# Re-engineering Relay Engineering

*by*

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## Introduction

Many utilities are in the process of down-sizing their organizations in order to become more competitive. Down-sizing works only if you re-engineer. If you down-size for the sake of cost cutting without re-engineering, it is called dumb-sizing. It is a dumb thing just to cut people; those people were there for a reason. Without them, systems need to be put in place to make sure that the operation is not affected. The operation needs to be re-engineered to become more efficient to remain viable with fewer people.

The term *re-engineering* was first introduced about two and a half years ago by Michael Hammer, a professor at Harvard [1]. When engineers hear the term for the first time they are usually shocked because they were taught to do it right the first time and never to re-engineer. After a month, Hammer's book was listed on the *New York Times* bestseller list, so obviously it created a lot of interest because it makes a lot of sense.

Re-engineering says that any process you perform, regardless of whether it is testing relays, analyzing faults, or any other procedure in your company, is based on some level of technology. This is the key: *anything we do is based on our technology window.* In time, this window changes because we have improved technology. With improved technology, it is time to ask some hard questions. Can we do what we are doing today differently? Can we do it better and become more productive by making use of the power of today's technology?

In relay engineering there are many procedures that were created back in 1950 with the then current technology. In 1950, slide rules were used to perform complex calculations, electro-mechanical techniques were used for designs and passive components were used for test equipment. Anyone who has ever used a slide rule knows the difficulty of making complex calculations. It is a long and tedious method.

In 1990, technology has changed dramatically. Today we have personal computers, microprocessor relay designs and active-source test equipment. With this technology we can, and should, do things differently.

## Electro-mechanical Relay Designs

Electro-mechanical relays that utilize induction principles were the basis of all relay protection designs in 1950. To achieve faster operation, manufacturers designed cup-type units. Because of the induction principle the design philosophy of comparing signals was used. Depending on the direction of the fault current, the cup-type unit would move in a specific direction. This technique of comparing signals was applied to electro-mechanical distance relays and carried over into solid-state relay designs and some digital relay designs [2].

All that is now changed. Today, relay designers are now applying innovative numerical techniques to relay protection. The newer relays are designed to operate under power system conditions. This approach enhances relay performance. If these relays are tested under pseudo power system conditions, problems in testing and understanding the relay's operation can occur.

## The Basis of Re-engineering

The basis of re-engineering is a two-step approach.

1. Challenge the assumptions of the process in place: If the result of that challenge says that the assumptions have not changed, then stop.
2. If challenging the assumptions indicates that they were based on older technology, then re-engineer by using the power of today's technology.

In this paper, three relay engineering areas will be covered:

- Fault analysis
- Documentation
- Relay testing

## *Fault analysis*

Authors of power engineering textbooks written in the 1950's assumed:

1. Only reactance for the power system
2. No fault resistance and no load flow

These assumptions had to be made because slide rules were used to make calculations. It is a very tedious process to use load flow and R+jX in the calculations on a slide rule. In fact, it would take so long to solve as to make the exercise unrealistic. So the best assumptions that could be made in the 1950's were limited by the technology available. While these assumptions are valid in calculating maximum fault current for determining circuit breaker ratings, they lead to erroneous conclusions when applied to how a relay actually performs.

For example, a phase-to-phase fault was shown as follows in textbooks written in the 1950's:

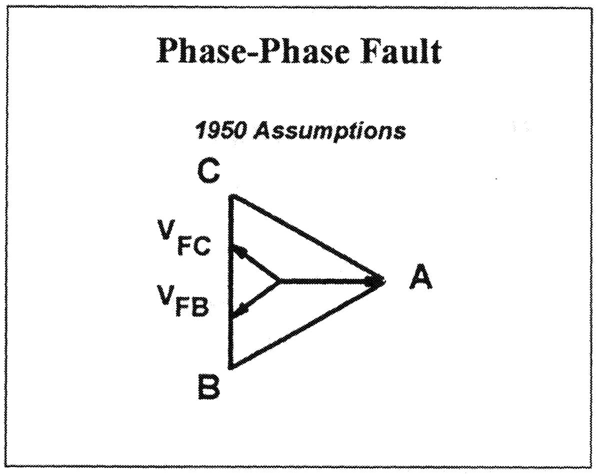


*Figure 1*

For a phase-to-phase fault on BC the fault voltages collapse such that their magnitudes $V_{FB}$ and $V_{FC}$ are equal. This is shown in **Figure 1**. Using 1950 assumptions of only reactance and no fault resistance, leads to this conclusion.

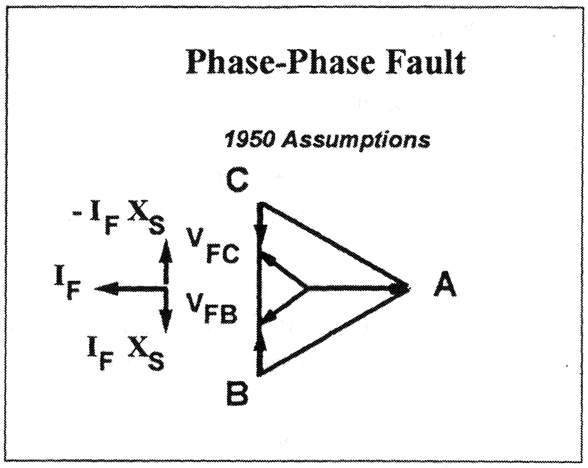
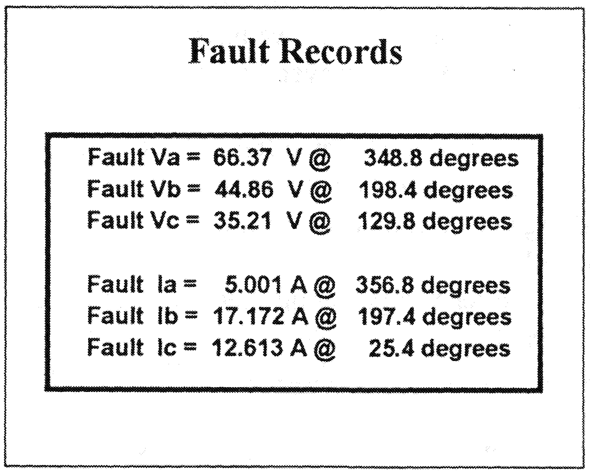


