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THE POWER OF IEC 61850

Bus-transfer and load-shedding applications

THE NEW COMMUNICATIONS technology and the newly developed International Electrotechnical Commission (IEC) standard IEC 61850 [1], for generic object-oriented substation events (GOOSE), bring many advantages to industrial protection and control applications. Some of the applications benefiting the most are those associated with the bus-transfer and load-shedding schemes, together with more beneficial communication-assisted schemes, like zone interlocking, fast bus trip, and arc-flash reduction. Some intelligent electronic devices (IEDs) are equipped with more than one high-speed Ethernet channel to transmit or receive hundreds of discrete and analog values. This offers two very big advantages over the copper-wired IEDs: 1) a single pair of network cables, either copper or fiber, can substitute for a big number of standard copper wires and 2) using two or more network channels provides

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very good data exchange redundancy and hence higher reliability. The savings from substituting a large number of copper wires with a communication medium like Ethernet copper twisted paired cables, or a pair of fiber-optic cables, can be easily calculated.

IEC 61850 GOOSE

The technological advancements in the design of relay hardware and the development of high-speed peer-to-peer communication protocols have resulted in a new generation of IEDs. An efficient way to apply these devices and obtain a custom-built automatic bus-transfer scheme is to use high-speed peer-to-peer IEC 61850 GOOSE messaging. IEC 61850 uses an Ethernet connection as the medium of communication between the protective relays. This article takes the reader inside the design of residual a voltage bus-transfer scheme, as well as load shedding and other schemes, using a pair of multifunctional IEDs, where the usage of copper wires is taken down to a minimum. This article clearly shows the areas of applications, where a reliable exchange of digital and analog information between the protection and control IEDs is achieved through a direct peer-to-peer communications, IEC 61850 standard, and an Ethernet network.

Application Requirements

The bus-transfer and load-shedding schemes are further discussed as applied to a medium-voltage industrial plant. The application requirements for both schemes are that they be fast, reliable, and secure. To implement these requirements, a distributed architecture connected by an IEC 61850-based GOOSE over Ethernet communications is proposed. This architecture has point-to-point, point-to-multipoint, or multipoint-to-multipoint performance available. The components of the bus-transfer and load-shed schemes include IEC 61850-enabled relays and a communication network.

Scheme Redundancy

Since both the bus-transfer and the load-shedding schemes are critical systems in an industrial plant, redundancy in the scheme is very much desired. In the utility world, this is typically achieved through complete duplication of all components. In the industrial plant environment, a good approximation of redundancy can be achieved with some component redundancy and through the use of the failure properties of the IEC 61850 GOOSE.

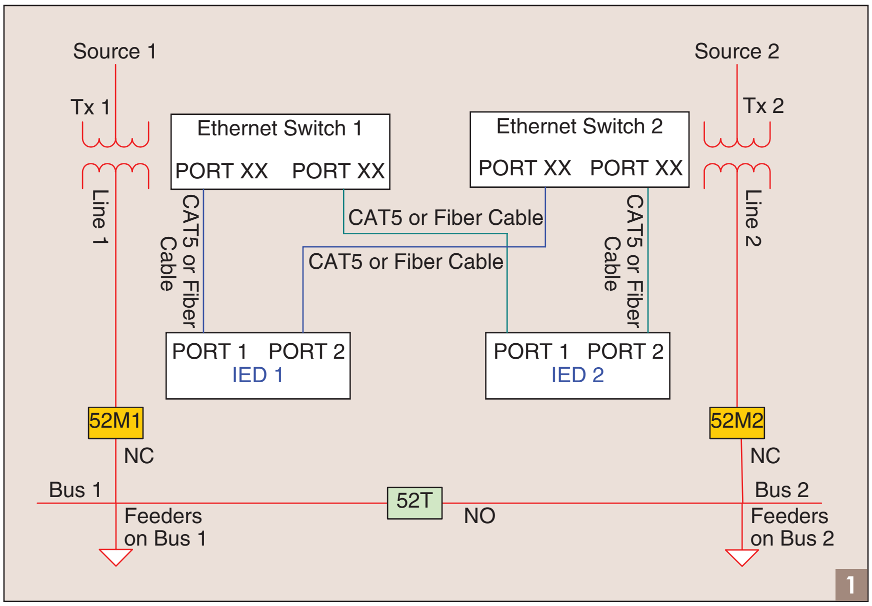
With the logic of the schemes residing in the relays, they become the first point of redundancy. The relays are connected to a redundant Ethernet communication system (Figure 1), such that no single failure of either device or a component of the Ethernet network affects the operation of the scheme. Each device is connected through both fiber-optic channels to two separate Ethernet switches, which send and receive measurements and commands securely. To operate the Ethernet network in a redundant ring, the IEEE Rapid Spanning Tree Protocol (RSTP) should be configured in the Ethernet switches. This algorithm detects rings and ring breaks and dynamically reconnects the communication system to reroute messages as needed.

