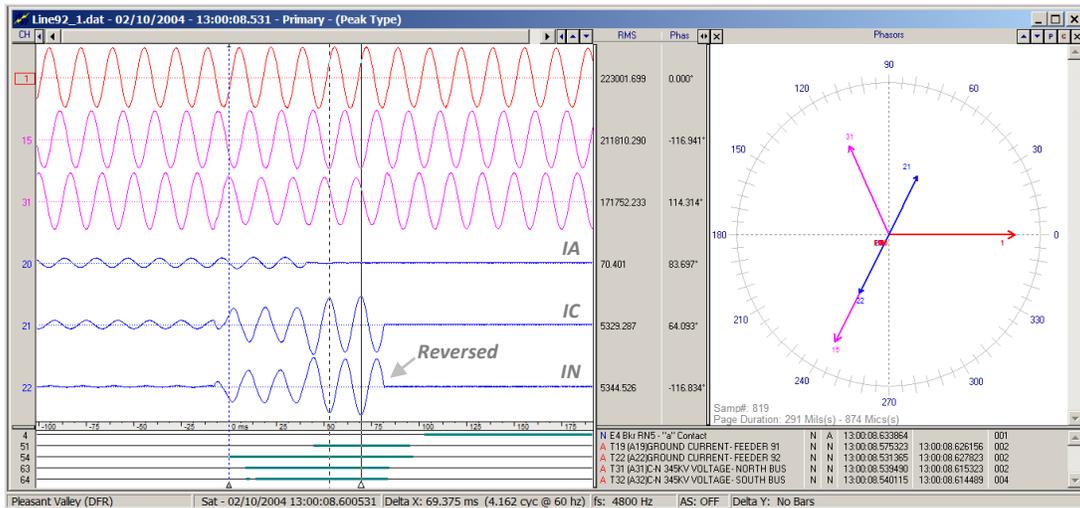


Figure-2; Fault Record from one end of a 345kV Line (Phase C to Ground fault)

The phase voltages *ABC* are shown at the top but the phase currents are not all present (phase *B* is missing). Having a missing phase is a common occurrence. It is standard practice to monitor 3 out of 4 currents especially when we don't have enough channels to monitor everything we need. Since the sum of phases *ABC* equals the neutral current *N* then we can always mathematically reproduce the missing phase. However, notice that the neutral current is in the opposite polarity of the faulted phase so it must be reversed prior to reproducing the missing phase. This too is common especially with neutral currents because it is difficult to check polarities of neutral CT connections without an actual ground fault. Manually correcting such records requires time and patience but with the proper tools it can be done in a few clicks. Figure-3 shows the corrected or now "conditioned" fault record. Notice that the prefault voltages are 120° apart as they should be and that the prefault currents are also 120° apart. This is good confirmation that the conditioned record is valid.

As for calibration and scale, we may get an RMS calibrated record from one end of the line and a peak calibrated record from the other end especially if the line is shared between two companies. The difference is a $\sqrt{2}$ multiplier. The prefault magnitudes of the phase voltages in Figure-3 are at 200 kV (line to neutral) which is correct for a 345 kV line ($200 = 345/\sqrt{3}$) so the data is peak calibrated. If the record was RMS calibrated then the phase voltages would have been at 144 kV. The main concept is to properly match the calibration of the fault data records from both ends of the line otherwise significant errors will result in the location calculation. The same is true for scale. Fault records and line impedance quantities could be either in secondary or in primary values. The difference is the CT and PT ratios. With the proper tools matching calibration and scale is simply a few clicks of the mouse. As long as everything matches, the equation works fine for peak or for RMS data and in primary or in secondary values.