*Figure 2*

**Figure 2** shows a BC fault and the respective voltage drops creating the fault voltages $V_{FB}$ and $V_{FC}$. The source voltage, $E_{BC}$, will drive the fault current such that it lags the source voltage by 90° because the circuit is assumed to be only inductance. The current flow will cause a drop in the source voltages, $I_F X_S$ and $-I_F X_S$. These source voltage drops produce the fault voltages $V_{FB}$ and $V_{FC}$.


Fault Records

Fault Va = 66.37 V @ 348.8 degrees
Fault Vb = 44.86 V @ 198.4 degrees
Fault Vc = 35.21 V @ 129.8 degrees

Fault Ia = 5.001 A @ 356.8 degrees
Fault Ib = 17.172 A @ 197.4 degrees
Fault Ic = 12.613 A @ 25.4 degrees

*Figure 3*

All this seems to make sense until the first fault record for a phase-to-phase fault is captured by one of the new digital relays.

**Figure 3** shows a typical fault record for a phase-to-phase fault. Notice that the magnitudes of the fault voltages are not equal and that their angles are not symmetrically displaced.

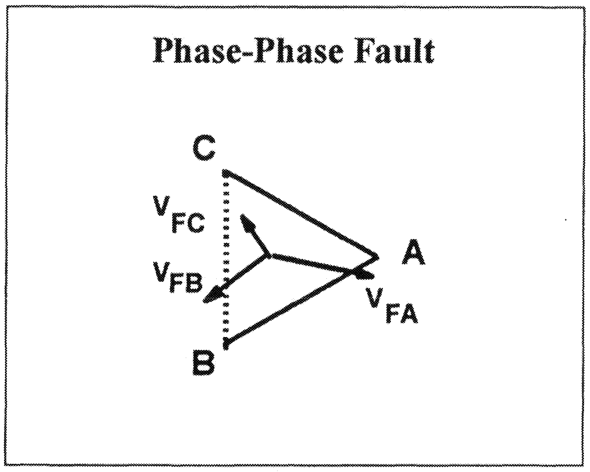


*Figure 4*

**Figure 4** shows the plot of these voltages. Notice that the leading voltage, $V_{FB}$, is larger in magnitude than the lagging voltage, $V_{FC}$. With the understanding of fault analysis based on 1950 assumptions, how can this be? Could something be wrong with the recorder or the relay because it doesn't follow the classical fault analysis?

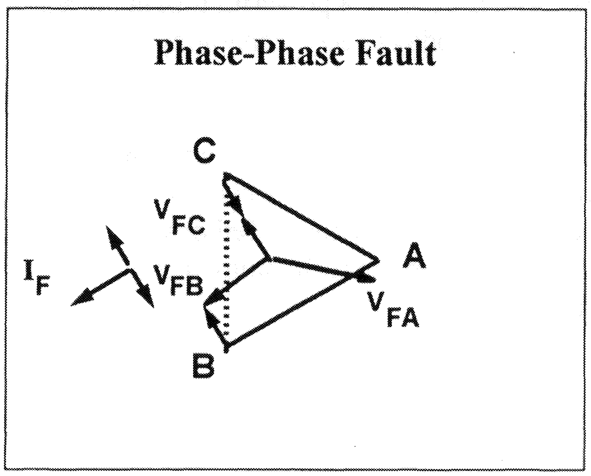


*Figure 5*

**Figure 5** shows how the unsymmetrical fault voltages are developed. For every phase-to-phase fault, there is fault resistance. What generally causes this type of fault is a wind storm that starts a section of the transmission line to gallop. At the point where the conductors become close to each other, a flash-over occurs and an arc is produced. The arc presents fault resistance to the faulted circuit.

If an analysis is performed with a pure reactive source and line with fault resistance, the fault current will lag the source voltage by an angle of less than 90°. The fault current flows through the reactive source impedances creating a drop of $\pm 90°$. When the voltage drops are added to the source voltages, it creates the fault voltages $V_{FB}$ and $V_{FC}$.

Therefore, if an analysis is performed based on the wrong premise, a wrong conclusion is reached. The point to be emphasized here is: it is important to have an understanding of what is happening on the power system because modern relays provide data that must be properly interpreted. Fortunately today, many companies use fault analysis short circuit programs such as One-Liner, CAPE, etc. These programs enable the user to enter resistance and reactance to obtain realistic results.

## *Documentation*

All new relay designs are multi-functioned devices. Technical manuals, if they are done right, are generally over 400 pages in length. The amount of information needed for these relays is ever increasing as their versatility and capabilities increase. The task of finding and assimilating this information is becoming worse. The new relays that will be introduced in the near future will have everything that can possibly be imagined in one device.

Today, a transmission line protective relay includes distance and pilot relaying elements with over twelve different types of schemes, each with different timers and selections for protecting weak and strong systems. Tomorrow, there may be breaker failure relaying, reclosing and numerous voltage and current detectors that work off phase quantities and sequence quantities to provide instantaneous or time-delayed operations. In addition, the user will also have the benefit to program the functions to customize the design.