Sending and Receiving IEC 61850 GOOSE Data Items

The ability of each device to receive line and bus ac information and the ability to send messages is achieved through the use of the IEC 61850 GOOSE. The IEC 61850 GOOSE is a multicast Ethernet data frame that contains packet description information and a user-defined data set. The GOOSE data set can contain information such as remote measurements of line and bus voltages, system frequency, phase angle, watts, vars, breaker status, etc., and it can initiate bus transfer and load-shed commands to the other devices in the scheme.

As a multicast Ethernet message, the GOOSE message can be sent to multiple locations simultaneously. As such, when one monitoring/measuring device (relay) sends voltage value from one location, it is simultaneously received by the other devices connected to the same network. The time on the wire of a small GOOSE message operating on a 100-MB Ethernet network is about 20 μs.

It should be noted that, for data security, all Ethernet physical interfaces should be implemented over fiber-optic media. This implementation has a second advantage: the Ethernet signal can travel up to 2 km in a single span of multimode fiber. In large industrial facilities, this becomes necessary. Distances longer than 2 km can be achieved through the use of an Ethernet switch as a repeater or using single-mode fiber or switch ports, which can then operate up to 40 km or even longer.



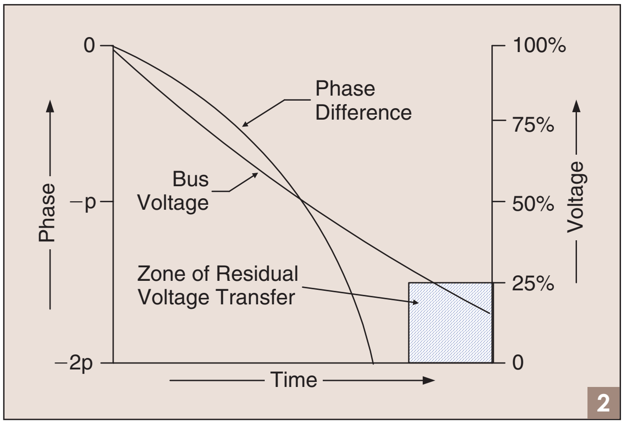
An MTM bus configuration with redundant communication networks.

The GOOSE message is sent several times in quick succession such that if one packet of information is missed or lost because of a communication error, a repeat of the packet is quickly resent. In the case of a binary-only GOOSE message (as would be used in sending the bus transfer and the load-shed commands), the first repeat time can be as little as 4 ms.

Transmission of the GOOSE is triggered by either a data change of an item in the data set being sent or by a periodic time delay. A data change in a binary value is obviously the change of the value either from zero to one or one to zero. In the case of an analog value, the data change is calculated as a user-defined percentage change in the analog value from a given base. For example, if the base value for volts was 13.8 kV and the percentage change detect was set at 1%, a 138-V change in the load voltage from the previous value would result in the transmission of the GOOSE containing the updated value of this data item in its data set.

If, however, the data in the GOOSE data set is not changing, the subscribing device cannot detect the integrity of the sending device. Detection of remote device integrity is accomplished through a data item in the header of the GOOSE message known as time allowed to live (TTL). The TTL value sent from the publisher tells all the subscribers receiving the published GOOSE, such that the next GOOSE transmission from the publisher will occur in XX time, where the XX is set typically in the range of 100 ms–60 s. If the receiving device fails to receive a new GOOSE from the publisher in the stated time period, the subscriber can declare the sending device as failed and use alternate values in logic or settings for those in the expected GOOSE.

It is the ability of setting alternative values in the subscribing device for those in a missing GOOSE that enables this architecture to operate without complete redundancy of the metering. For example, if the metering device measuring the load in a facility fails, the subscriber of this load information can choose to substitute either the last known value of the load, or it can select a worst-case load value that was preset by the designing engineer (user-selectable option). In this manner, the scheme can continue to effectively operate.



Voltage decay and phase difference.

Residual Voltage Transfer

One of the methods for transferring loads from one source to another is the residual voltage transfer. This method is designed to trip the old source breaker before closing the new source breaker, whereby the voltage magnitude of the disconnected bus must fall below a predetermined level before the close command is issued to the new breaker. For main-tie-main (MTM) schemes, the new source breaker would be the tie breaker, as in normal conditions, the tie breaker is normally open and the two main breakers are normally closed.

