Improve Substation Control and Protection by Communication of Analog Information

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Presented at the
4th Annual Western Power Delivery Automation Conference
Spokane, Washington
April 2–4, 2002

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INTRODUCTION

The earliest days of electrical generation, distribution, and transmission presented a problem that persists today. The system must survive changing conditions of power demand, faults, equipment failures, and other unforeseen conditions while continuing to serve as many people as possible. This requires either armies of operators or automatic systems to detect changes and adapt appropriately. Regardless of the technology, the individuals or devices in control follow a process of evaluating input information, making decisions, and affecting changes in system configuration and operation.

In this paper, we consider protection a control function as it allows the system to automatically remove faulty equipment from service and maintain service to the maximum possible number of customers. We also use the term control to mean any automated protection or system configuration function. Early electric power control systems consisted of operators in bowler hats standing in front of large knife switches, looking at meters. If the current on a circuit went too high, the man opened the knife switch and fanned the arc out with his hat. In the next generation of power control systems, electromechanical devices replaced human operators and provided automated protection. Presently, engineers design systems that utilize powerful microprocessor-based equipment capable of more sophisticated protection and automated control. However, the process is the same and is shown in Figure 1.

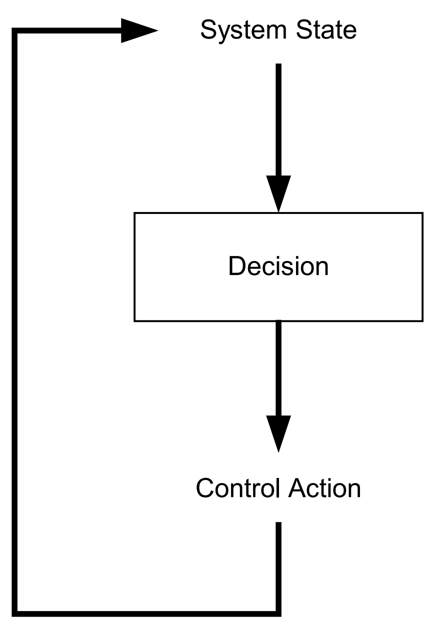

Figure 1 Automatic Control Process

As you can see from the diagram, we have several possible ways to improve automatic control. We can enhance control by changing the control actions that are possible. We can also enhance the decision algorithms. Both of these, however, are completely dependent on information about the system state that reaches the decision-making process.

There is a limit to the degree to which you can optimize a system by refining the decision process or choosing the most effective control actions. Often the best place to innovate and enhance operation is through improved information about the system state. In power system protection and automation, engineers have spent considerable effort refining decision algorithms and power system configurations. One area where we can improve protection is to change the collection and communication of system information to allow new protection methods and enhance existing methods.

Previous generations of protective devices have had limited capability to transfer analog data (measurements) between protective devices. The communication technologies available further limited the capability to send information between devices. Recent advances in the devices and communications protocols coupled with new communication technologies and connections between devices are improving protection operation. This paper examines the background and present state of the communication of analog measurements between devices as well as several example applications where this technique leads to improved control capabilities.

Communications Systems

Today there are many ways to provide communications paths between protection devices. The most popular include leased lines and pilot wires, digital point-to-point and communications networks (including microwave), and Power Line Carrier (PLC). Because of PLC's limited bandwidth, it has a negligible analog capability and will not be discussed. This section will examine these different methods, including some of the considerations when applying communications enhanced protection schemes.

Leased Line and Pilot Wire

Some of the first analog data transfers for protection and control occurred through pilot wire systems. A pilot wire system is a two-conductor wire that provides an uninterrupted path from one control device to another. New communications systems use direct fiber-optic cables as well as several types of wireless and digital network communications paths.

Pilot wire systems are susceptible to several problems that can result in misoperations of equipment using the quantities transmitted on pilot wires. The list below summarizes issues that must be considered with pilot wire systems [8]:

- Maximum distance determined by loop resistance and shunt capacitance
- Resistance matching of each leg
- Pilot monitoring systems to detect if a pilot has become open, shorted, grounded, or reversed
- Pilot wire protection from ground potential rise, induced voltages, and lightning

These considerations do not make it impossible to properly apply pilot wire communications, but they do point out that careful calculations and design are required for successful application. In the re-regulated electrical market, utilities have fewer engineering resources to expend on communications system design and protection. Digital systems allow a much more "plug-andplay" approach that is prone to fewer errors and much less demanding of engineering resources to understand, commission, and maintain.

Pilot wires are traditionally provided in one of two ways. First, the pilot wire is provided by the utility by including some kind of cable under-build on the line. Second, a local telephone carrier provides the pilot wire. Both of these systems are impractical in long line situations either because of the limitations on cable length or the difficulty of coordinating services between different local telephone utilities.

Utilities have long known that leased wire pairs are often re-routed without notice so that the precise setup of the system is corrupted. This problem has grown worse in recent years. A technician must immediately work to assess the new communications path and restore proper operation. Utility companies are also finding that communication utilities are using more and more fiber-optic and digital systems and are making an effort to stop supporting leased pairs as their internal system no longer contains the infrastructure necessary.

Another concern of pilot wires is that they are frequently strung on the same poles or right of way as the power line they protect. This increases the probability of a single event impacting both the power line and the communications involved in its control.

