DIGITAL TRANSFORMER PROTECTION FROM POWER PLANTS TO DISTRIBUTION SUBSTATIONS

Charles J. Mozina
Beckwith Electric Company
6190-118th Avenue North • Largo, FL 33773-3724 U.S.A.
Phone (727) 544-2326 • Fax (727) 546-0121 • E-Mail: marketing@beckwithelectric.com

INTRODUCTION

Traditionally, the protection of power transformers has been relegated to the application of transformer differential and backup overcurrent relays to provide short-circuit protection. With the advent of modern multifunction transformer packages, differential and overcurrent protection are only two of many protective and logic functions that can be incorporated into the transformer protection package to enhance value to the user. Other protective functions include overexcitation protection (24), neutral overvoltage (59G), ground differential (87GD) and underfrequency (81U)/undervoltage (27) load shedding. Presently, many of these functions are handled via separate discrete relays or not applied at all because of economic considerations.

Transformer protection requirements also vary depending on the location of the transformer on the power system. This paper discusses transformer protection at various locations: power plants, industrial plants, transmission substations and distribution substations.

Since transformer protection requirements vary depending on the application, users typically want only those functions which are needed for that specific application. To accommodate this customized functionality, the selection of transformer protective functions should be determined by users as opposed to manufacturers—the same as is done with discrete relay applications. This paper discusses user-selectable functionality that tailors the relay to specific applications.

In addition, the use of programmable logic extends the benefit of digital multifunction transformer protection especially for distribution transformer applications. Logic schemes have been developed to provide distribution bus fault protection, digital feeder relay backup protection and load shedding at two-bank distribution substations. This paper addresses these types of schemes and their benefits.

The following specific areas of transformer protection are addressed in this paper.

1. Power Plant Transformer Protection
   - overexcitation and differential restraint
   - generator step-up unit (GSU) transformer ground fault protection
   - auxiliary / start-up and industrial transformer protection
2. Transmission Substation Transformer Protection
   - overexcitation (V/Hz) protection
   - sudden pressure relay (SPR) blocking
3. Distribution Substation Transformer Protection
   - underfrequency / undervoltage load shedding
4. Distribution Substation Logic Schemes
   - bus fault logic
   - feeder back-up logic
   - two-bank substation load shedding

The application of transformer differential protection (87T) has been discussed in detail in many other papers and will therefore not be discussed here. Instead, this paper concentrates on other protective functions within digital multifunction transformer relays as well as the logic that can be applied with this technology.

USER-SELECTABLE FUNCTIONS

Since transformer protection requirements vary with the application, user-selectable functions are an important feature. The specific configuration of the multifunction digital relay is then controlled by the user rather than the manufacturer. Cost is proportional to the level of functionality required. The user that purchases an expensive multifunction transformer package, only to disable several functions because they are not appropriate for this application, dilutes the economic advantage of multifunction protection. By using a relay with the basic functions needed in most applications and then selecting from a library of optional functions, the user configures the protection for the specific application at the lowest cost. Figure 1 shows a typical two-winding application of this approach.

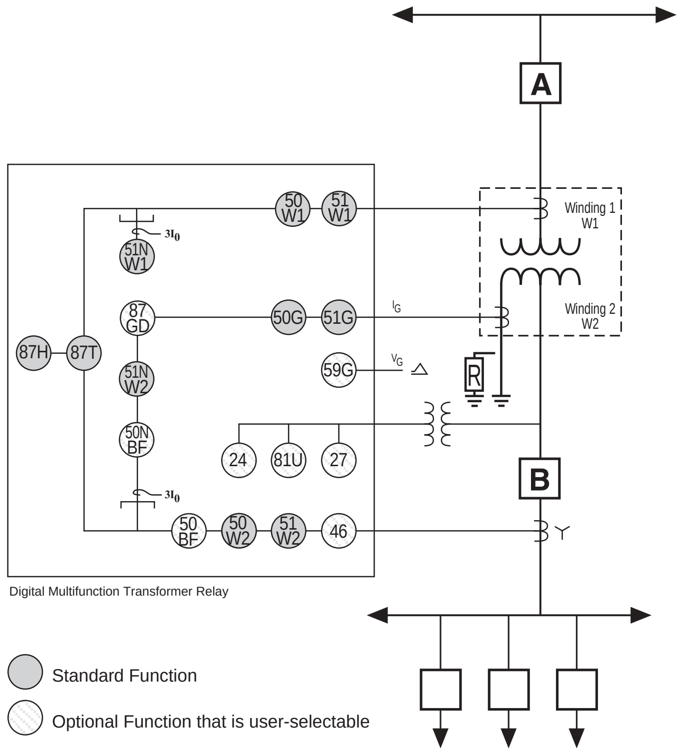


Figure 1 Typical Two-Winding One-Line Functional Diagram

POWER PLANT TRANSFORMER PROTECTION

Overexcitation and Differential Restraint

Most of the discussion of transformer protection centers on the application of differential protection to detect internal faults. Transformers, however, can also be damaged due to overvoltage and underfrequency operation outside their design limits. Transformers operate close to the knee of their saturation curves, therefore even a small increase in voltage results in a very large increase in excitation current as shown in Figure 2a.

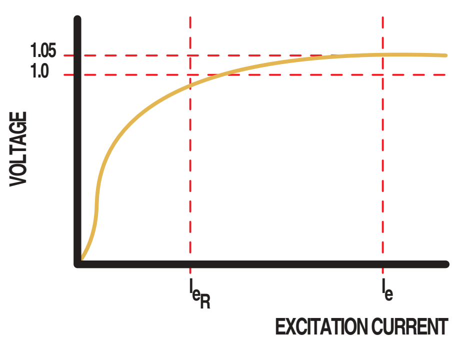


Figure 2a Typical Transformer Saturation Curve

Continuous V/Hz Capabilities of Transformers C57.12

1.05 p.u. (on transformer secondary base) at rated load, 0.8 pf or greater;
1.1 p.u. (transformer base) at no load

2b V/Hz Continuous Capability

The flux in the transformer core is directly proportional to the voltage and inversely proportional to the frequency. Thus V/Hz (24) relays are used to provide overexcitation protection. When V/Hz ratios are exceeded, saturation of the magnetic core of the transformer occurs. This causes excessive core flux resulting in a high interlamination core voltage which, in turn, results in iron burning. Also, at this high flux level, the normal magnetic iron path designed to carry flux saturates and flux begins to flow in leakage paths not designed to carry it, again causing damage. Figure 3 shows a typical short-time V/Hz power transformer capability curve.