Since this scheme is unsupervised as to phase angle or slip frequency, this method must prevent closure of the new source breaker until the bus voltage drops below a predetermined voltage limit (Figure 2) or usually <25% of its nominal voltage level. This voltage level is defined safe to avoid excessive torque on the motor shaft upon connecting the disconnected motor bus to the healthy source. The transfer of large motors to the healthy bus is associated with a voltage dip, which may cause the contactors from some other motors connected to this bus to drop out. Thus, some under-voltage analysis and timing coordination must be performed. The set-point accuracy and speed of response of the motor bus transfer under-voltage relay must measure and operate correctly at frequencies below nominal and with a significant rate of change in voltage decay.

During the time necessary to wait for sufficient voltage decay, it is of concern that the frequency may have already decayed past the stall point of the motors on the bus. In such cases consideration must be given to necessary load shedding and also in the case where the new source cannot reaccelerate all bus motors simultaneously or the new source cannot power up all load on both buses because of its capacity limitation. Thus, a detailed analysis of the plant process is required to determine the effects of such a residual voltage transfer.

MTM Residual Voltage Transfer Scheme with Traditional Three-Relay Setup

The traditional method (Figure 3) of providing protection, control, and transfer logic in an MTM substation arrangement involves the following components:

- two multifunction relays for transformer differential protection
- three feeder relays for line and bus tie phase and ground over-current protection, and performance of MTM transfer scheme (the MTM transfer can also be performed by using a separate PLC)
- two tap changer controllers for transformers equipped with tap changers
- a total of seven to eight devices.

In this arrangement, the bus transfer is performed by Relay 3, Relay 4, and Relay 5. These three relays exchange only digital information over copper wires. This information is further used by the specific relay to execute the proper transfer scheme logic equations. For example, one transfer scenario may include the following: A fault on Source 1 trips the Main 1 breaker 52M1. Relay 3 detects 52M1 breaker open condition, detects a line under-voltage condition lasting for an amount of preprogrammed time delay, and sends a command to Relay 5 to close the tie breaker. Simultaneously, Relay 5 makes its own measurements and runs its own programmed logic to determine whether or not to send a close command to the tie-breaker 52T such as no presence of block transfer signals, disconnected bus voltage <25% of its nominal level, and healthy voltage on the other bus exist, the tie-breaker relay sends a close command to the tie-breaker 52T. Closing the 52T effectively ends the sequence of switching bus 1 to the healthy Source 2.

In this setup, the Main 1 and Main 2 relays monitor or measure the corresponding line and bus voltages, and the tie-breaker relay measures the Bus 1 and Bus 2 voltages. The tie-breaker relay will not issue a close command to the tie breaker until the selected logic condition DB&DL, LL&DB, DL&LB, DL/DB, or DLxDB checks true. These logic conditions refer to dead line (DL), live line (LL), dead bus (DB), and live bus (LB), where the "&" symbolizes logical "AND," "/" stands for logical "OR," and "x" is the logical "XOR" operand. These conditions are set with reference to the both the line and bus voltage magnitudes as part of the residual voltage bus-transfer scheme.

Simple MTM transfer scheme logic would require that the three relays be wired and exchange the following digital information at a minimum:

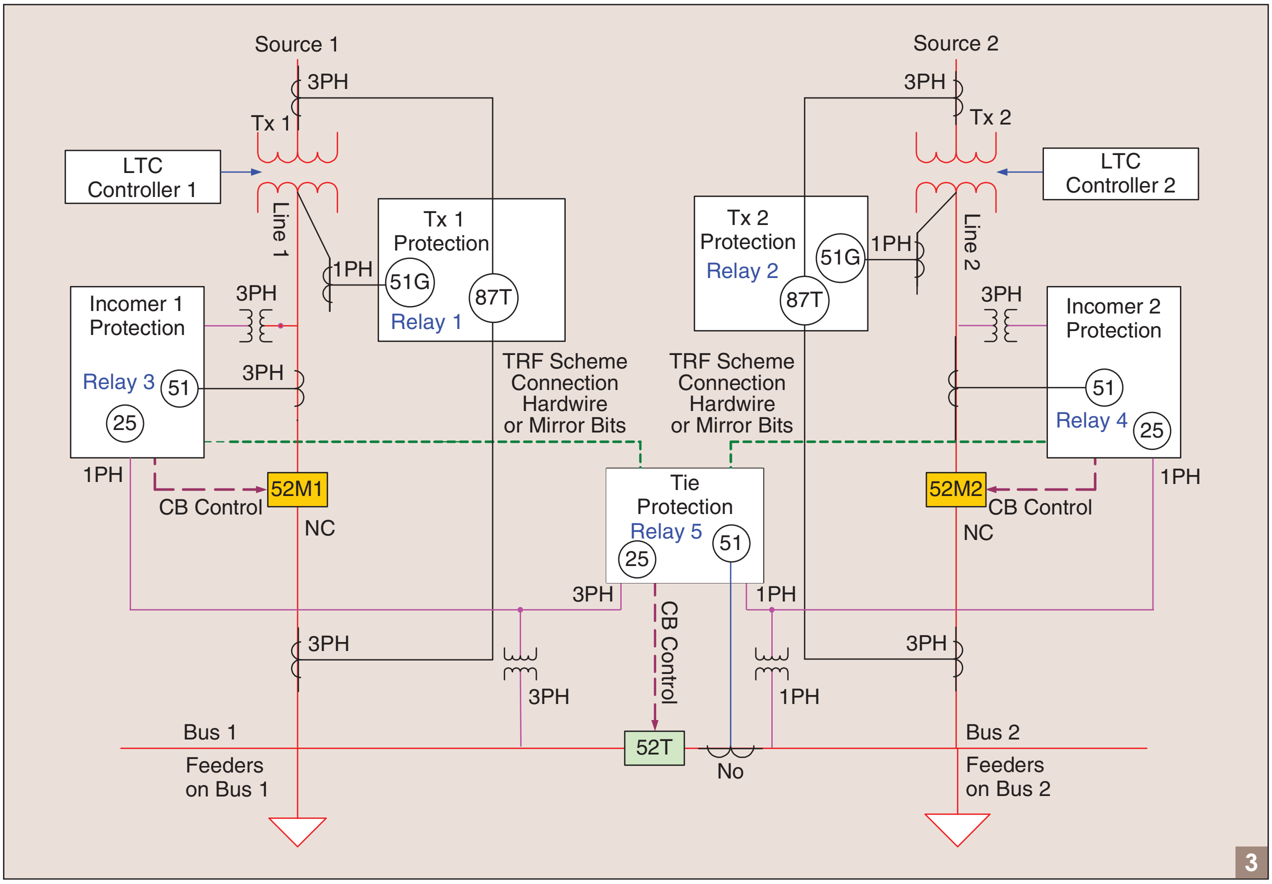
- Source 1(2) breaker racked-in/racked-out status
- Source 1(2) breaker open/close status
- tie-breaker racked-in/racked-out status
- transfer initiate signal from each source relay
- tie-breaker open/closed status
- under-voltage operation from each source
- healthy voltage from each source
- source trip
- transformer trip lockout
- block transfer
- trip breaker selection
- close from Incomer 1
- close from Incomer 2
- transfer ready.

The number of copper wires connected between the relays to exchange only the information above can be high and can lead to a risk of making wiring and/or logic mistakes.

The proposed two-relay scheme eliminates these risks, as it provides a sound solution using advanced communication media and protocol for sending a large number of both digital and analog signals without jeopardizing the logic.

MTM Transfer Scheme with Two Relays and IEC 61850 GOOSE Peer-to-Peer Communication

The technological advancements in the design of relay hardware and the development of high-speed peer-to-peer communication protocols have resulted in a new generation of IEDs. These protective and control devices have the capability to accept multiple levels of current and voltage inputs, analyze measured ac signals at significantly increased speeds, and issue commands upon solving complex logic.



An MTM arrangement with traditionally applied protection and control devices.

The main advantages of using these numerical devices are simplification of the automatic bus-transfer system, component cost reduction, increased system reliability, and the availability of events for transfer analysis.

An efficient way to apply these devices and obtain a custom-built automatic bus-transfer scheme is to use high-speed peer-to-peer IEC 61850 GOOSE messaging. IEC 61850 uses an Ethernet connection as the medium of communication between the protective relays. Remote I/Os via Ethernet communications are used in place of the traditional hard wires to exchange information. The information sent over the network might include the status of the main and tie breakers, voltage detector status, current detector status, and transfer scheme status. Modern IEC 61850 implementations can send messages between relays at speeds of around 2–4 ms. The two relays exchange not only digital data but also analog data over the same Ethernet media and the same IEC 61850 standard. The relays exchange their measurements and actual values. For the purpose of the residual voltage bus transfer and, more specifically, for the part of restoration, the two relays need to exchange information on voltage magnitudes, phase angles, and frequency over the high-speed network. Figure 4 illustrates some of the digital data exchanged between the two relays.