The relay manufacturer will provide one manual that covers everything. They no longer have the problem of customizing the design; configuring and setting the relay becomes the user's problem. When the relay is sent to the field to be commissioned, it becomes the technician's nightmare. The test engineers and technicians will have a different view: "You want to install what, when?"

The problem is that we are trying to use paper which provides a sequential presentation of information. This sequential approach is a one-dimensional solution. There are many documents that need to be reviewed when configuring and setting a multi-function device. In order to keep track of the information when using a one-dimensional platform, one would usually put *post-it* stickers in numerous places in the documents in order to keep track of the needed information. When the equipment is more complex, the complications of using a paper solution to find information rises exponentially to the point where it almost becomes impossible. In the face of down-sizing when there is less manpower and less time to perform a given task, it definitely becomes impossible.

Fortunately, there is a better way. That better way is move from a one-dimensional solution, called paper, to a multi-dimensional solution called *electronic documentation*. During seminars on re-engineering, a number of powerful examples of the work being done are presented and a demo disk provided [3]. Some of the advantages of electronic documentation are shown in **Figure 6**.

**Electronic Documentation**

- **Fast Retrieval of Information**
- **High Speed Image Display**
- **User Customization**
- **Links to Software**
- **Just-in-Time Training**

***Figure 6***

### *Fast Retrieval of Information*

The first advantage of electronic documentation is fast retrieval of information. If the information is readily available, immediate answers to questions can be retrieved regarding the installation and application of new equipment. If a manufacturer was called with a question and an immediate answer was given, this would be perceived as very good service from the manufacturer. But imagine if the phone call never had to be made because the answer is at your desk with a click on an icon. The PC has become a powerful tool in the application of today's relay technology. This tool can be used for more than communication, checking and changing settings or downloading fault records. The PC is not only for the relay. The PC is the portal to information: what is needed, when it's needed. Methods need to change based on the technology that is available.

The two-step approach of re-engineering applies to all aspects of this discussion. What is being challenged now is how to manage the volume of information needed to apply today's technology. The answer is to use the PC for multi-functional tasks. The PC is used to enhance system operations with relay communications. The same PC can also be used as a solution to the information problem with electronic documentation.

### *High Speed Image Display*

The information presented here could not have been done on a laptop computer that was designed three to four years ago. If an E-sized engineering drawing were to be displayed on a laptop, it would take a number of minutes to display the drawing. All that is changed with today's technology. Laptop computers today allow a fast display, even fast enough to show a video.

### *User Customization*

User customization is a very powerful way to improve productivity. Suppose all the instruction manuals were in electronic form and easily accessible to all over a network. A test engineer could plug in a laptop computer at the relay panel to access the information on the network. Comments and notes can be easily added so that a useful technique or explanation discovered by one technician would be shared among all technicians. There is no need to re-discover information. Personalized instruction manuals are filled with a number of technicians' notes that explain how to do something. This is all creative work that is done over and over again by each technician. If the information gained could be captured and distributed, it would result in higher productivity. This special information can be captured and distributed to all on the network. With shrinking resources, higher productivity and enhanced efficiency are needed now more than ever.

### *Links to Software*

Links to other software such as setting software, testing software and communication software can be established to allow an integrated access to information. All information and tools needed to operate, test and interrogate relay protection is just a click away.

### *Just-in-Time Training*

Many companies believe in training and send their employees to numerous seminars. What generally happens is that the employee returns, pleased with the quality of the course, carrying volumes of information. Well, there is a new Murphy's Law that says you are never challenged with a problem until one year after you send someone to a seminar.

One year later, a problem surfaces and the employee that was sent to the seminar is questioned: "What's the answer to the problem?" The general response would be: "I know there's an answer but let me find the course material from my seminar." One or two days later the volumes of books are found where they had been stored and forgotten. The next challenge is to find which of the many binders has the information that describes the solution to that particular problem. Searching the binders, the right section is finally found. Now the one-dimension solution, called paper, is encountered with its hallmark of time consumption caused by reading and looking and reading and looking in an attempt to figure out what it is all about.

If the information was in electronic form and linked through an electronic library, the information would easily be found and the power of the computer, with animation and video, would be used to provide a quick re-understanding of the information. The adage of "a picture is worth a thousand words" is especially true when trying to re-understand information. Also, with the information in electronic form, calculation tools can be provided that allow the user to simply insert the values of the application to obtain the correct solution. All this technology is here today.

### *Relay Testing*

What's different from 1950? In 1950 we had passive test equipment: Variacs, Load Boxes and Phase Shifters. Since relay manufacturers wanted to insure that the products they sold were set properly, they developed test procedures. In order to develop these procedures, the relay manufacturer asked the question: "What test equipment can I assume the user has in order to set the relay?" Well, in 1950 the best that a manufacturer could assume is that the user would have Variacs, Load Boxes and Phase Shifters. So the test procedures were based on these components.

However, if relays are tested with these components and conclusions drawn on how the device operates, one can be easily misled. For example, if a mho characteristic was tested with these components, a characteristic circle passing through the origin would be plotted. This is believed to be true just as the example of the phase-to-phase fault assumption was believed to be true. Hours can be spent testing the relay with data collected that will plot a perfect circle through the origin. The same result would occur if an automatic test set was used. One would have to assume that this has to be right because it was done both manually and automatically with the same results. **Figure 7** shows the conclusion drawn.