Digital Point-to-Point Communications

There are several forms for digital communications. Fiber-optic cable and wireless are two of the most popular. In this paper, we use the term point-to-point to denote that the communication travels across a medium provided on a point-to-point basis from one location to another. It is true that point-to-point connections can operate across networks and this is discussed in the section below, ***Digital Communications Networks***.

Fiber-optic systems require that fiber-optic cable be connected between substations. This fiber-optic cable provides the communications path with fairly simple transceivers at distances up to 80 km. The digital signaling methods provide communications paths from 9600 to 64,000 bits per second. Simple relay coordination and low-speed analog communications can operate on slower links while the high-speed links accommodate communications for more demanding applications including line current differential. Even though point-to-point fiber may not have some of the problems of copper pilot wires (ground potential rise, induced signals), care should be taken to avoid the common point of failure noted earlier.

You can also utilize wireless systems including microwave or spread-spectrum radios for point-to-point communications. These technologies can be helpful where it is impractical to add or purchase a dedicated connection between two locations. Spread spectrum radios also operate in an unlicensed band in many areas of the world, which greatly decreases design and deployment costs.

Digital Communications Networks

Digital communications networks provide point-to-point data transfer similar to point-to-point connections, but perform that transfer across a shared network. Messages are routed from one point to another forming a virtual circuit or link. The advantage from a communications perspective is that communications networks are much more efficient than point-to-point networks because you can significantly increase the utilization of the connections that combine to make the network. For example, a single fiber-optic pair is capable of data rates much higher than the 56,000 bps required by many applications.

The logical operation of a digital network is shown in Figure 2. Switches, muxes, or other network management devices are access points to virtual circuits that provide point-to-point data flow. The physical construction of the network is a large number of point-to-point connections that each carry many logical connections. In large networks and networks that are interconnected, the actual data path can be very complex when compared to the virtual circuit across the network. There may also be multiple data path that can supply the same virtual circuit operation.

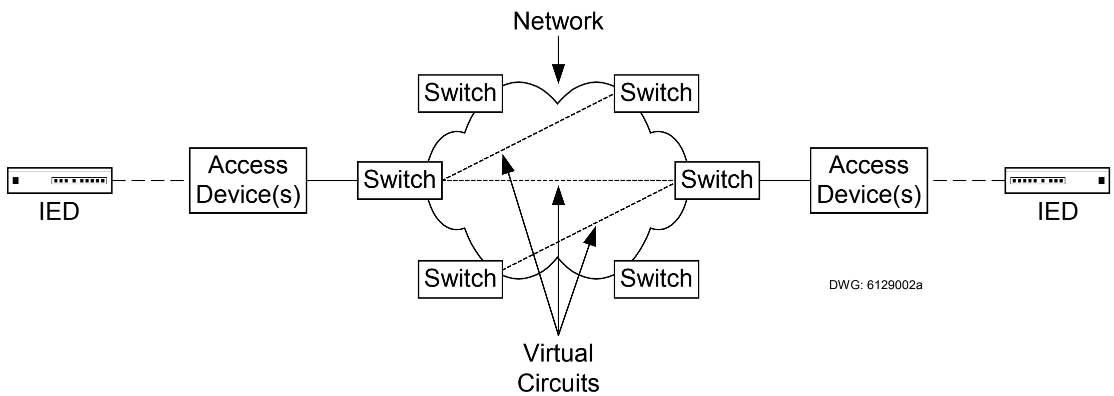

Figure 2 Virtual Circuit on a Digital Communications Network

Unless you install a separate point-to-point medium, communications between two locations will probably travel (at least for some distance) across a shared network. Many utilities have installed fiber-optic cables between substations and are now using that system as a digital network rather than a series of point-to-point connections. Digital communications networks have also replaced the backbone communications used by telephone companies. This means that calls and communications using analog telephone equipment are converted to digital, travel across the network, and are converted back to analog.

One advantage of operating over a digital communications network is that the data path probably does not follow the path of the transmission or distribution line in question. Also, the digital network has multiple paths available to create virtual circuits and can automatically reroute traffic around failed sections of the network. These mean that if the system is properly installed and maintained, there may be a higher likelihood that it is functional when you need it.

One drawback to this system is that paths can be rerouted at will by the network. This means that systems must be tolerant of changes in data transmission time and the occasional shifts in data transmission time. For a discussion of problems with data shifting, please see ***Differential Relaying*** below.

Security, Availability, and Speed

Security is also a vital consideration for overall system integrity. There are several types of security to consider. First, can the system take some kind of uncommanded or unexpected action that is not required? For example, can a message containing corrupted data be interpreted as good data for an operation or a value that would lead to an operation? Next, is the system vulnerable to an external attack that would attempt to disable operation or cause misoperations?

When considering security of a digital communications network, there are many paths and openings where system attacks can occur. However, there are also many strategies for encoding, encrypting, and securing data transmissions and connections to foil malicious attacks.

Reliability and availability are critical issues for any type of communications system used to enhance power utility protection systems. Reliability is often expressed as a MTBF (Mean Time Between Failures) for individual components or systems and describes the expected failure rate. Availability is the combination of reliability measurements for a complete system and is often expressed as a time describing how much of one year a system or component will not be performing its job because of a failure and the time to discover the problem and repair or replace the offending item. Fault trees [1] offer a mathematical structure for combining the reliabilities of individual devices into composite system availability.