Modern overecitation V/Hz protection uses inverse V/Hz curves that can closely match transformer capability.

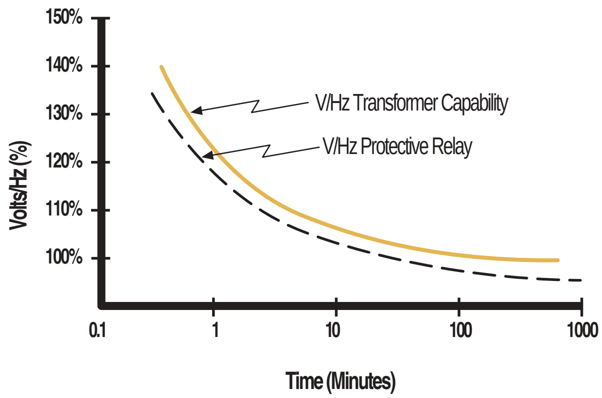


Figure 3 Typical Transformer V/Hz Short-Time Capability Curve

Under normal system operating conditions, generator voltage regulators and other control devices on the power system maintain voltage within the transformer continuous ratings. However, this does not occur during abnormal conditions such as the following.

1. An islanded power system operating condition which results in the sudden loss of load causing a voltage rise. Prolonged overvoltage can occur if the system control measures are unsuccessful in reducing voltage during such disturbances.
2. A generator voltage regulator "runaway" condition which causes the GSU (generator step-up unit) and the auxiliary transformer to encounter high voltages. Though this event frequently occurs off-line, overexcitation can occur with the generator and the GSU connected to the power system. V/Hz levels exceeding 1.25 p.u. for such events have been recorded.

Power plant transformers, especially GSU and auxiliary transformers, are susceptable to overvoltage for the reasons cited above. A substantial unbalanced current will result in the differential circuit due to overexcitation. If the off-line case is examined, as illustrated below, the unbalanced current can exceed 30% of the transformer rating. An actual in-service case is illustrated in Figure 4a for off-line voltage regulator "runaway." Figure 4b shows the build-up of current for such a condition.