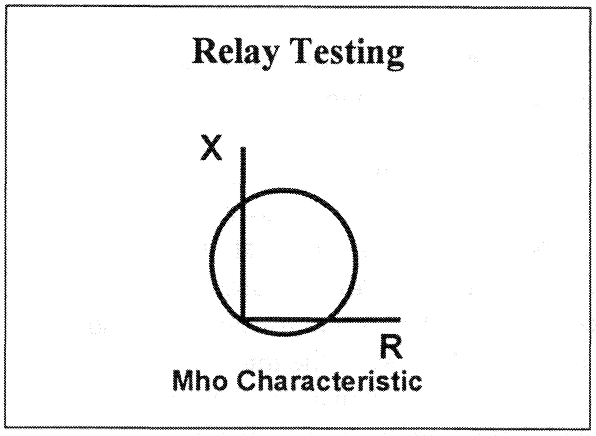


*Figure 7*

First of all, no relay manufacturer designs a Zone 1 or Zone 2 mho distance relay that plots through the origin. It would never work. The reason it won't work is that if you have a fault on a line you will get arc resistance as part of the fault resistance. The arc resistance is not constant. It depends upon the voltage across the arc, divided by the fault current. The voltage across the arc is fixed and depends on the length of the arc. To ionize air and create an arc takes about 500 - 550 volts per foot. If the length of the arc is known, the arc voltage is known. The fault current is the function of the source impedance. If you have a strong or moderate source, the arc resistance may plot within a characteristic circle passing through the origin. Such a characteristic circle is called a self-polarized mho characteristic.

Given the same fault location in the middle of the night when source generation is weak, the fault resistance will plot outside the self-polarized mho characteristic. As shown in **Figure 8**, it would never work.

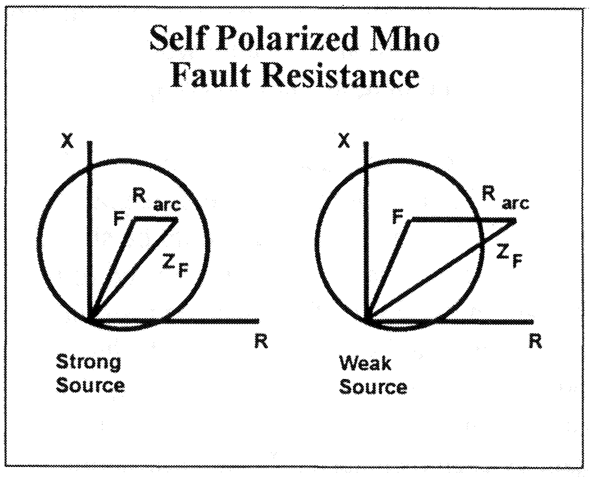


*Figure 8*

Relay designers have known this for many years. They designed an adaptive relay characteristic so that the characteristic expands through the source impedance of the source creating the current seen by the relay and the relay setpoint. These two points, the relay setpoint impedance and the source impedance create the diameter $Z_D$ of the expanding characteristic. When there is a weak source condition, the source impedance is very large, resulting in a large expanding characteristic. The circle reaches out to accommodate the increased arc resistance. It does the right thing.

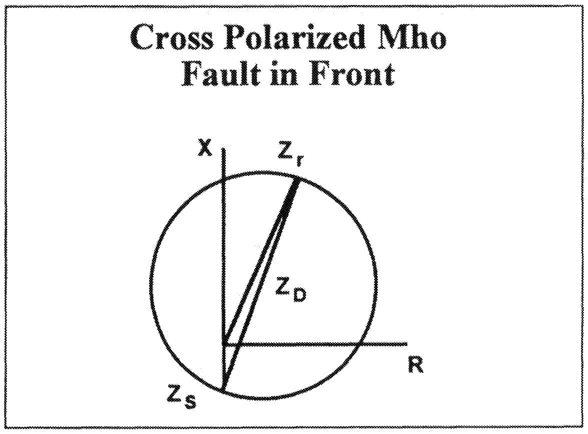


*Figure 9*

**Figure 9** shows the relay characteristic for a fault in front of the relay. The source is behind the relay location.

For a fault behind the relay, the characteristic will not misoperate. This is shown in **Figure 10.** This fault represents a different condition because the source creating the fault current is now at the remote end of the line.

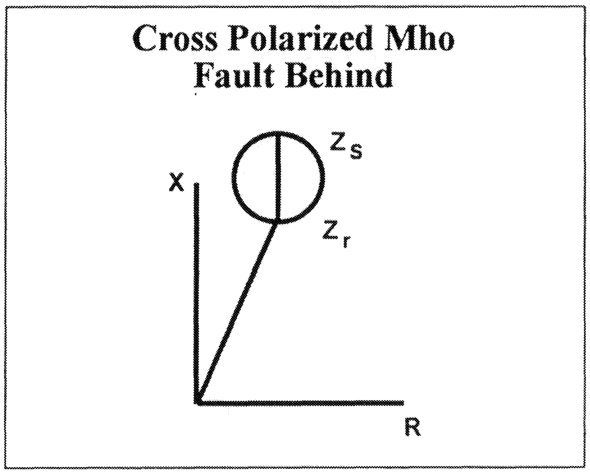


*Figure 10*

So the characteristic for faults behind cannot be plotted on the same diagram. The remote source will drive the fault current through the line for a fault behind the relay. The operating region of the characteristic moves away from the fault location. A cross-polarized or memory-polarized or a positive sequence voltage-polarized relay behaves this way [2].