When you consider speed of data transfer in the application, you must consider the total amount of time that is required to pass data from the control algorithms of one device to the control algorithms of another. This is very different from the data rate of the channel that you are using. For example, neglecting channel delay, with one type of protective relay you can send discrete data between two devices using a point-to-point 38,400 bps channel in 4.2 ms. Ethernet systems proposed for similar purposes on 10 Mbps or 100 Mbps networks have a specification that guarantees data availability across the link in 4 ms. It is important to consider the data speed requirements of your application and then design a system which provides the required data delivery performance based on overall system operation, not channel speed.

An example of the demands of the application is line current differential protection. In this application, high-speed protection requires that a complete set of measurement data crosses the link and becomes available to the control algorithm in 1.42 ms over a 56,000 bps channel. Some applications may allow slower channels and methods resulting in data exchange of 100 ms or slower. Develop the response speed requirements for your application independently of the communications design and then compare those requirements to the overall system performance to determine if your system will operate as expected.

APPLICATIONS

There are many applications where communication of analog values between devices will increase protection and control performance. The paragraphs below examine differential relaying that has been available for many years, but requires additional understanding when using digital communications. We will also look at double-ended fault location, load shedding applications, and automatic reclosing control that present new principals for protection and automation operation enhancement.

Differential Relaying

Protection based on differential calculations has been a mainstay of protection systems for many years. The concept of differential protection is that the total current into a system must be equal to the total current out of a system. Otherwise, there is a fault or other problem and current is taking paths other than those intended.

When differential protection is applied to a transmission line, as shown in Figure 3, we exchange information between two protective relays at opposite ends of the line. This requires some kind of communication path between the two locations.

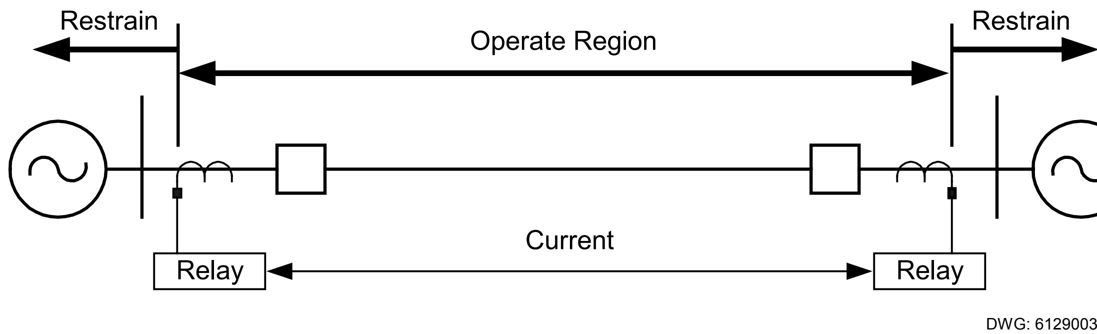

Figure 3 Simple Transmission Line Differential Protection System

Communicating analog information regarding current into or out of a transmission line has been used for differential protection since the 1930s [5]. Combinations of positive- and negative-sequence currents were circulated on a copper pilot wire to create an operating quantity that showed whether the current on the line summed to zero. The advantage of comparing a true analog signal in real time was balanced by the inherent risk of misoperation due to numerous communication or operation mistakes [5].

Using digital communication channels to communicate individual phase currents has enhanced differential protection while reducing the possibility of mistakes compromising system security. Receiving individual phase currents from the remote relay(s) permits more advanced operating elements than were previously possible. Because traditional pilot wire systems automatically derived the operating quantity, protection performance was limited by the operating quantity. With digital communications, systems can communicate raw measurements and derive an operating quantity that provides the optimum protection operation for the application.

For example, protection systems that combine sequence elements will incur limitations. If the operating principle uses $I_2 - kI_1$ then the sensitivity to balanced faults is limited by the "k" factor. Because pickup must be set considering the operating quantities together, sensitivity to unbalanced faults will be decreased by security concerns during load flow. Increasing the security for heavy load will inherently decrease the sensitivity to unbalanced faults. Because the digital communications channel allows us to calculate phase, negative-sequence, and zero-sequence differential quantities separately, we can consider system conditions without undue compromise of sensitivity or security [6]. Negative-sequence differential sensitivity can be set based on maximum unbalance, while phase differential sensitivity can be based on minimum fault currents and load flow for security.

Coordinating protection for tapped loads, historically a difficult relay problem now becomes easier. Consider the system shown in Figure 4 with a tapped line that includes a delta-wye transformer. In relays using a combined quantity differential element, the pickup setting must be increased to account for the maximum load, including magnetizing inrush of the transformer. This causes a corresponding decrease in sensitivity to ground faults.