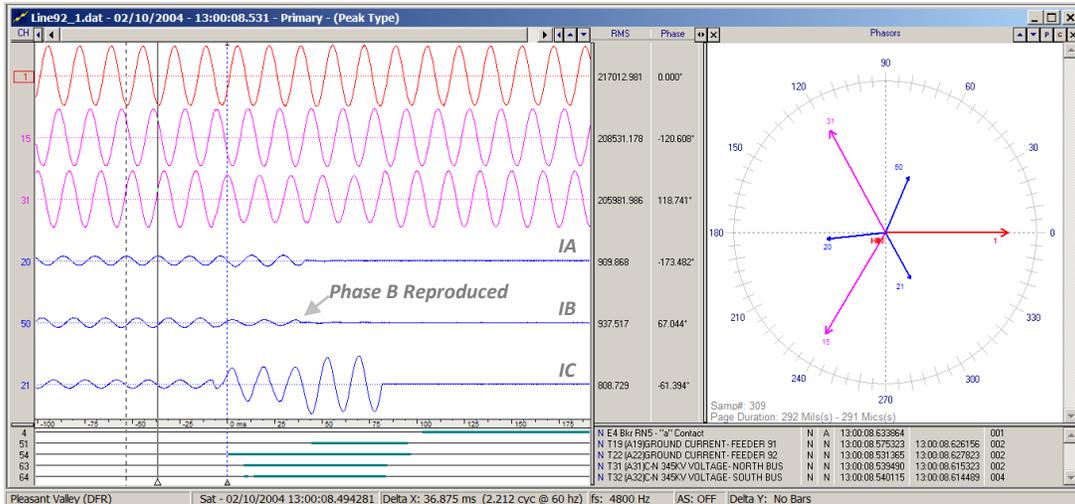


Figure-3; Polarity Corrected, Missing Phase Reproduced and Neutral Discarded

In summary, preparing fault records for a double ended calculation is a complex process of matching formats, phases, polarities, calibration, and scale but with the proper tools the effort is seamless. More importantly, the long term effect of using such tools leads to a structured environment meaning a well tuned system where everything matches and running the double ended calculation is a simple and quick procedure. A good example of such an environment is at Dominion Virginia Power where the double ended equation is being benchmarked and a considerable number of case studies have already been accumulated. These case studies have helped provide insight into the performance of the double ended equation using the various types of recommended sequence components. Two of these case studies with unbalanced and balanced faults are detailed in the next sections.

V – Double Ended Application (Case One)

An unbalanced phase C to ground fault occurred on Line 54 on 5/17/2010. The Line length is 36.99 miles. The actual fault location was at 1.66 miles from the near end. With a few clicks of the mouse, the fault data records from both ends of the Line were opened, tiled, and aligned as shown in Figure-4 (the near end record is the top record).

The alignment process is critical for the accuracy of the calculation. The process entails matching angles of the reference phases in each record. The reference phase is the phase used to reference the calculation of the sequence components which for the purposes of this paper is phase A. The process also entails picking the proper set of current and voltage phasors from the fault area. By “proper” we mean a point in the fault area where the phasors are stable. By “stable” we mean away from the point of fault inception (the phasors at that point are unstable due to phase shifts, DC components, and harmonics which affect the Fourier transformation and corrupt the calculation of the sequence components) and before the remote end opens (because at that point the system model becomes a single ended radial line which is not a double ended exercise).

The stable point in the fault area is highlighted by the black data bars of Figure-4 (the reference angles are also encircled). Running the double ended equation at that point using positive components yields a fault location of 1.01 miles out from the top record (see Figure-5).

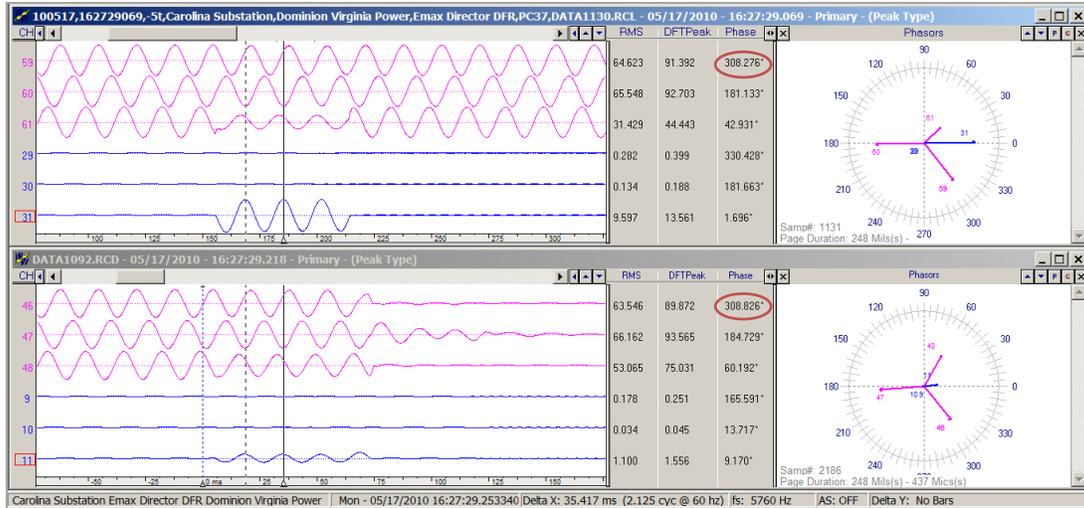


Figure-4; Aligned Fault Data Records from both ends of Line 54

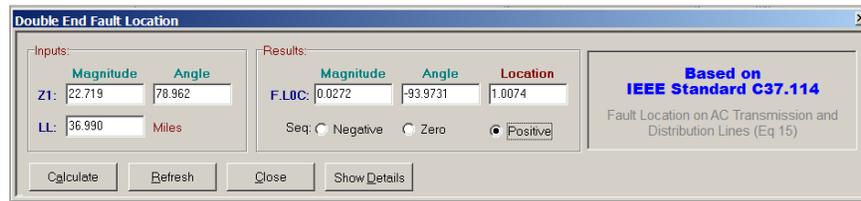


Figure-5; Near Side Double Ended Fault Location

Rerunning the double ended equation using now negative and zero sequence components yields the fault locations shown in Table-2.