Now there is the question of why, when the relay is tested with a routine test method, a characteristic that goes through the origin is the result, but the instruction manual for the relay shows true expanding characteristic. **(Figure 11)**

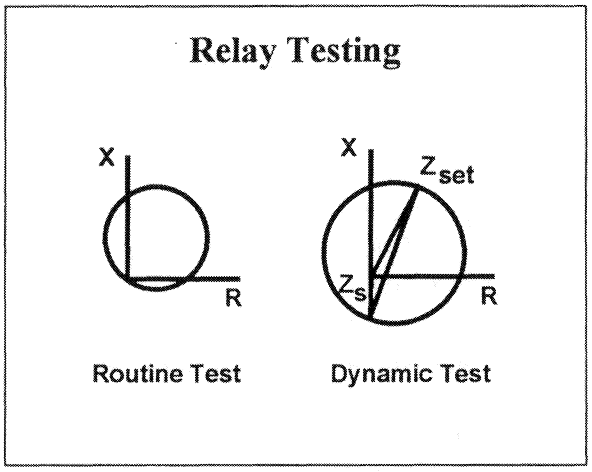


*Figure 11*

What's the difference? To develop the solution, the question must be asked - "What type of power system is represented by the test phasors that are applied for the routine test method?" Relays are designed to protect power systems. So to solve the problem, the question of what type of power system is represented must be answered. Only then, how the relay will respond to it can be found.

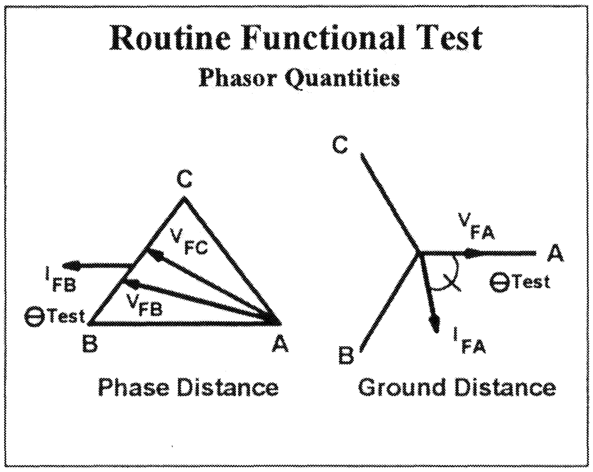


*Figure 12*

For a phase distance relay test, **Figure 12** shows the set of test phasors that would be applied. Using two Variacs, symmetrical voltage drops for each of the faulty phases can be set. The current magnitude is set by a Load Box where you can increase or decrease the amount of test current. The phase shifter is used to set the test angle, $\theta_{Test}$, which is the angle between the test voltage and the test current applied to the relay.

A similar test using a Variac, Load Box and Phase Shifter is conducted for the ground distance relay test.

But the question to be considered now is: "What type of power system is represented by these tests?" On investigation, three observations can be made.

1. The first observation is very simple: you are dealing with a radial line as shown in **Figure 13**. No matter what fault type is tested, only one fault current is applied to the relay. For a BC fault, only current is applied to the BC phases. No current is applied to phase A. Similarly for an A-to-ground test, current is only applied to phase A and ground. No current is applied to phases B and C. Therefore, the only type of power system that represents this is a radial line. This is the easy observation.

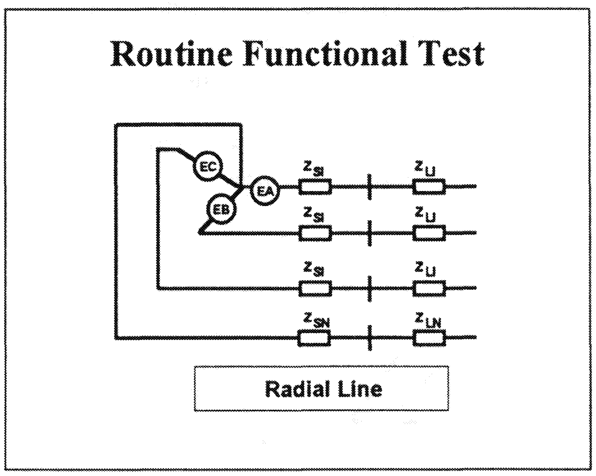


*Figure 13*

2. The second observation is the key. A homogeneous power system is represented in **Figure 14** which means that the angle of the line and the angle of the source are exactly the same.

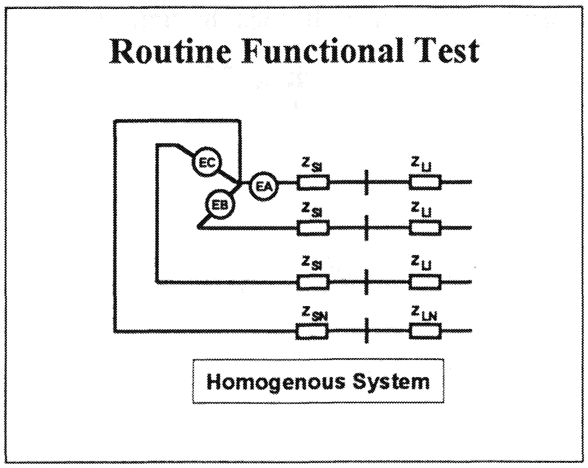


*Figure 14*

Let's look at a BC fault with the set of voltage phasors as shown in **Figure 15**.

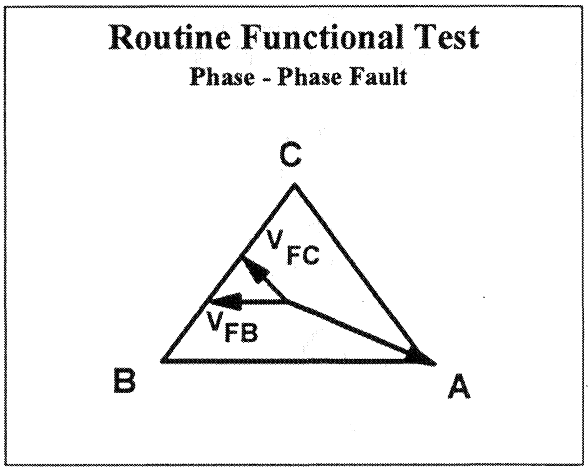


*Figure 15*

**Figure 16** shows the power system that develops these voltage phasors. Applying the fault on B and C, the voltage drop across the line is the voltage $V_{FBC}$. The voltage drops across the sources are from B to $V_{FB}$ and from C to $V_{FC}$.