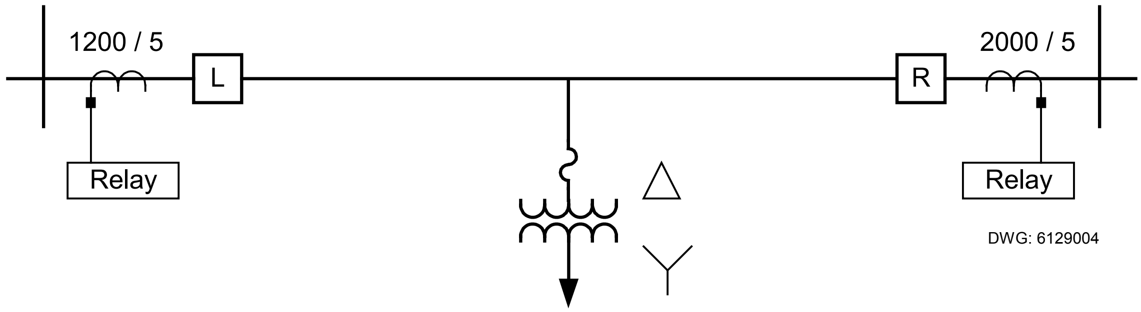

Figure 4 Tapped Transmission Line Differential Protection System

When we use the full set of received currents to create differential elements, we can set the phase units above maximum tap current to provide operation for severe faults with security. A zero-sequence differential element will not look through the transformer and can be used to provide enhanced sensitivity.

Because both relays have access to the current for each phase, the relays can perform summations at each end to calculate the tap current. The relays can use this summation current for a differential time-overcurrent element to coordinate with the fuse at the tap.

In the tapped system, a very difficult loop coordination problem now becomes a radial coordination that is faster and more secure. Digital communications increases protection performance by eliminating combined quantities that were previously used in differential protection schemes.

It is also important to consider what potential problems arise from the shift in technology. The shift in technology may require a new approach to traditional protection elements. Typical differential protection systems have a characteristic slope that defines the protection operation. This behavior emulates the electromechanical relays first used for line differential protection. This characteristic provides restraint against certain types of communications conditions, but is susceptible to asymmetric channel delays that may occur when digital networks change communications paths. This is related to time delay measurements that are critical to using the measured data properly in the receiving relay.

One approach to overcoming the asymmetric channel delay issue is to design an algorithm that quickly observes that there is a problem and changes the overall sensitivity to avoid tripping. This, however, can also lead to decreased speed of operation while the relay measures wave shapes and channel delay. One approach which takes advantage of increased data communications is to change the restraint characteristic by setting it directly on the complex vector ratio (alpha) plane, sensitivity and security can be de-coupled [7]. This innovative approach, using a concept developed many years earlier, provides a system that is simple to apply and increases immunity to issues introduced by the use of digital networks.

Double-Ended Fault Location

Fault location has been recognized as an important part of transmission line protection since the mid 1980s. Algorithms which use only local quantities to determine fault location are limited in accuracy because of conditions such as mutual coupling with parallel lines that can change with system configuration, higher fault resistance, tapped loads and non-homogeneous infeeds [2], [3]. Double-ended fault location calculations, those that utilize data from both the local and remote ends of the line, can improve fault location accuracy.

July 3, 1996, provides us with a notable example of the limits and consequences of inexact fault location. A fault on the Jim Bridger-Kinport 345 kV line started a chain of events that shut down several power plants and interrupted service to a significant portion of Boise, Idaho. A fault at the exact location the prior day had resulted in a major system disturbance. Line crews patrolling to find the fault using data from a single-ended fault location calculation had not been able to determine exactly where the line had sagged into a tree. As the load increased the next day, the fault repeated [4]. The more precise location available with double-ended fault location algorithms could have increased the likelihood of a patrol finding the fault agent leading to line right-of-way maintenance to prevent the second fault.

Implementing previously available algorithms has required phase alignment of data sets along with prefault load information and extensive data communications from the remote line end. In Reference [2], Tziouvaras, Roberts and Benmouyal introduce a fault location design which requires the transmission of only three pieces of information for a typical two-terminal line (US patent 6,259,592):

1. The magnitude of the negative-sequence current, $|I_{2S}|$
2. The magnitude of the negative-sequence source impedance, $|Z_{2S}|$
3. The angle of negative-sequence source impedance, θ_{2S}

The algorithm combines these values with local quantities to provide the solution to the fault location as:

$$\text{Location (m)} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{1}$$

where:

$$A = |I_{2R}|^2 (g^2 + h^2) - (c^2 + d^2) \tag{2}$$

$$B = 2|I_{2R}|^2 (eg + fh) - 2(ac + bd) \tag{3}$$

$$C = |I_{2R}|^2 (e^2 + f^2) - (a^2 + b^2) \tag{4}$$

With the definitions of a, b, c, d, e, f, g, h given by the following equations:

$$I_{2S} \bullet Z_{2S} = V_{2S} = a + jb \tag{5}$$

$$I_{2S} \bullet Z_{2L} = c + jd \tag{6}$$

$$Z_{2R} + Z_{2L} = e + jf \tag{7}$$

$$Z_{2L} = g + jh \tag{8}$$

Subscript S refers to the source end (local) and Subscript R refers to the remote end. For analysis purposes we assume that the line is properly transposed such that the negative-sequence line impedance equals the positive-sequence line impedance ($Z_{2L} = Z_{1L}$).

In this case, the communication of the analog information required is only part of the solution. The relay receiving the information must perform the math necessary to manipulate the analog quantities to solve the problem or implement control. If you are implementing this function in user programming in the relay, you must have access to calculation elements including trigonometric functions for polar to rectangular conversions, square roots or logarithms to solve quadratic equations, and intermediate variables to simplify equations. These elements and the programming flexibility required are available in advanced transmission line relays.