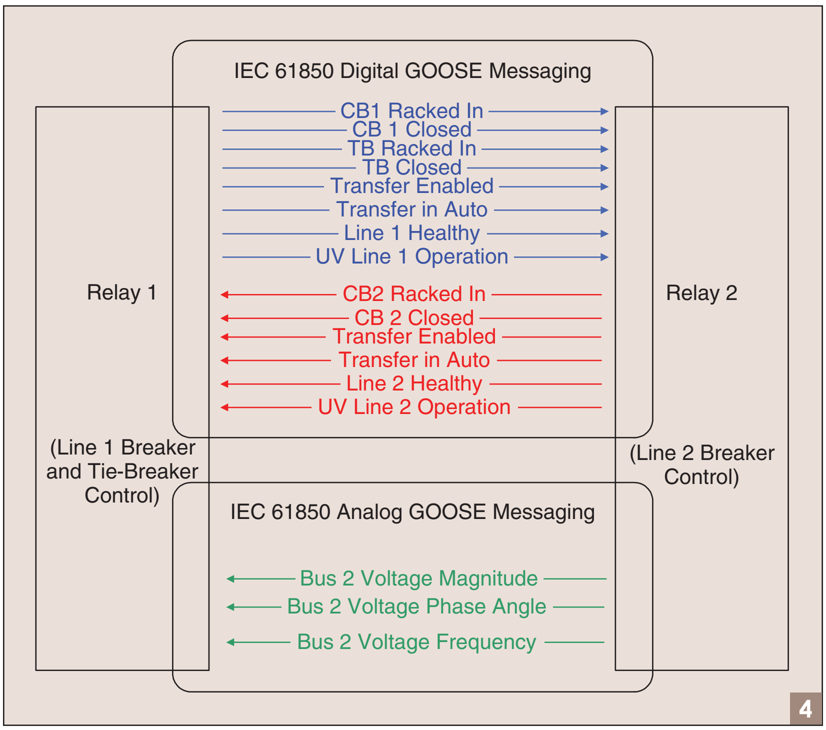
Two-Relay MTM Functionality

The careful selection of protection relays defines the digital multifunction differential protection relays as the ones providing all the required protection, control, and IEC 61850 communication-assisted transfer scheme flexibility. Refer to Figure 5. These two relays are set to perform the following functions.

- Relay 1 is set to send or receive digital and analog values over network communication and IEC 61850 standard, provide Line 1 and Bus 1 voltage metering, control the Main 1 breaker applying sync check and voltage permissive logic and necessary interlock, control the tie breaker applying sync check and voltage permissive logic and necessary interlock, protect transformer 1 by applying the 87T, 50/51, and 50G/51G functions, and protect the bus tie by applying the 51/51G function.
- Relay 2 is set to send/receive digital values using IEC 61850 protocol, provide Line 2 and Bus 2 metering, control the Main 2 breaker applying sync check and voltage permissive logic and necessary interlock, and protect transformer 2 by applying the 87T, 50/51, and 50G/51G functions.

The relays are equipped with a number of hard-wired inputs and outputs for breaker monitoring and tripping, control switches, selection switches, etc. With the use of IEC 61850 GOOSE messaging, these inputs and outputs can be limited to the following:

- three-phase and ground currents
- three-phase line voltages
- one auxiliary bus voltage
- 52a contact
- breaker racked-in/racked-out contact
- 63X transformer sudden pressure
- ten-switch breaker trip selection
- trip output
- close output
- relay control power.



The digital and analog IEC 61850 GOOSE data items exchanged between the two transfer scheme relays.

MTM Autotransfer

The two relays execute the bus transfer in either automatic or manual mode in the following manner. The autotransfer mode applies a break-before-make sequence intended to operate when voltage from any main incoming source is dropped to a value below the transfer initiate value for a predetermined time delay, whereas the second incoming source remains healthy. The time delay is used to avoid nuisance automatic transfer operations caused by a voltage dip in the source. The line voltage is monitored by the relay, which produces a flag if voltage goes below the programmed transfer initiate voltage level. This level is usually set to 0.75 per unit. After the time delay expires, the relay issues open command to the corresponding normally closed main breaker 52M1 or 52M2 and continues to monitor the residual voltage from the disconnected bus. When the residual voltage decays to the applied preset dead bus voltage level (usually 0.25 per unit), the relay sends a command to the tie-breaker 52T to close. To send the close command to the tie breaker, the corresponding relay needs to receive information from the other relay related to the other main line such as health of the line voltage, the closed state of the main breaker, and no under-voltage operation as well as information related to the bus tie, such as the tie-breaker open status. All this data is sent through the GOOSE data set using the IEC 61850 standard and the dual fiber-optic Ethernet channels.