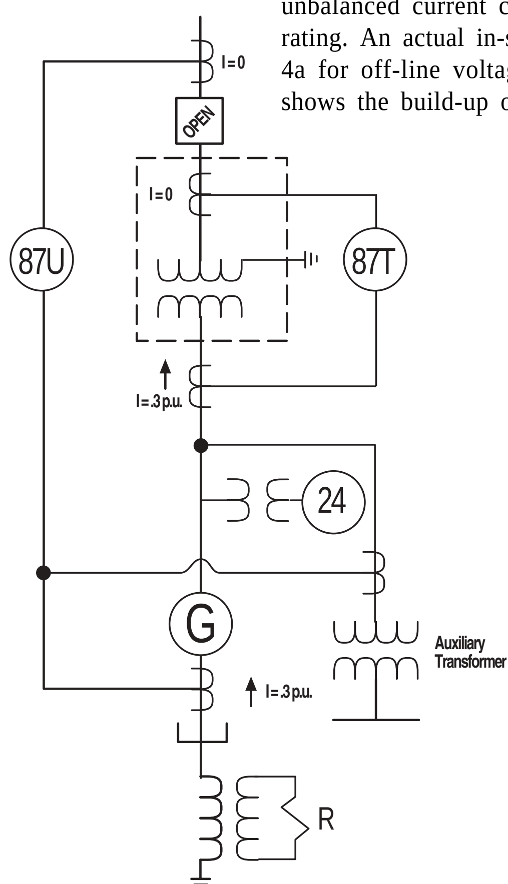


Figure 4a Off-Line Overexcitation Condition One-Line Diagram

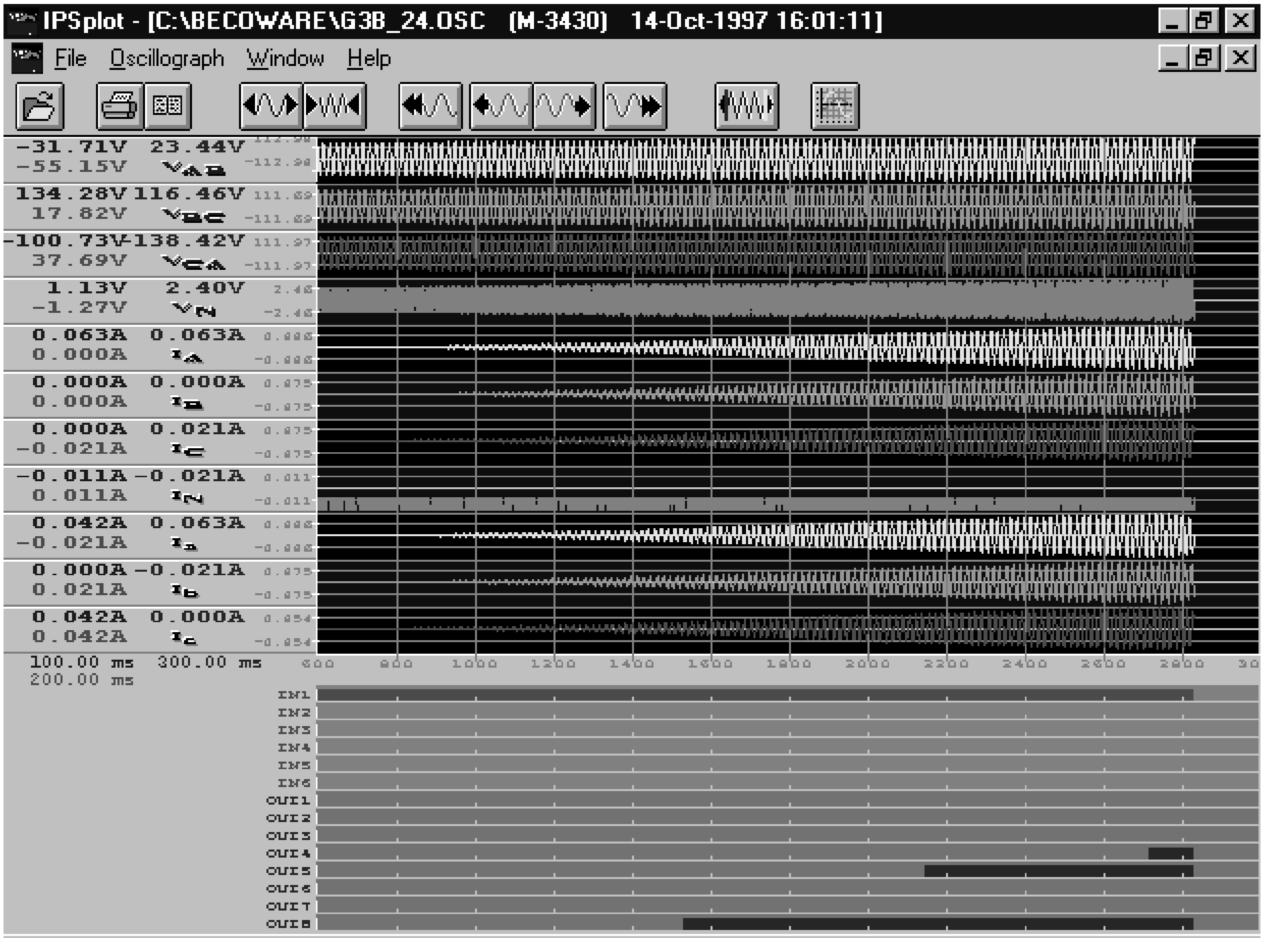


Figure 4b Off-Line Overexcitation Condition Oscillograph

In cases such as these, the generator transformer differential relay (87T) should restrain and the V/Hz (24) protection should operate. Electromechanical and static differential relays were known to operate and improperly indicate an internal transformer fault. Some relay engineers accepted this as a "good false operation" since it tripped the transformer for a damaging event. For off-line events, this may be acceptable even though it indicates falsely a transformer failure. But for on-line events, especially those that are triggered by system islanding during major disturbances, such false operations are not acceptable. In modern digital and static relays, fifth-harmonic is typically used to provide restraint for overexcitation conditions. In such cases, a V/Hz (24) relay needs to be installed to detect overexcitation, since these new digital transformer differential relays will restrain even for severe V/Hz conditions. In some applications, such as the typical gas turbine one-line diagram shown in Figure 5, this protection is provided within the transformer differential zone to provide V/Hz protection when the generator is off-line.

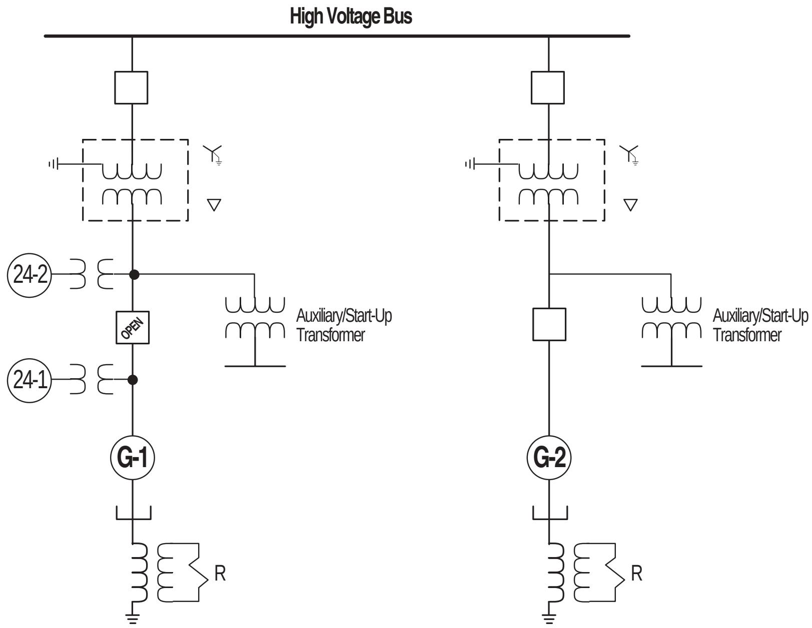


Figure 5 Typical Gas Turbine One-Line Diagram with V/Hz Protection

GSU Ground Transformer Fault Protection

Figure 6 shows a typical gas turbine one-line. This type of arrangement is also used at some hydro plants.

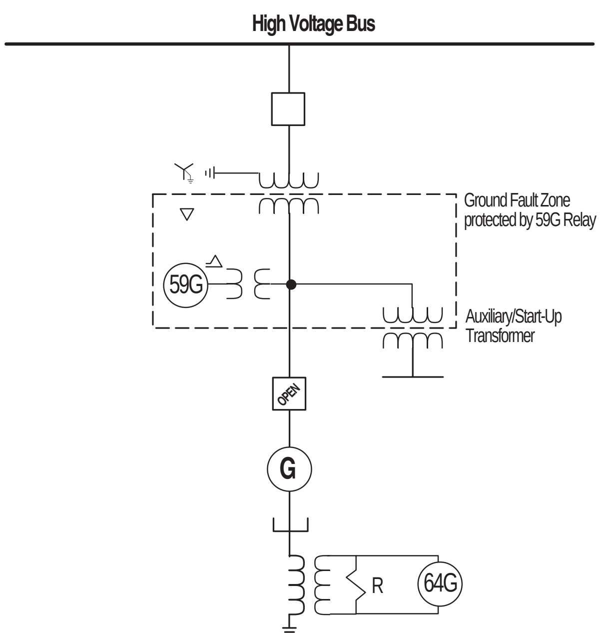


Figure 6 Typical Gas Turbine One-Line Diagram using 59G for Ground Fault Protection

The system ground at the low voltage side of the GSU is provided by the generator neutral grounding transformer. Ground fault protection is provided by the 64G relay. However, when the generator is out of service, the GSU remains in-service to supply the auxiliary transformer which now acts as the start-up supply for the plant. For this condition, ground fault protection needs to be provided in the zone indicated in Figure 6. This protection is provided by a broken-delta VT connected to a 59G overvoltage relay. Third-harmonic voltage will be present across the broken delta when the generator is in-service. For this reason, the 59G relay should be tuned to fundamental (60 Hz) frequency.