In the equations above, the solution then becomes:

$a = |V_{2S}| \cos\angle V_{2S}$

$b = |V_{2S}| \sin\angle V_{2S}$

$c = |I_{2S}|\,|Z_{1L}| \cos(\angle I_{2S} + \angle Z_{1L})$

$d = |I_{2S}|\,|Z_{1L}| \sin(\angle I_{2S} + \angle Z_{1L})$

$e = |Z_{2R}| \cos\angle Z_{2R} + |Z_{2L}| \cos\angle Z_{1L}$

$f = |Z_{2R}| \sin\angle Z_{2R} + |Z_{2L}| \sin\angle Z_{1L}$

$g = |Z_{1L}| \cos\angle Z_{1L}$

$h = |Z_{1L}| \sin\angle Z_{1L}$

We can then insert these intermediate variables into an additional intermediate step to solve for A, B, and C in equations 2, 3, and 4 above. We can then use these values in Equation 1 to develop a solution for fault location.

While the solution system developed by Tziouvaras, Roberts, and Benmouyal removes the requirement for synchronized elements from the remote line end, it is important that both ends be looking at the same fault. This may seem obvious, but with the possibility of fault evolution and sequential tripping, other qualifications to the communication system are added. The communicating and processing of the data must be done fast enough so that both ends have the same fault applied to their elements. Digital relay-to-relay communications can also be used to transmit information such as relay triggers and trips to improve the accuracy of the location result.

Load Shedding

During the July 3 incident discussed above there was a sequence of manual control actions that prevented system collapse. The incident report describes the actions following the tripping of 345 kV transmission lines:

> Voltage on the heavily loaded 230 kV system between the Brownlee area and the Boise, Idaho, area began to decline and stabilized at a near-normal voltage of 224 kV . . . plant operators, seeking to reduce local plant stress, lowered generating plant reactive output away from the [generator] limits to a less stressed operating level for the units. This action further induced declining voltages in the Boise area. [4]

This was following the same sequence as the prior day which had resulted in widespread outages and islanding. Fortunately, "system operators recognized the potential for an incident similar to that of July 2, and manually interrupted electric service to some customers in the Boise area" [4]. System operators used load shedding to avert large-scale outages.

Human operators observed system conditions and made an intelligent decision and initiated control actions that prevented complete system collapse. They were assisted in their decision-making by their memory of the prior day's events. Often, events either happen so fast that human action cannot be taken, or the operators have been unable to quickly determine what actions are necessary to prevent system instability. Underfrequency and undervoltage load shedding can help to prevent a cascading system collapse. The limitation of present implementations is that they only act on local information.

System load flow studies are performed for a wide variety of configurations. Var support requirements and limitations are modeled for anticipated contingencies. The results of these studies can be set into high-speed control devices that can operate directly or by alarming a dispatcher.