Measurements	Positive	Negative	Zero	Actual Location
Fault Location	1.01	1.63	2.40	1.66
Percentage Error	1.76 %	0.08 %	2.00 %	NA

Table-2; Line 54 Unbalanced Fault (Line Length is 36.99 miles)

All of these measured locations are good engineering estimates because the main concept is to provide sufficient accuracy to place line crews within a reasonable distance from the fault. The worst case scenario here is the zero sequence at 2.00 % which is still sufficient accuracy. The best case scenario is the negative sequence at 0.08 % which is amazing accuracy. The effects of mutual coupling and pre-fault imbalances were not considered in this study. These effects whether due to power system issues or induced by recording inaccuracies may further explain the measured errors for the zero and positive sequence components.

The performance of the double ended method was benchmarked (at the point where the remote end opened) against two single ended methods: reactance and radial line. The reactance method placed the near side fault at 3.7 miles out while the radial line method placed it at 5.4 miles. Clearly in this case the double ended method performed much better than the single ended methods.

VI – Double Ended Application (Case Two)

A balanced phase A to B fault occurred on Line 47 on 12/06/2010. The Line length is 33.85 miles. The actual fault location was at 14.66 miles from the near end. The fault data records from both ends of the Line are shown in Figure-6 (the near end record is the top record). Here again the alignment process was done with respect to phase A as depicted by the position of the data bars (the reference angles are also encircled). However, if the reference phase is highly corrupted by the fault then aligning with respect to an unfaulted phase would also work (notice phase C angles are both at 164°). Now if all three phases are highly corrupted by the fault then common practice is to align with respect to the point of fault inception and then move the data bars 2 cycles into the fault.

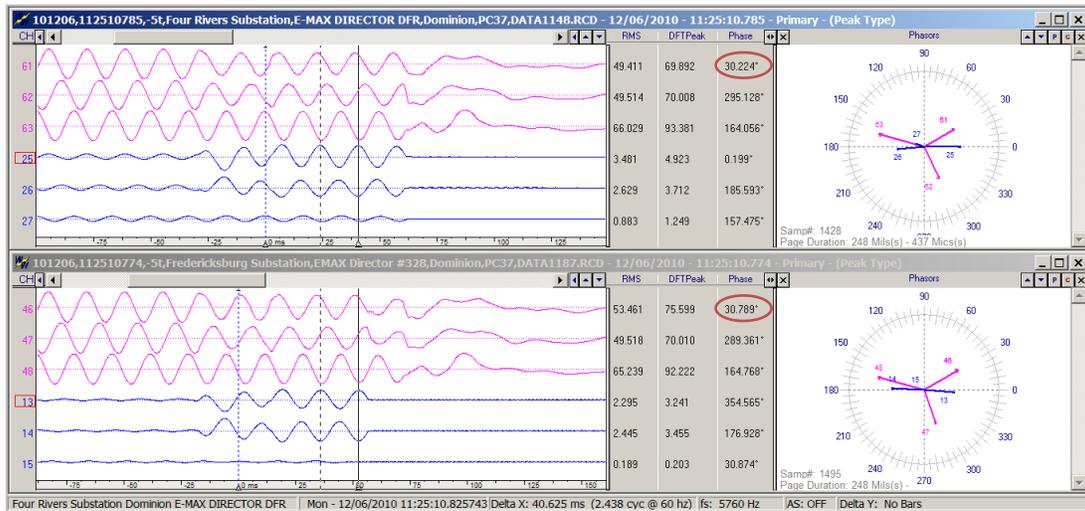


Figure-6; Aligned Fault Data Records from both ends of Line 47

Running the double ended equation at the point of alignment using positive and then negative sequence components yield the near side fault locations shown in Table-3. Zero sequence components were not used in this case because they are not produced by balanced faults.

Measurements	Positive	Negative	Zero	Actual Location
Fault Location	13.93	14.30	NA	14.66
Percentage Error	2.15 %	1.06 %	NA	NA

Table-3; Line 47 Balanced Fault (Line Length is 33.85 miles)

As noted in the previous section, both of these measured locations are good engineering estimates but notice that the negative sequence again performed better than the positive sequence. A pattern seems to be developing where the negative sequence is providing the best results. This pattern is addressed in the next section.