Auxiliary/Start-up and Industrial Transformer Protection

Auxiliary and start-up transformers at power plants, as well as transformers at industrial facilities, are generally grounded through a grounding resistor in the transformer neutral. The obvious reason for this is to reduce ground fault current levels to minimize damage at the point of the fault. These systems are almost entirely made up of cable and generally supply a significant motor load. The most frequent type of fault is a single line-to-ground fault.

A second and very important reason for resistance grounding is that it reduces the voltage disturbance caused by a line-to-ground fault. With this type of grounding, loads must be connected phase-to-phase. There is very little reduction in phase-to-phase voltage during a ground fault when currents are reduced to the 100-600 A level

which is typical of these systems. Thus, motors are not "shaken-off" due to voltage dips caused by line-to-ground faults.

This type of grounding reduces the ground fault current within the secondary-winding transformer-differential zone. This current can be below the threshold of operation of the traditional 87T transformer differential relay. Figure 7 illustrates the zone of operation where the 87T relay may not detect a ground fault. In many cases, the 51G neutral time overcurrent relay provides time delay protection for faults in this zone.

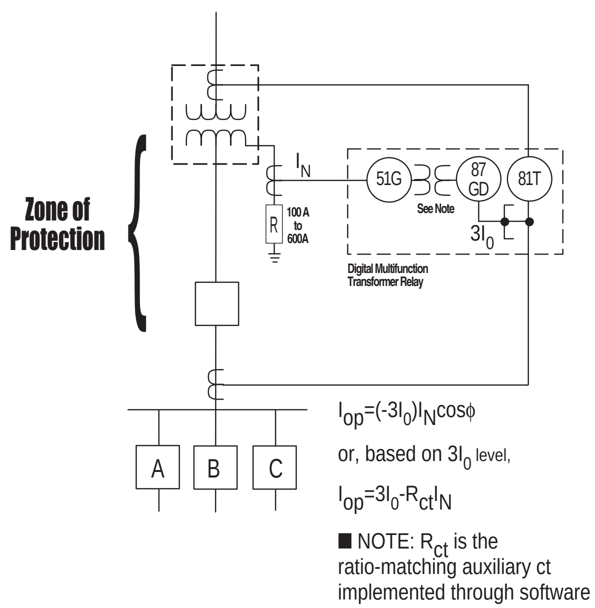


Figure 7 Power Plant Auxiliary or Industrial Application of Ground Differential Relay

High-speed protection can be provided by use of a product type ground differential relay. The concept was available in electromechanical technology and is now available in digital transformer protection packages. The product relay uses $(-3I_o)(I_n)\cos\phi$ as its operating quantity. For faults external to the protective zone, the net operating quantity is negative and the relay will restrain from operating. For low values of $3I_o$, the relay uses a balancing of $3I_o$-$R_{ct}I_n$ to determine an internal fault where R_{ct} is a ratio-matching auxiliary CT. This auxiliary CT is provided as part of the software algorithm for this relay function as opposed to being an actual CT as it was in electromechanical technology.

TRANSMISSION SUBSTATION TRANSFORMER PROTECTION

Overexcitation (V/Hz) Protection

Power plant transformers, as described in the previous section of the paper, are not the only transformers that can be subjected to overexcitation conditions. Autotransformers tapped onto EHV lines have been known to sustain prolonged overvoltage. Figure 8 illustrates such a one-line configuration.

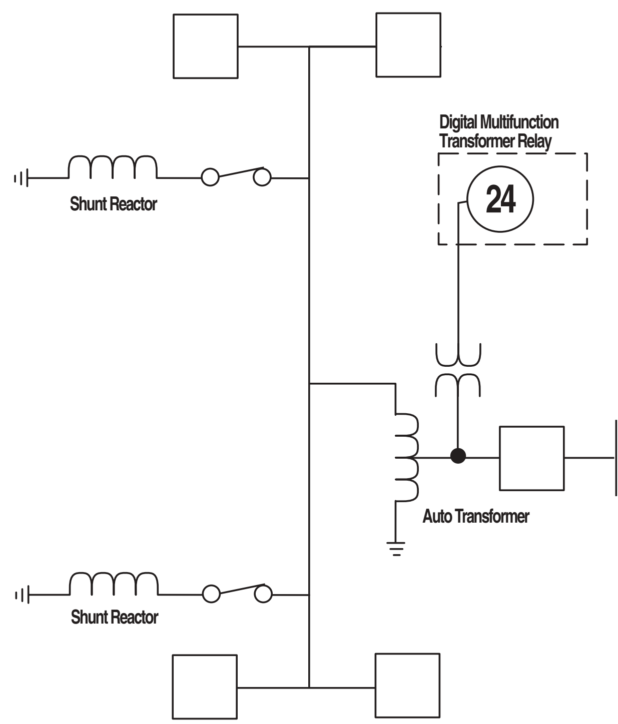


Figure 8 Tap Autotransformer on EHV System

Voltage control on these circuits is performed with shunt reactors. These reactors control overvoltage due to distributed line-shunt capacitance when the line is being switched in and out of service. Incorrect switching of the line with shunt reactors inadvertently left out-of-service can cause a V/Hz condition at tapped transformer locations. Thus, V/Hz protection needs to be considered for this type of application.

Sudden Pressure Relay (SPR) Blocking

The principle upon which the SPR was designed is as follows. The relay was developed to respond to sudden increases in gas or oil pressure in a transformer which is generated by the arc of an internal transformer fault. The breakdown of transformer oil, due to the electric arc, results in the creation of combustible gas. As

the gas evolves, the oil, being incompressible, is displaced upward—compressing the gas in the gas cushion and thereby causing a rate-of-change of pressure. This rate-of-change of pressure is a function of arc current magnitude and time. The SPR is sensitive enough to respond to the pressure increase caused by turn-to-turn faults and will respond very quickly to severe internal faults.

A cutaway view of the Westinghouse SPR relay is shown in Figure 9. It is mounted in the gas space at the top of the transformer tank. Normal pressure changes created by a change in loading or ambient temperature are equalized by a small port between the transformer and the relay chamber. A rate-of-pressure change in excess of the normal rate (0.29 to 0.44 psi per second) creates a pressure differential across the bellows. The bellows actuate the microswitch, shown in Figure 10, which picks up a high-speed auxiliary relay (63X) that initiates tripping of the transformer.