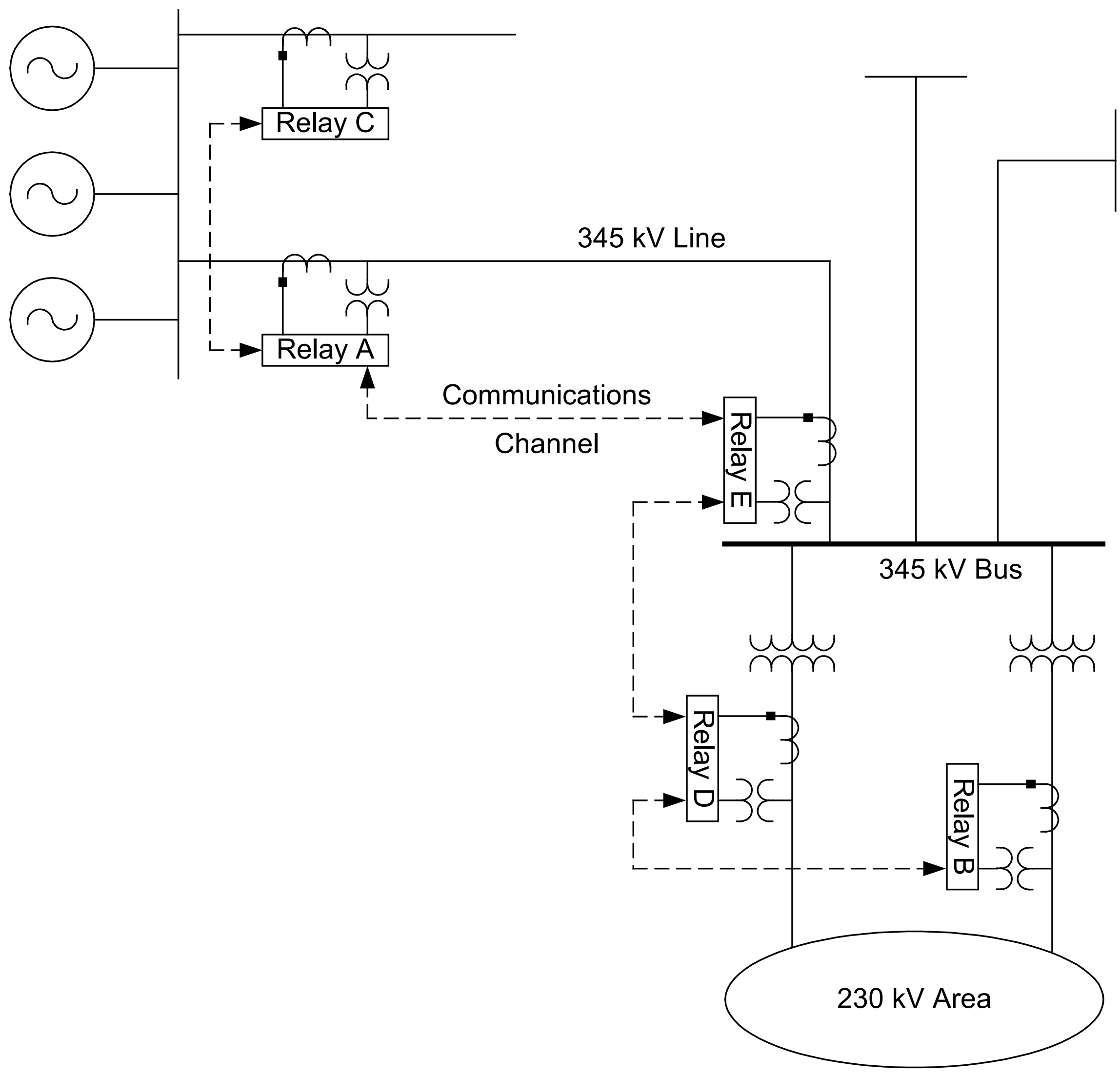

Figure 5 Load Shedding and Protection System Assisted by Communication of Analog Values

In the example system shown in Figure 5, the relays in each of the two systems have access to local system conditions. Relay A, on the 345 kV line end away from the 230 kV system measures its own voltage, current, and frequency. With local calculations, using line voltage and current, it can even determine the voltage at the remote 345 kV bus. Without direct information from the 230 kV area, however, it cannot determine voltage levels in the 230 kV area or total Var requirements for the 230 kV system.

Bi-directional communication of analog data between areas in the system allows fast, intelligent decisions to minimize system disruption following an event. In Figure 5, analog data can be included in the communications channel used for communications-assisted tripping between Relays A and E. Relay A has information not available to Relay E. It can determine from contact inputs which generators are on line and therefore available Watt and Var output. By exchanging local analog information with relays in its own station, Relay A also has the total station Watt and Var outflows.

Now the relays on both ends can make high-speed decisions based on system-wide conditions. Relays in the 230 kV area can be instructed to initiate undervoltage load shedding when Var support from the 345 kV area is at its limit. Relays at the generating end (Relay A) can determine from multiple remote Var demands if remedial action is necessary. These steps occur without operator intervention and therefore do not require that the operator remember the operating sequence for another set of conditions and contingencies. For more precise control action, additional high-speed analog logic can be used. Rate-of-change of frequency and voltage, as well as their present values, can be used to add conditions to control action.

Transmission Line Reclosing

We cannot predict or control faults, but we can use information about the fault to limit the damage caused by reclosing into a permanent fault and help to prevent system instability. With multicircuit line systems, both loss of power transfer capability and equipment damage are related to the amount of fault current at a particular location. The example interconnected system in Figure 6 allows us to look at the impact of reclosing into different faults on power transfer and system stability.