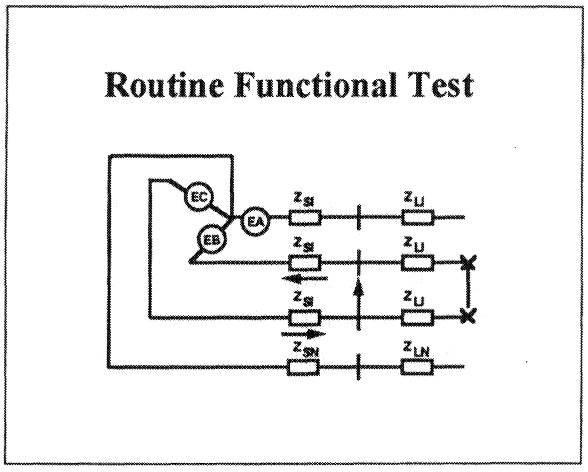
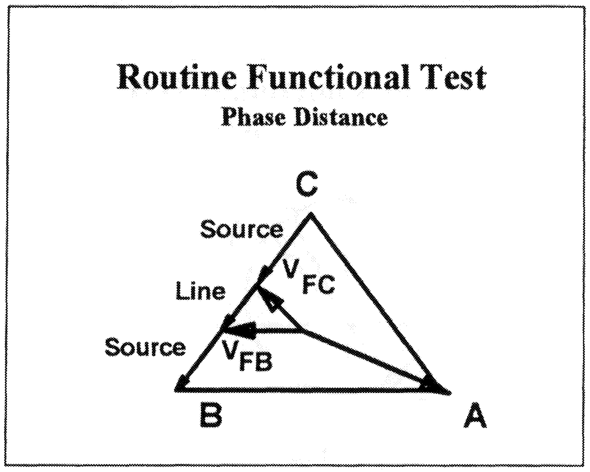

Routine Functional Test

*Figure 16*

The result is that there are three co-linear phasors, i.e. three phasors all in phase with each other. This is shown in **Figure 17**.


Routine Functional Test

Phase Distance

*Figure 17*

The question can be asked: "What power system circuit impedances represent the sources and line so that the three voltage drops are in phase?"

First consider a case where they do not line up. Assume that there are three completely different impedance elements **(Figure 18)** consisting of a capacitor, an inductor, and a resistor. If a voltage is applied across these elements, the current will flow and create three voltage drops. The voltage across the resistor will be in phase with the current, whereas the voltage across the capacitor and the inductor will either lag or lead the current by 90°.

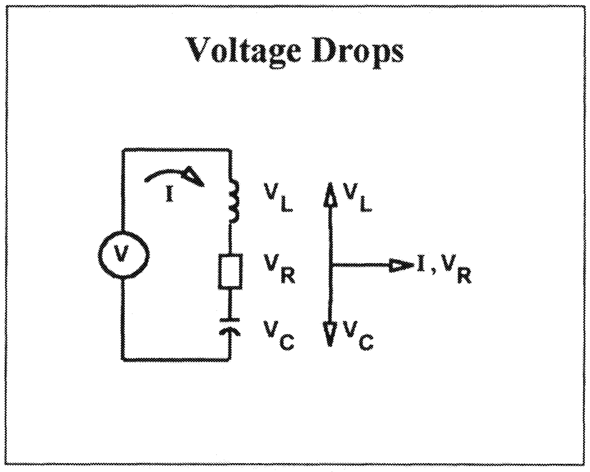

Voltage Drops

*Figure 18*

If the angles are different, the voltages are not going to line up. The only way the three voltages are going to line up is if each element (source, line and source) has the same angle as shown in **Figure 19**. They can have different magnitudes but they must have the same angle. The result is a current that flows in that circuit and the voltage drops $V_S$, $V_T$ and $V_R$ are in the same direction. So, in order to create this, the angle of the line and the angle of the source must be equal.

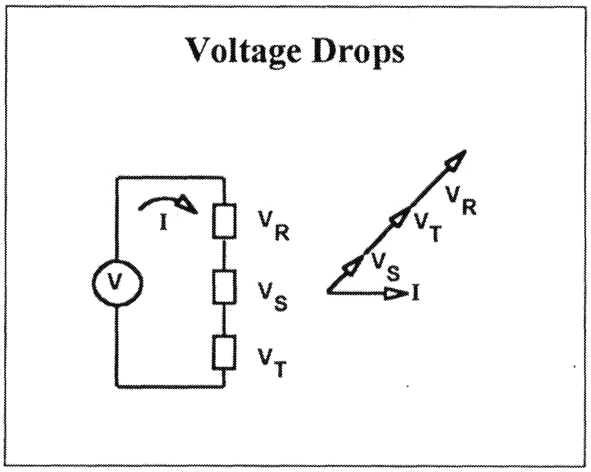

Voltage Drops

*Figure 19*

3. The last observation has to do with ground relays. Because of the passive components - Variac, Load Box and Phase Shifter - the

unfaulted phases cannot be changed; they are fixed. So the question is, "What conditions of the power system give fixed voltages on the unfaulted phases for a single phase-to-ground fault?"