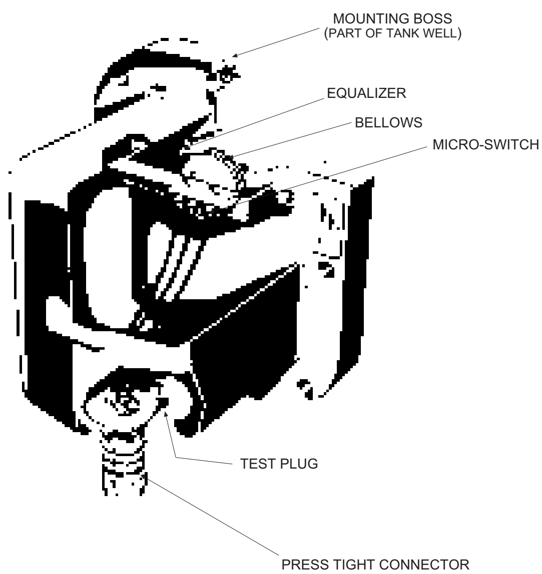


Figure 9 SPR (Sudden Pressure Relay)

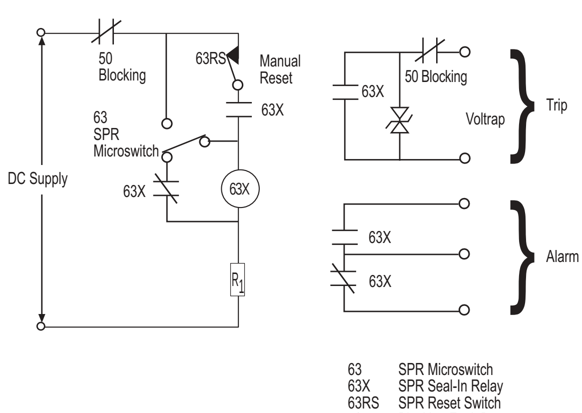


Figure 10 SPR Auxiliary Control Diagram

The physical size and volume of EHV transformers, coupled with the high fault current levels available on today's EHV systems, create forces within the transformer during a through-fault. These forces can cause winding movement or tank-wall deflection of sufficient magnitude to cause oil displacement. This, in turn, compresses the gas cushion causing a sufficient rate-of-change of pressure to gas- or oil-type SPR relays. The SPR cannot distinguish between the rate-of-change of pressure caused by a through fault or a legitimate internal fault. The experience of many utilities confirms that SPR false operations can occur due to through-faults.

The speed of the SPR operation is proportional to the rate-of-change of pressure that occurs within the transformer. Figure 11a indicates the operating time as a function of rate-of-change of pressure. It is believed that most through-faults develop a pressure change in the 10 to 20 psi per second range. Once actuated, the SPR will not immediately reset since the pressure oscillation continues within the transformer keeping the relay picked-up. Reset times are shown in Figure 11b. Reference 3 provides a more detailed discussion of SPR operating/reset times and includes information on the responses of oil pressure SPR relays.

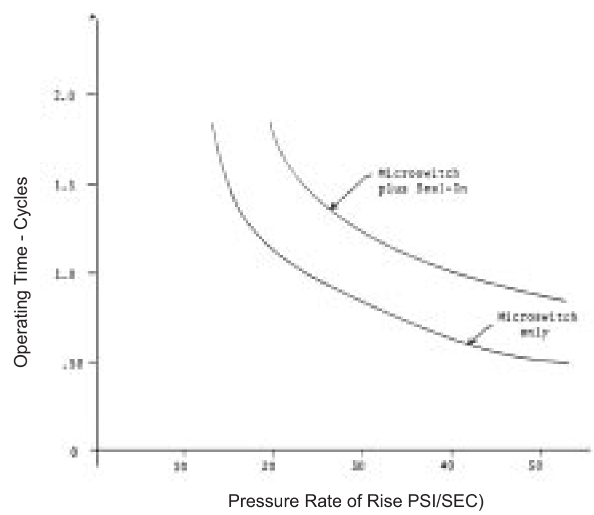


Figure 11a SPR Operating Time (gas type)

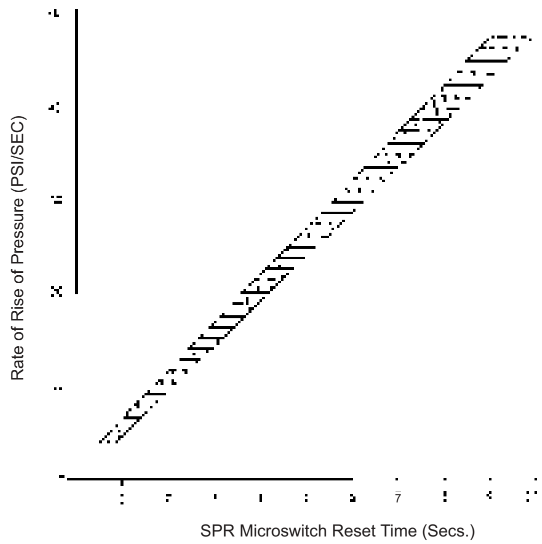


Figure 11b SPR Reset Time (gas type)

Faced with the above situation, only two alternatives were initially available to relay engineers:

- remove the tripping by SPR relays;
- retain the tripping and accept the risk of misoperation.

The development of current supervision schemes provided a third option which retains sensitive transformer protection, while increasing through-fault security. This supervision scheme can now be integrated into a digital transformer relay package. Figure 12 shows the logic for such an application.