VII – Benchmarking the Negative Sequence

Seeing that the negative sequence gave the best results in both studies, it became necessary to try one more time (third time's the charm). The third case study involved an unbalanced fault that occurred on Line 127 on 8/19/2010. The Line length is 29.04 miles and the actual fault location was at 18.64 miles

from the far end. Running the double ended equation using the three components yields the far side locations shown in Table-4.

Measurements	Positive	Negative	Zero	Actual Location
Fault Location	18.11	17.98	18.89	18.64
Percentage Error	1.82 %	2.27 %	0.86 %	NA

Table-4; Line 127 Unbalanced Fault (Line Length is 29.04 miles)

Again all of these measured locations are good engineering estimates but in this case the zero sequence gave the best performance. Even positive sequence performed better than negative sequence so we can now address the conflicting industry recommendations on which sequence components to use. C37.114 recommends positive instead of zero components while Turner and other experts recommend negative components. Clearly this study is proof that none of the components should be ignored. The selection of which components to use depends on the type of fault and on the extent of the effects of system imbalances and recording inaccuracies.

VII – Summary and Closing Remarks

The C37.114 double ended method does not depend on load or fault resistance and works for temporary or intermittent faults. The method is a valuable tool for line restoration and maintenance efforts. Having quality fault records from both ends of the line is critical for the successful application of the method. Manually calculating the needed voltage and current components from both ends of the line is complex and time consuming but with the proper tools the calculation is seamless. The long term effect of using such tools leads to a structured environment where fault records are tuned, conditioning is not required, and running the double ended calculation is simple and quick. Continued application at such environments further enables the ultimate goal of fully automating the double ended method including both collection and alignment procedures.

As for the question of which components should we use, the answer is we can use all of them. For unbalanced conditions we can use positive, negative, or zero components. For balanced phase to phase conditions we can use either positive or negative components. For balanced three phase conditions we can only use positive components because they are the only ones present. As for accuracy, three case studies presented in this paper show that good accuracy is provided when the fault records are aligned with respect to the reference phase and in a stable part of the fault area. The authors hope these results will help clarify the issue of which components to use and guide the next revision of C37.114.

VIII – Author Biographies



Amir Makki has worked at Softstuf since 1991. He has BS and MS degrees in Electrical Engineering from Tennessee Tech University and pursued his Ph.D. studies in Software Engineering at Temple University. His main interest is automating fault and disturbance data analysis. He is extensively published and holds a number of U.S. patents and trademarks. Amir is a senior member of IEEE and is an active member of the Protection Systems Relay Committee where he chaired a number of working groups including COMTRADE, COMNAME, and the Cyber Security Task Force for Protection Related Data Files.



Maria Rothweiler has worked at Softstuf since 1991. She has a Bachelor of Arts degree in Computer Science from Temple University and pursued her associate degree in Mathematics at Bucks County Community College. Her main interest is developing software tools for display and analysis of power system fault and disturbance data. She is extensively published and holds a number of U.S. patents, trademarks, and copyrights.

Maria is a member of IEEE and an active member of the IEEE Standards Association.



Robert Orndorff has worked at Dominion Virginia Power for over 25 years (since 1984). He spent 11 years as a field relay technician and in 1997 transferred to the Fault Analysis department where he currently works. Current responsibilities include maintaining and configuring Dominion's Digital fault recorders, event retrieval and analysis from smart relays and DFRs. Robert is an IEEE member and has been a member of the Transient Recorder's User Council (TRUC) since 2002.



James B. Starling has worked at Dominion Virginia Power since 2003. He has a BS degree in Electrical Engineering from Virginia Commonwealth University. His experience includes testing, installing, and repairing relay systems and calculating line impedances and relay settings. He also has extensive experience analyzing and documenting transmission system operations. He is currently responsible for compliance reporting, misoperation investigations, and fault recorders. Brian is a Master Black Belt Six Sigma for helping reduced Dominion's transmission operations by 22%.

IX – References

The following listing of books, papers and standards is provided as a source for additional information:

- [1] IEEE Std. C37.111-1991, Standard Format for Transient Data Exchange
- [2] IEEE Std. C37.111-1999, Standard Format for Transient Data Exchange – Second Edition
- [3] IEEE Std. C37.114-2004, Guide for Determining Fault Location (Transmission/Distribution)
- [4] IEEE Std. C37.118-2005, Standard for Synchrophasors for Power Systems
- [5] IEEE Std. C37.232-2007, Recommended Practice for Naming TSD files
- [6] NERC Std. PRC-002-NPCC-2010, Requirements for Disturbance Monitoring Equipment
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- [8] Turner, S., "Simple Techniques for fault Location"; GT Protective Relaying Conference, 2002
- [9] Ibrahim, M., "Disturbance Analysis for Power Systems", Wiley and IEEE, 2011
- [10] Rauch and Hindin, "A Guide to Commercial Artificial Intelligence", Prentice Hall, 1988