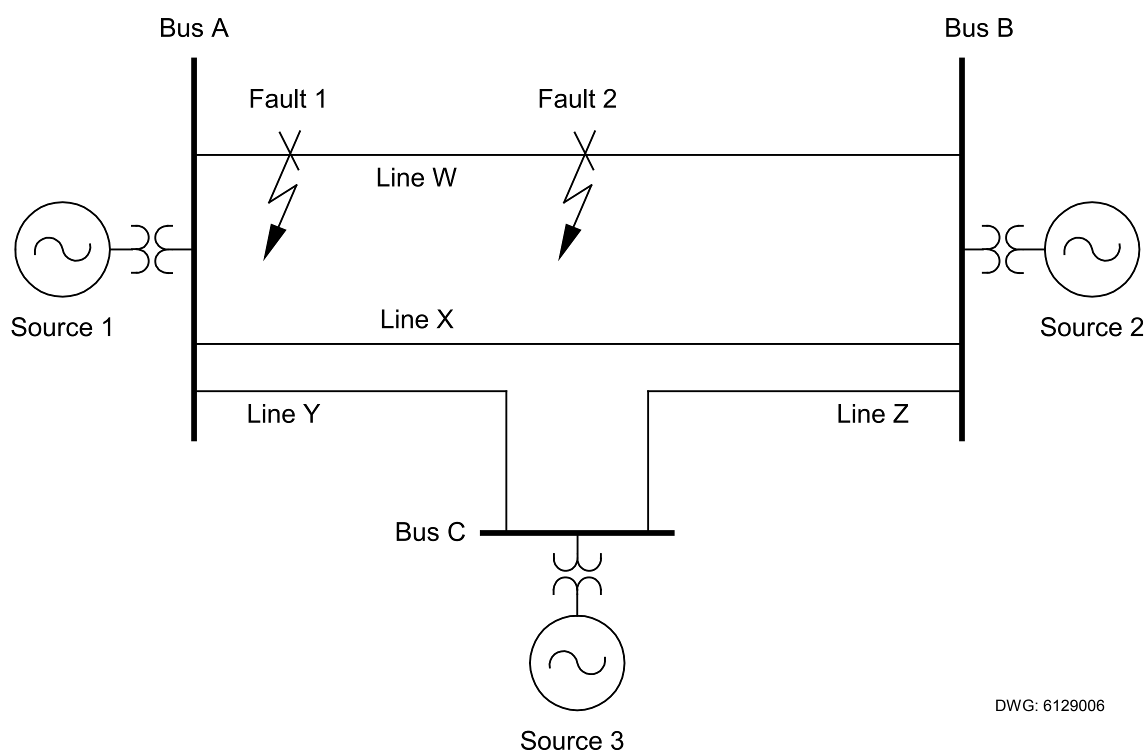

Figure 6 Example Interconnected System

Load transfer capability across the system during a fault and the impact that the load transfer capability will have on system stability depends on the fault location and the status of other connections on the system. In the example system of Figure 6, if we look at the power transfer curves when reclosing into a permanent fault indicated by Fault 1 we see the curves show in Figure 7.

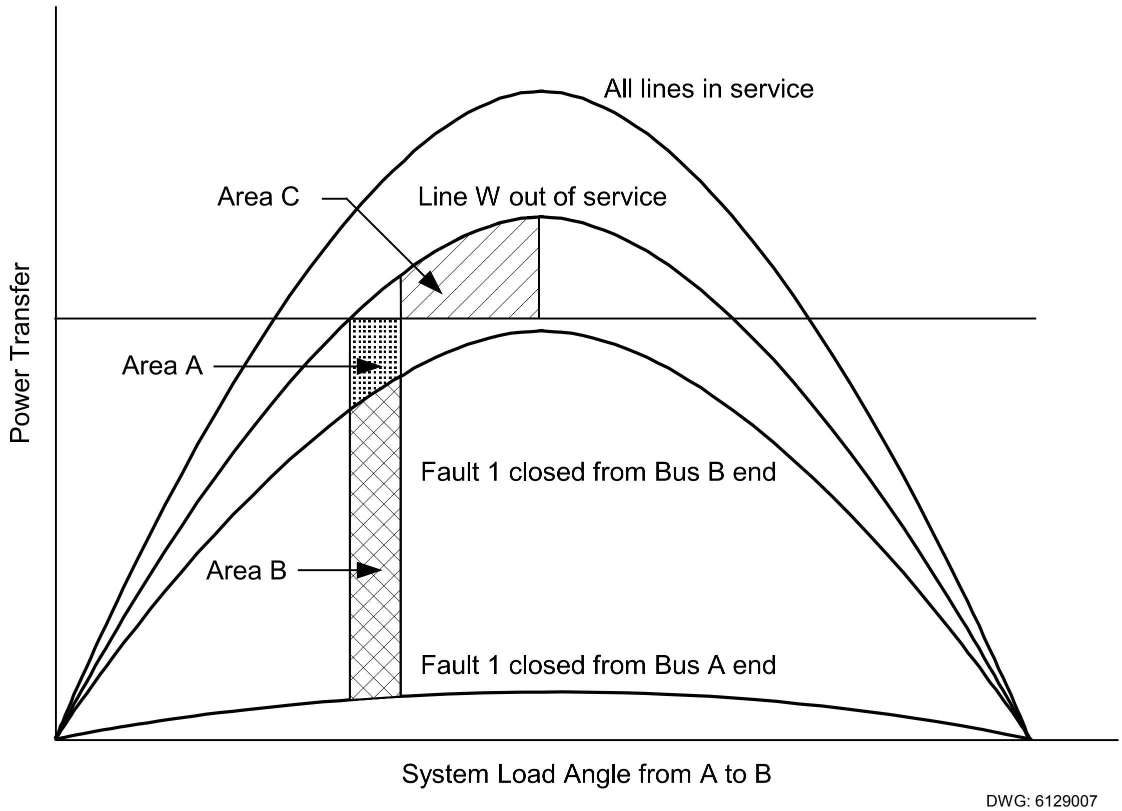

Figure 7 Bus A to Bus B Power Transfer Curves

In Figure 7, the distance between the two vertical lines represents the degree of system separation that results after a reclose into a permanent fault. The area between the lines from the Power Transfer line to the associated reclose curve represents the amount of energy that accelerates one generation system away from the other. If the total amount of energy exceeds the decelerating energy (Area C), the system becomes unstable and there is a significant possibility that generators will trip and cause a severe system disturbance.

If we reclose from the Bus A end, represented by the bottom curve, the energy accelerating the generation on the A end relative to the B end is high (Area A and B). Because this area exceeds the available decelerating area, the loss of transfer capability for a close in fault on Bus A is too great to overcome with Line W out of service. The system will become unstable and trips will likely be observed in the generation system.

On the other hand, if we reclose from the Bus B end, the acceleration energy is indicated by Area A. The decelerating energy available remains the same in both cases. In this case, the decelerating energy is sufficient to maintain stability. The line impedance from the source to the fault allows significant power transfer to continue over the unfaulted lines and the system does not become unstable. This demonstrates the importance of reclosing from the line terminal with the lowest fault current in maintaining system stability and integrity.