MTM Autorestoration (Autoretransfer)

The autoretransfer mode applies the make-before-break sequence intended to restore the scheme back to normal. When the voltage on the previously disconnected line comes back to normal for a predetermined time delay, the main breaker will need to close automatically so that all three breakers are closed at that time. The main breaker closes automatically only after the sync-check 25 function is performed for matching line and bus voltage magnitudes, phase, and frequency. Next, the automatic operation sends the open command to the tie breaker, and puts the scheme back in normal condition.

Closing of a main breaker for scheme autorestoration does not occur without permission of the sync-check function. Since the relay on the main breaker measures both the line and bus voltages, no analog GOOSE messaging is involved.

MTM Manual Transfer

The manual transfer and manual retransfer through ten-switch also go through the make-before-break sequence and are intended to transfer the loads from the two incoming sources to one incoming source and transfer back. This transfer starts with manually closing the tie breaker after permission from the sync-check function and opening one of the main breakers preselected using the ten-switch selection. The ten-switch is a selector switch for tripping one of the three breakers from the scheme. For the described GOOSE-enabled two-relay scheme, the Main 1 relay performs not only the sync-check function needed to close the 52M1 breaker during autorestoration and manual operation mentioned above but also performs sync-check function for the tie-breaker 52T during manual transfer. To accomplish this functionality, the Main 1 relay is set to receive Bus 2 voltage—the magnitude, phase, and frequency through the analog IEC 61850 GOOSE messaging from the Main 2 relay. Further, together with the locally available Bus 1 magnitude, phase, and frequency-metered voltage values, the received GOOSE analog values are fed into a programmable sync-check function that compares analog IEC 61850 GOOSE values.

The manual transfer does not require fast tie-breaker closing action, so that it is not so important whether or not the tie breaker will close a second or more after the manually initiated close command. This implies that analog values may be originated from a separate GOOSE data set that has a relatively slower interrelay communication speed, as compared to the high-speed digital GOOSE messaging data set, to smooth the network traffic.

However, it is still important to open the main breaker as fast as possible during the manual transfer process. Paralleled lines from an MTM arrangement is not a desired mode, as any fault on any of the two sources or buses, without applying a more complicated protection scheme like 67, will lead to trip from both main breakers, leaving both motor buses disconnected. If the fault occurs at a feeder location while two lines are paralleled, the fault current may exceed the interrupting capacity of the feeder breaker.

Other Communication-Assisted Schemes Using Two Relays and IEC 61850 GOOSE Messaging

Load-Shed Schemes

A simple load-shed scheme needs to be fast and reliable to detect under-frequency or under-voltage conditions that may be present during system overloading. The overloading conditions are dangerous for the system, as the system components (such as transformers, lines, and generators) may operate above their ratings and may overheat, resulting in component damages.

For radial feeders connected to the two buses from an MTM line-bus configuration, the load-shed scheme is employed using the relays from the main breakers and the feeder relays. The GOOSE messaging between these relays is used to exchange load flow values (watts), voltage, and frequency as well as to initiate commands for opening/closing feeder breakers.

The two-relay transfer scheme uses the following ways to perform feeder load-shed applications. All communications between the main relay and the feeder relays use IEC 61850 GOOSE messaging.

Normal Application

For a double-ended industrial substation with MTM configuration, the normal scheme state is defined when the two main breakers are closed and the tie breaker is open. Figure 6 illustrates a source relay (main), which constantly detects voltage and frequency of the incoming lines, and two feeder relays. When the detected incoming line voltage or frequency, or both, are low enough and have reached the preset thresholds, the need for feeder load shed arises. The source relay sends an IEC 61850 GOOSE message to preselected feeder relays to perform load-shed tasks. Multiple levels of under-frequency or under-voltage signals may be sent to the feeder relays, where further logic can be performed on the basis of the priority level of each feeder.