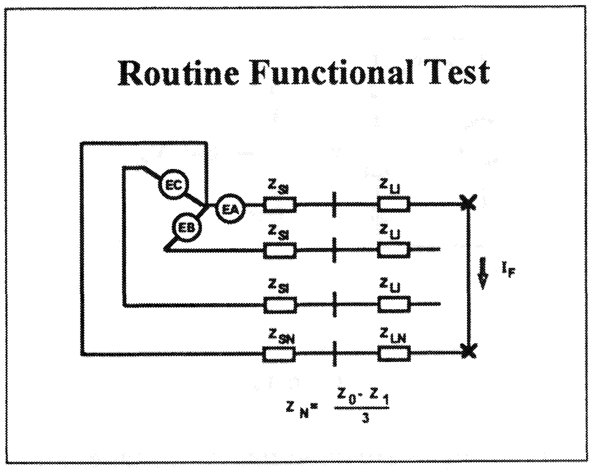

Routine Functional Test

*Figure 20*

For a radial line model with an A-to-ground fault, the generator will produce a fault current that flows to the fault point and back through the neutral as shown in **Figure 20**. The current is going to flow through the neutral circuit impedances $Z_{SN}$ and $Z_{LN}$. The neutral circuit impedance for the source, $Z_{SN}$ , or line, $Z_{LN}$, is the zero sequence impedance (source or line) minus the positive sequence impedance (source or line) divided by three. For the test condition, $V_B = E_B$ and
$V_C = E_C$

However, if current is flowing in the neutral circuit, how can the voltages be equal?

Since current $I_F$ is flowing through the neutral circuit source impedance, there must be a voltage drop. However that drop is assumed to be zero because the voltages are equal. For this to be true, the neutral circuit source impedance must be equal to zero. Therefore, the zero sequence source impedance equals the positive sequence source impedance.

To summarize briefly: for this functional test, the power system that is represented is a radial line and a homogeneous system with a special case for which the zero sequence source impedance equals the positive sequence source impedance.

Now, returning to the original question, "Why is it when testing with routine test procedures, a circle through the origin is generated, whereas the instruction book shows the true expanding characteristic?" The answer is that the expanding characteristic is there but it is not seen. When a routine test is performed at 45°, what is modeled is a 45° homogeneous power system which means the model has a 45° line and a 45° source. The relay characteristic expands through the source impedance and the set impedance as shown in **Figure 21**. This sets the diameter of the expanding characteristic.

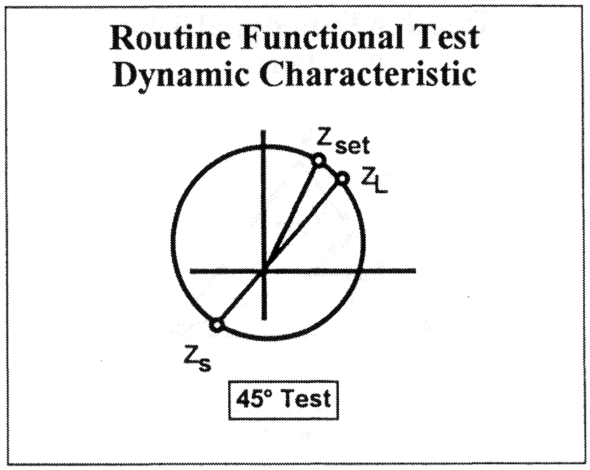

Routine Functional Test
Dynamic Characteristic

*Figure 21*

As the current is slowly increased, you move along this fictitious 45° line until there is an operation. Then it's all over. Values are collected for voltage and current for the 45° test and put into a database. Then the next test is performed.

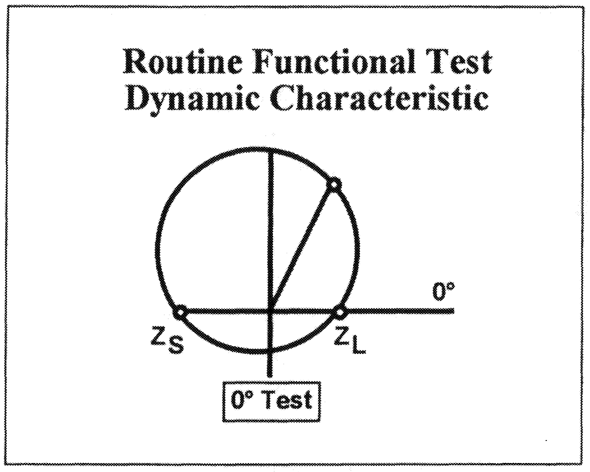


*Figure 22*

For a 0° test, the power system represents a pure resistive line and a pure resistive source which is pure nonsense. But it is run anyway.

The relay characteristic will expand through the setpoint impedance and the source as shown in **Figure 22**. When the current is slowly increased , there is an operation, the test is stopped and the values collected and added to the database. These points are then plotted and a perfect circle is seen as shown in **Figure 23**. *But each of these points is from a different test.* This does not represent a real power system.

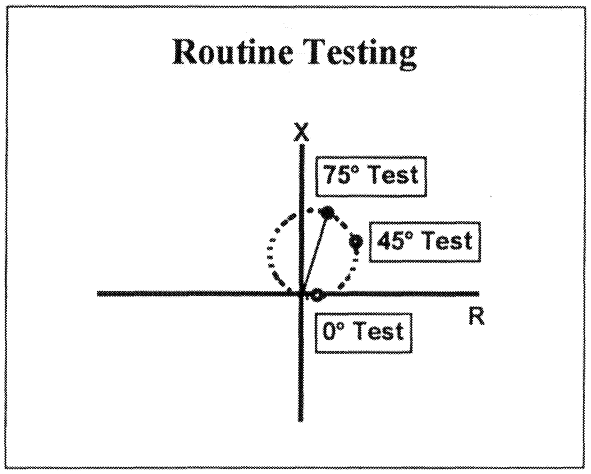


*Figure 23*

The result is a plot of points, as shown in **Figure 24**, that are snapshots in time from different expanding characteristics.