Transformer damage measured as a consumption of available equipment life because of passage of fault currents or prolonged operation at currents that exceed equipment ratings has long been recognized and is described in detail in ANSI C57.12.00–1993. As a general rule, a transformer will be able to withstand, thermally and mechanically, roughly 0.25 - 2.0 seconds of fault current (ANSI C57.12.00–1993 7.1.3). While this standard describes loss of life for a single fault event, the cumulative stress of multiple faults and resulting loss of life accumulates over time.

Both transformer winding heat and mechanical damage to the transformer winding during a fault are proportional to the square of the fault current. If we reduce the through fault current by half, the thermal and mechanical damage leading to a reduction in transformer life, can be cut by a factor of four.

This leads to the question of whether fault location is sufficient to determine reclosing order without information from the remote end. Looking again at the interconnected system of Figure 6, consider how the fault duty will vary depending on the status of Lines Y and Z and fault location (Fault 1 or Fault 2). The contribution of Source 3, and whether Line Y or Z are out of service dramatically affect the fault current. This leads to different balance point criteria for reclosing for different system operating conditions making fault location alone inadequate.

If we use currents from both ends of the line to determine reclosing order, questions of system configuration are automatically taken into account. We can use a simple criterion to compare the fault current at the remote (I_R) and local end (I_L) of the line:

- If the ratio $I_R / I_L \geq 1$, reclose the line end on a dead line criterion. This makes the weak source the lead breaker.
- If the ratio $I_R / I_L < 1$, reclose the line end on synchronism check. This closes in the strong source, only after the line shows "healthy."

In order to ensure that the system operates properly we use a digital indication from the lead end to inhibit remote reclosing. The fault current used for the comparison can be the maximum phase current, or the positive-sequence fault current.

Future Applications

Several things have become clear in recent events associated with the power industry. First, world economies are more dependent than ever on the availability of inexpensive and reliable electric power. Second, the systems that provide this power will require increasing automation in order to deliver the power with minimum expense and maximum reliability and safety. Third, system interconnections are making power system operation too complex and too rapid for operators to take the responsibility of preventing system collapse during adverse conditions.

These factors propel the industry toward more sophisticated automatic control that will require enhanced distribution of information. Distribution of this information will increasingly be through digital communications networks requiring that we take appropriate steps to optimize the relationship between control and communications.

Conclusions

1. Existing pilot wire systems may require conversion to digital network communications.
2. The security, availability, and speed of communications systems are important considerations in system design.
3. Digital communications allows communication of more measurements without combining them into an operating quantity. This allows increased sophistication of protection algorithms that can overcome deficiencies of the combined operating quantities traditionally employed.
4. Changes in the communications method or communications technology employed may require a fresh look at the protection algorithms to provide a system that is robust, simpler, and takes advantage of increases in performance afforded by new communications techniques.
5. Communications of analog data can supplement operator system control actions and increase the speed of remedial action and other schemes designed to prevent total system collapse.
6. Smart reclosing using data from the far side of the line decreases the possibility of system instability when reclosing into a fault and reduces transformer loss-of-life due to fault currents.

References

[1] E. O. Schweitzer, III, Bill Fleming, Tony J. Lee, and Paul Anderson, "Reliability Analysis of Transmission Protection Using Fault Tree Methods," Proceedings of the 24th Annual Western Protective Relay Conference, Spokane, WA, October 21 - 23, 1997.

[2] Demetrious Tziouvaras, Jeff Roberts, and Gabriel Benmouyal, "New Multi-Ended Fault Location Design for Two- or Three-Terminal Lines," Proceedings of the CIGRE Colloquium, Florence, Italy, October 11 - 15, 1999.

[3] E. O. Schweitzer, III, "Evaluation and Development of Transmission Line Fault Locating Techniques Which Use Sinusoidal Steady State Information," Proceedings of the 9th Annual Western Protective Relay Conference, Spokane, WA, October, 1982.

[4] Jon F. Daume, "Summer of Our Disconnects, 1996 Western Systems Coordinating Council Power System Disturbances, July 2 - 3 and August 10, 1996," Proceedings of the 24th Annual Western Protective Relay Conference, Spokane, WA, October 21 - 23, 1997.

[5] Walter A. Elmore, "Ways to Assure Misoperation of Electromechanical Pilot-Wire Relays," Proceedings of the 28th Annual Western Protective Relay Conference, Spokane, WA, October 23 - 25, 2001.

[6] Jeff Roberts, Demetrious Tziouvaras, Gabriel Benmouyal, and Hector J. Altuve, "The Effect of Multiprinciple Line Protection on Dependability and Security," Proceedings of the 55th Annual Georgia Tech Protective Relaying Conference, Atlanta, Georgia, May, 2001.

[7] Jeff Roberts, Tony Lee, and George Alexander, "Security and Dependability of Multiterminal Transmission Line Protection," Proceedings of the 28th Annual Western Protective Relay Conference, Spokane, WA, October 23 - 25, 2001.

[8] "Application Guide: AC Pilot Wire and Relaying System," General Electric Corporation, GET-6462A.

[9] Sidnie Feit, *Wide Area High Speed Networks*, Macmillan Technical Publishing, 1999.

[10] E. O. Schweitzer, III, Ken Behrendt, and Tony Lee, "Digital Communications for Power System Protection: Security, Availability, and Speed," Proceedings of the 25th Annual Western Protective Relay Conference, Spokane, WA, October 13 - 15, 1998.

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