Transfer Process with Equal Line/Transformer Capacity

The entire load on the two buses, Bus 1 and Bus 2, is supposed to be fed by two incoming lines/transformers. Each line/transformer is usually sized to handle 70–80% of the total load resided on the two buses. If the load on the two buses reached the maximum-allowed value when one of the incoming sources is lost, transferring the entire load to the single healthy source will place a great overloading threat to healthy line, and transformer. To avoid such a situation, when the relay detects the loss of one of the incoming lines and issues a command to open the corresponding main breaker, it also sends IEC 61850 GOOSE messaging to the preselected feeder relays as feeder load-shed signals. These signals are used to automatically shed some of the feeders to avoid single incoming line/transformer overload. These signals are not only used to trip the preselected feeder breaker but also used to block them from closing. The tie breaker will not be allowed to close unless the main relay receives all confirmation signals from the feeder relays (also IEC 61850 GOOSE) that the feeders are load shed and feeder breakers are blocked from closing. These load shed signals will be withdrawn after the previously lost line returns back.

Transfer Process with Unequal Line/Transformer Capacity

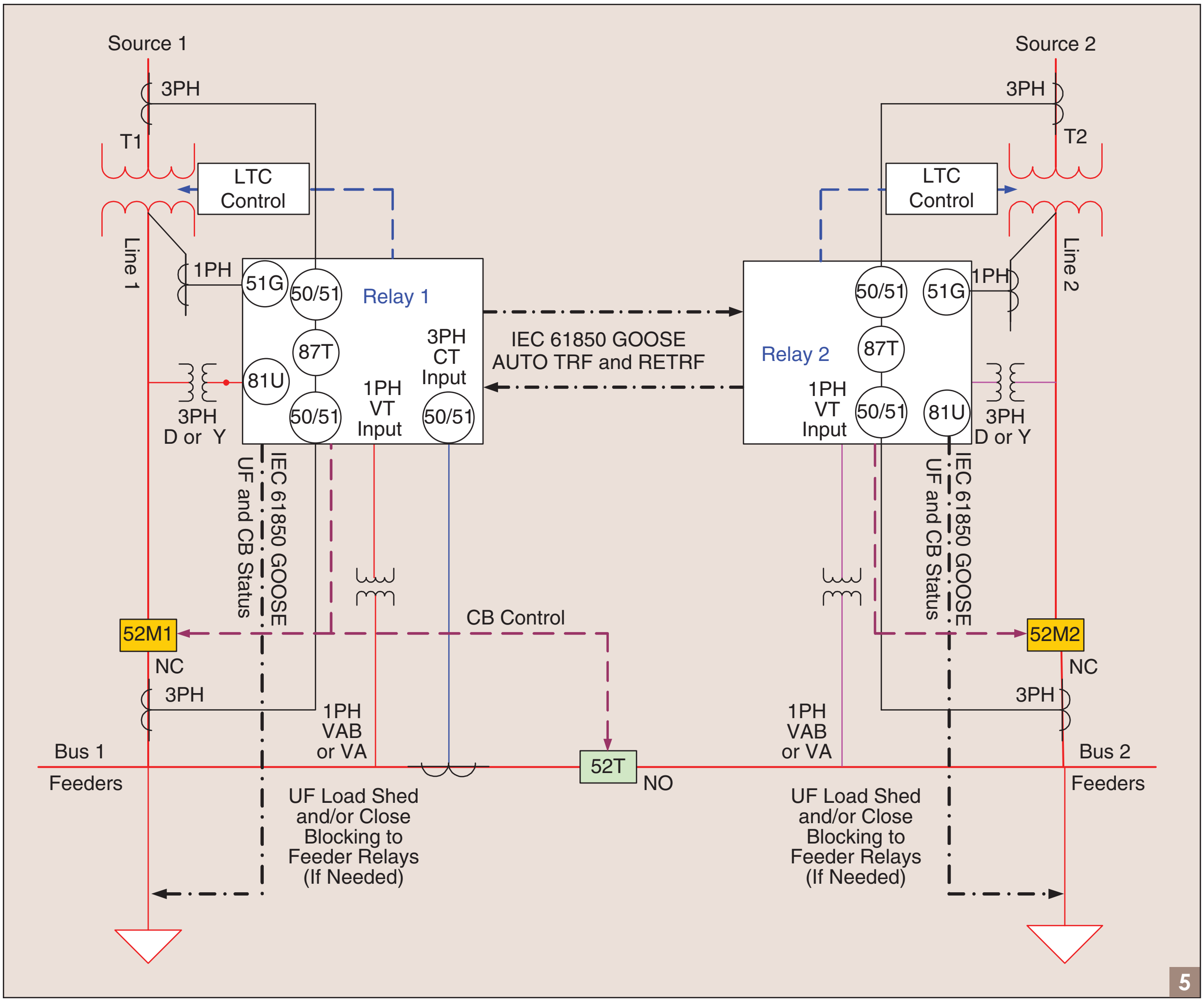
Similar to the first point from above, automatic feeder load shedding is also performed to prevent source overloading when the transformers from the two lines are of different sizes (ratings), particularly transferring the load from two sources to a single source with smaller size of power transformer. The GOOSE messages are sent to some of the preselected feeder relays to shed loads automatically and block them from closing. This prevents overloading of the transformer.