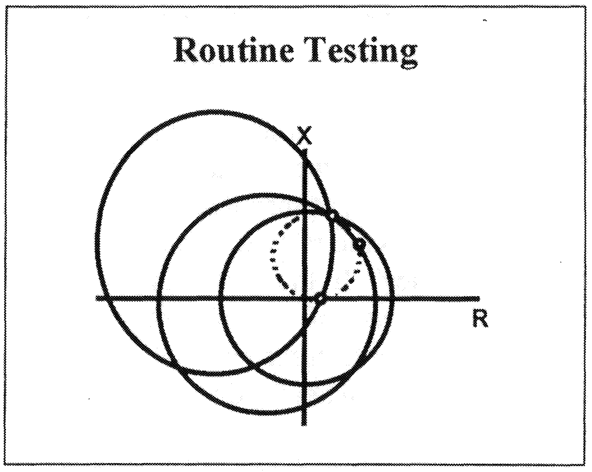


*Figure 24*

### Dynamic Relay Testing

Dynamic relay testing means testing under true simulated power system conditions [4]. A two-machine equivalent model is created with line and source values (**Figure 25**). Faults are simulated on the model with varied fault locations, resistances and load flows. Each case is tested for reach and direction (faults behind and in front) and for the various zones and combinations of zones.

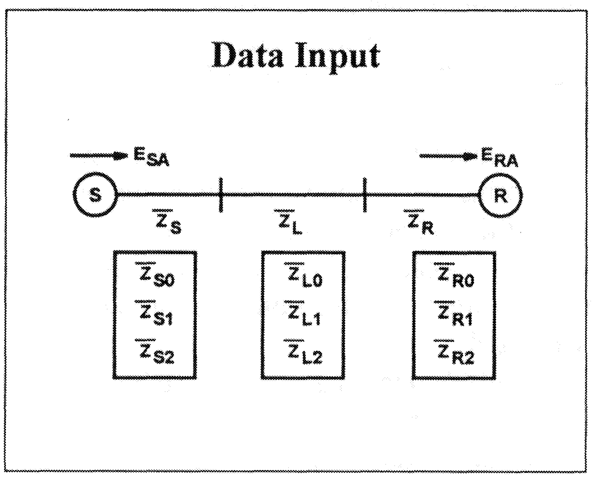


*Figure 25*

These tests will move fairly quickly. You can do an op, non-op case. For a Zone 1 relay with ± 5% accuracy, an operation should always occur at 95% of setting (op case). For a fault at 106% of setting, there should be no operation (non-op case). These two cases confirm the accuracy of the relay.

The confirmation of the accuracy is what is important for any relay test. If someone said to a relay manufacturer, "Five years ago we tested your relay and it just operated at 97% of setting. Today we tested it and it just operated at 103%." The manufacturer would say, "So what?" Is the relay within its ± 5% published accuracy? If the answer is yes, it is the end of the discussion. The accuracy claimed by the manufacturer was met, that is all that matters. From an application point of view, the relay application engineers want to know that the manufacturer's published accuracy is confirmed because this is what they use to establish their settings [5].

Other dynamic relay tests that can be performed are operating time tests at different system impedance ratios (SIRs) - the ratio of the source impedance behind the relay to the set impedance of the relay. Additional application tests such as: switch on to fault, blown fuse, memory, adaptive characteristics and programmable logic can also be performed. With dynamic relay testing, these events can be very quickly modeled and played back [6].

A new report from IEEE entitled *Relay Performance Testing* [7] discusses how dynamic-state testing and transient simulations provide a far better understanding of how the relay system performs. By making a profile of the operation of the scheme, malfunctions can be found faster because it is easier to identify the changes in areas that don't operate the way they are expected.

Today's relays have the capability of telling us when there is a problem. Moreover, the technology exists to enable, with the proper monitoring and modeling, to know when there *will be* a problem [8].

Test intervals are being extended now because of the shrinking resource of manpower and the time intensive nature of test procedures that don't match today's technology. To have the capability of developing an understanding of the power system and the protection scheme's function within that power system means that diagnostic test intervals can be realistically extended. Running dynamic simulation tests on schemes means that test intervals can be safely extended and productivity can be improved [9].

Work is in progress on an expert system that is an on-line diagnostic system that continuously measures the performance of the power system. Based upon years of testing experience with all aspects of equipment on the power system, this integrates the knowledge gained with today's technology to form a new level of diagnostics and monitoring of the power system as a whole.

## Conclusion

Re-engineering is all about challenging assumptions and applying the power of today's technology when original assumptions are no longer valid.

The principles of power engineering have not changed; voltage is still voltage, current is still current and a fault will cause the power system to react in the same way. But, the tools we employ to protect the system have changed. The way we test, maintain and document the protection must be questioned because of the new technology . Changes need to be made to enhance the efficiency of the operation. It is now time to re-engineer relay engineering.

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## About The Author

A.T. Giuliante is President and founder of ATG Exodus. Prior to forming his company in 1995, Tony was Executive Vice President of GEC ALSTHOM T&D Inc.- Protection and Control Division, which he started in 1983. From 1967 to 1983, he was employed by General Electric and ASEA.

In 1994, Tony was elected a Fellow of IEEE for "contributions to protective relaying education and their analysis in operational environments". He has authored over 35 technical papers and is a frequent lecturer on all aspects of protective relaying, including electromechanical, solid state and digital based equipment.

Tony is a past Chairman of the IEEE Power System Relaying Committee 1993-1994, and past Chairman of the Relay Practices Subcommittee. He has degrees of BSEE and MSEE from Drexel University 1967 and 1969.