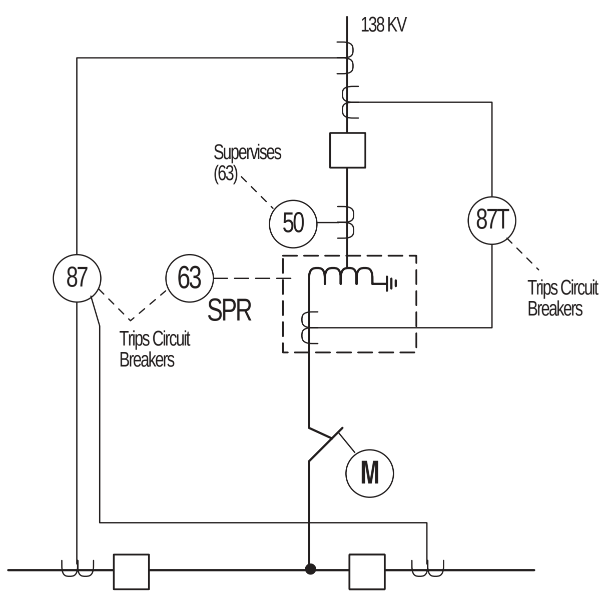


Figure 12a SPR Blocking One-Line Diagram

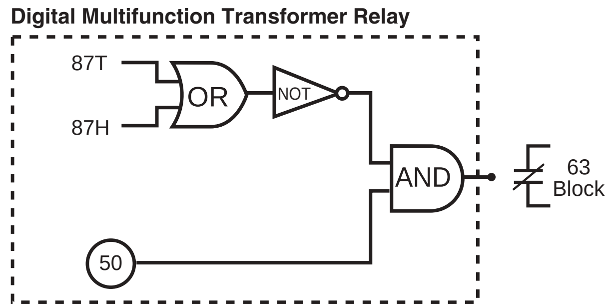


Figure 12b SPR Blocking Logic Diagram

The major disadvantage in applications with this type of scheme is that the SPR relay is blocked from tripping for a time after the occurrence of a through-fault in order to allow the relay to reset. During this time, the transformer differentials provide the sole protection of the transformer. This trade-off has been deemed acceptable by many utilities to enhance through-fault SPR security.

DISTRIBUTION SUBSTATION TRANSFORMER PROTECTION

Underfrequency/Undervoltage Load Shedding (see Figure 13)

Underfrequency load shedding is widely implemented at distribution substations. With multiple output contacts available on most digital transformer protection packages, there is no reason not to incorporate load shedding within these relays. Undervoltage load shedding, however, has been implemented only in a few locations within the U.S. As U.S. power systems experience more voltage collapse events, this practice will probably become more common. Just as underfrequency is a measure of the degree of megawatt overload on the power system, undervoltage is a measure of the degree of the deficient VArs. If VArs are not available, the voltage drops and can even drop to the point of collapsing the power system.

Distribution and subtransmission LTC's play a role in a system-wide low-voltage event. During system undervoltage conditions, as the LTC begins to operate, the secondary transformer voltage will tend to rise, but to the detriment of high-side system voltage. This brings the bulk power system close to an unstable point where collapse becomes more likely. When the system voltage dips to such a low point, the LTC which is intended to raise the secondary transformer voltage will, in fact, cause both high- and low-side transformer voltages to go down. The mitigating measures for voltage collapse phenomenon include:

- coordination of voltage and reactive scheduling between neighboring utilities to ensure adequate VAr support;

- blocking of LTC's during declining system voltage as is done by many European utilities;
- undervoltage load shedding.

Undervoltage relays for this application must be designed to restrict their operation to a narrow bandwidth or range and then to a specific value within that bandwidth to avoid false operation under fault conditions. In some cases, the voltage load shedding and LTC blocking is put in service only when the power system is in a high-stress condition. This is accomplished via a SCADA command for the central dispatch center.

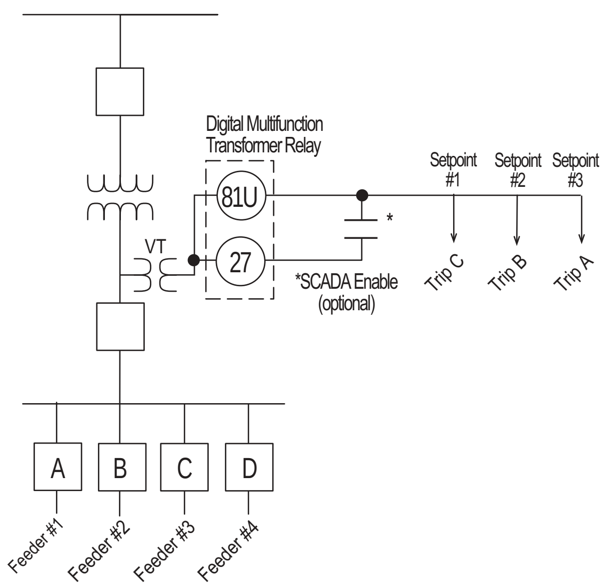


Figure 13 Underfrequency / Undervoltage Load Shedding

DISTRIBUTION SUBSTATION LOGIC SCHEMES

Schemes that integrate the logic of transformer and feeder digital relays can be used to enhance the benefits of digital protection. Such schemes can provide bus fault protection and feeder relay failure backup protection and can increase the utilization of two-bank distribution substations.

Bus Fault Logic

Distribution bus fault protection can be accomplished by using instantaneous overcurrent fault detectors in the feeder and transformer relay packages. Such a scheme is shown in Figure 14. A transformer instantaneous overcurrent relay (50) is used as a fault detector. It is set to overreach the bus and its operation is blocked by any feeder instantaneous relay. A slight time delay of 5 to 8 cycles is usually added to ensure that the blocking has taken place. The scheme provides relatively high-speed bus fault protection without the addition of separate bus differential relaying.

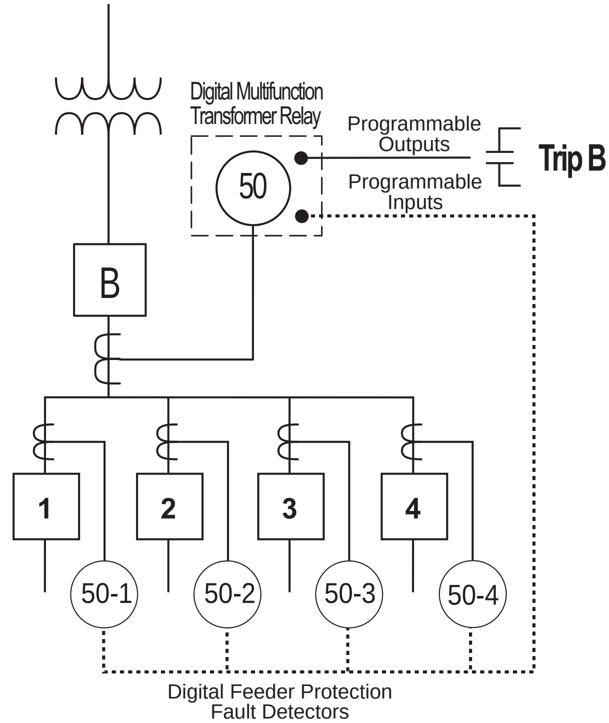


Figure 14a Bus Fault Protection Functional Diagram

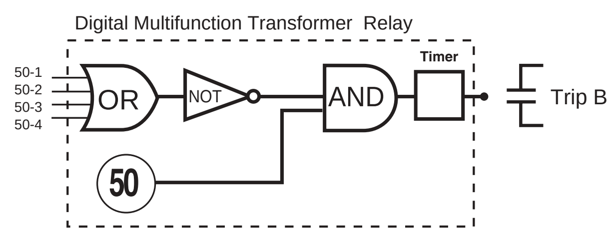


Figure 14b Bus Fault Protection Logic Diagram

Feeder Back-up Logic

The self-test failure output contacts on digital feeder protective relays can be used in conjunction with logic and programmable multiple setting groups within the transformer protection package to provide back-up for a failed feeder relay. The scheme logic and use of an alternate setting group are shown in Figure 15. A scheme such as this can eliminate the need for separate independent back-up relays on each feeder panel.

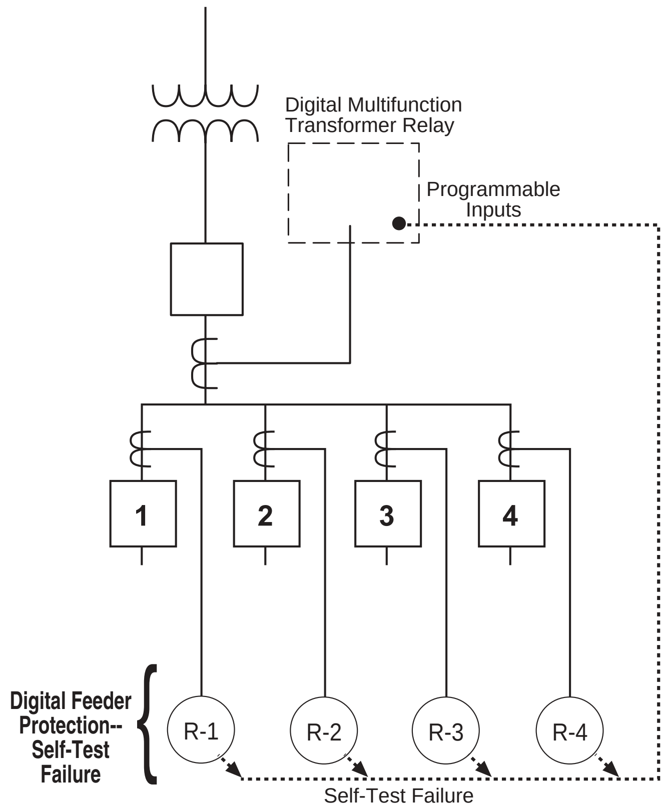


Figure 15a Feeder Digital Relay Failure Backup Functional Diagram

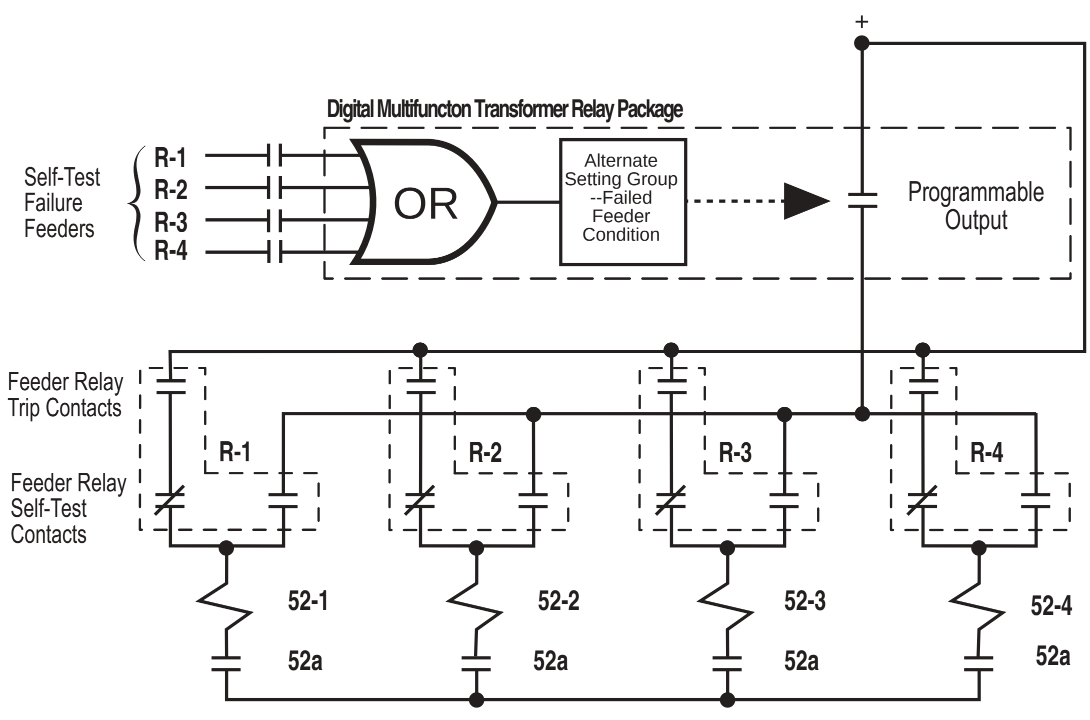


Figure 15b Feeder Digital Relay Failure Backup Logic Diagram

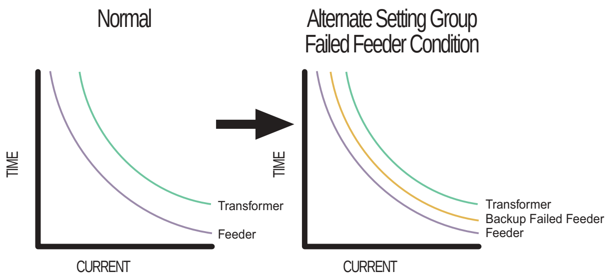


Figure 15c Feeder Digital Relay Failure Backup-Use of Alternate Setting Group

Two-Bank Substation Load Shedding

Increasing the utilization of two-bank distribution substations can provide a substantial economic benefit to a utility. Figure 16a shows a typical two-bank substation. It is common practice to operate under normal conditions with the bus tie breaker open to reduce duty for feeder faults. On the loss of a transformer, or in some cases also the supply line, the affected bank breaker (A or C) is opened and the bus tie breaker (B) is closed to automatically transfer the outage bus section to the companion bank. To accommodate this type of automatic restoration, the loading of the two-bank substation is limited to the N-1 rating of one transformer. This is typical of values above the nameplate rating of one transformer and is a short-time rating. The time involved in establishing this rating is usually based on the utilities estimate of how quickly (typically one day) load can be relieved through load shifts to other substations or through the installation of a mobile substation transformer.

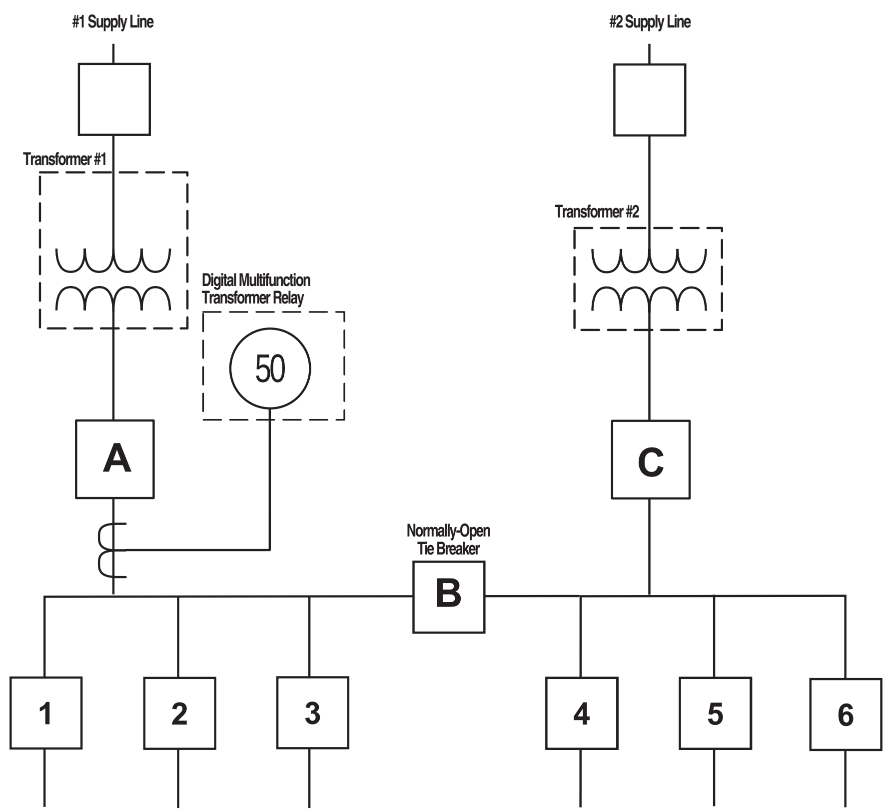
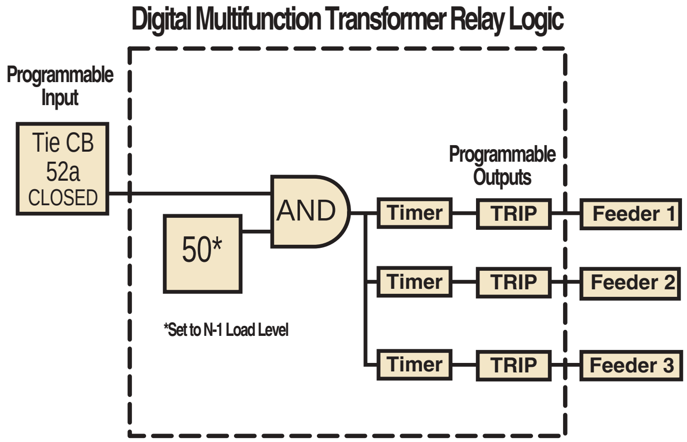


Figure 16a Two-Bank Distribution Substation Overload Shedding Functional Diagram



Example:

N-1 Rating 30 MVA Bank	40 MVA
Full Capacity (30 MVA x2)	60 MVA
Loading Increase	20 MVA

Figure 16b Two-Bank Distribution Substation Overload Shedding Logic Diagram

As shown in the example in Figure 16b, loading the distribution substation to the combined rating of both transformers can provide a significant load capacity increase. Typically, distribution peak loads occur only during a small percentage of time each year. Thus, the concurrent loss of a transformer or supply line at peak load is a fairly rare event. Reference 4 provides an analytical method of evaluating the impact of this type of planning philosophy on customer reliability. A logic scheme can be implemented within a digital transformer relay package that can trip feeders to shed load to protect the remaining transformer from being exposed to loads above its N-1 short-time rating. The increase in distribution capacity by adopting such a planned protection philosophy can be significant.

CONCLUSION

With the advent of more powerful microprocessor-based digital transformer relays, integration of additional functions beyond transformer differential and overcurrent relaying is possible within these relay packages. Functions such as V/Hz overexcitation, neutral overvoltage, ground differential and underfrequency/undervoltage load shedding add enhanced protection features within the transformer protective zone. User-selectable functions allow these relays to be configured to meet specific protection application requirements. Schemes that integrate the logic of the transformer and digital feeder relays further enhance user benefits. This paper outlined a number of specific applications and logic schemes that can benefit users.

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ABOUT THE AUTHOR

Chuck Mozina is Manager of Application Engineering for Protection and Protection Systems for Beckwith Electric Co. He is responsible for the application of Beckwith products and systems used in generator protection and intertie protection, synchronizing and bus transfer schemes.

Chuck is an active member of the IEEE Power System Relay Committee and is the past chairman of the Rotating Machinery Subcommittee. He is the U.S. representative to the CIGRE Study Committee 34 on System Protection and chairs a CIGRE working group on generator protection. He also chaired the IEEE task force which produced the tutorial *The Protection of Synchronous Generators*, which won the PSRC’s 1995 Outstanding Working Group Award. Chuck is the 1993 recipient of the PSRC’s Career Service Award.

Chuck has a bachelor of science in electrical engineering from Purdue University and has authored a number of papers and magazine articles on protective relaying. He has over 25 years of experience as a protective engineer at Centerior Energy, a major investor-owned utility in Cleveland, Ohio. He is also a former instructor in the Graduate School of Electrical Engineering at Cleveland State University.