Fast Bus Trip Scheme

A fast bus trip scheme using GOOSE messaging is performed by the relays from the main breakers without the need of adding a bus differential relay. In such cases, relays from the main breakers are connected via fiber-optic or copper twisted pair Ethernet cables to all of the feeder relays to exchange GOOSE data. Any of the two relays from the Main 1 and Main 2 breakers can trip the corresponding bus, if during bus fault, the main relay detects the 50 function operation, and none of the bus feeders detects overcurrent conditions. As the fault must be on the bus, depending on the need of various applications, the main relay would either trip all the beakers in the zone and block them from closing, or would just trip the main breaker and block it from closing.

Zone Interlocking Scheme

Trip-zone interlocking through GOOSE messaging can be implemented between the main relay and the feeder relays. By using trip-zone interlocking, the main relay can also use the 50 function, instead of 51, which would reduce the coordination time interval from at least 200 ms to less than 100 ms (for a five-cycle breaker), to speed up the trip operation, simplify relay protection coordination study and reduce arc-flash hazard.



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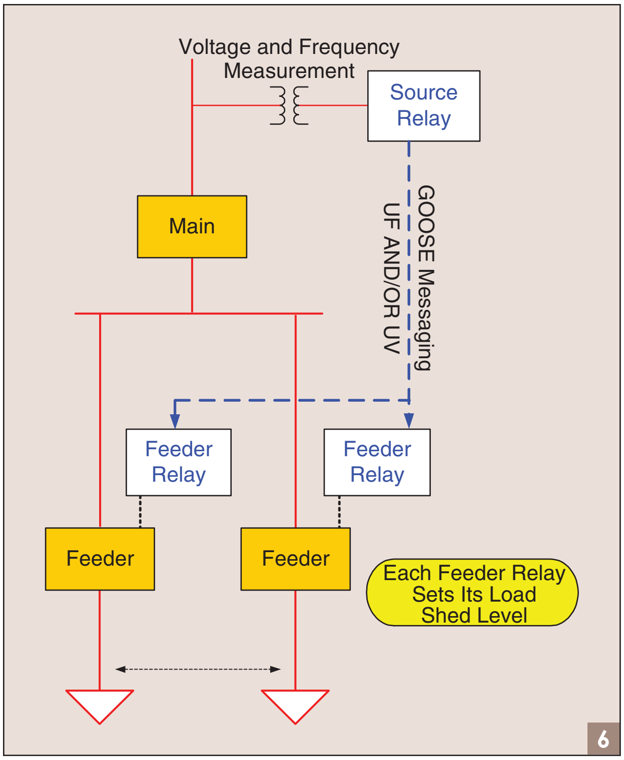
An MTM scheme with two relays performing protection, control, and scheme logic.



A load-shed scheme with GOOSE messaging.

Automatic Transfer Applications for Other Substation Configurations

By expanding the same principles and concepts described above, the other substation configurations can easily adopt the IEC 61850 GOOSE applications. These applications include:

- Two generators as the power sources—the relay selected to perform the automatic transfer must have generator protection as the major protection element.
- Instead of using two incoming power transformers as the power sources, substations that use one generator and one transformer form the two different power sources. The relay selected to perform the automatic transfer must have generator protection with 87G, 50/51, 64, 46, 47, etc., for the generator source and must have transformer protection with 87T, 50/51, etc., for the transformer source as the major protection elements.
- The use of a second functional tie breaker has been gaining greater acceptance in industry to facilitate safe equipment maintenance without sacrificing production. This can be as a variant of a normal MTM substation but can also be accommodated with the two-relay transfer scheme using IEC 61850 GOOSE.
- Industrial substations that have only two main breakers but do not have a tie breaker as a primary–secondary source configuration.

Conclusions

A reduction in wiring is attractive to switchgear builders and allows them to limit the wiring across shipping splits. The advantages of using two protective relays and IEC 61850 GOOSE communications are as follows:

- a significant reduction in hardwiring as compared to that between traditional bus-transfer schemes
- transmitting and receiving digital status and analog values between two main protective relays as well as between main relays and feeder relays at high speed via Ethernet port
- the use of programmable logic functions such as protection and logic flags, timers, Boolean gates, provides flexibility to implement a custom bus-transfer scheme to best meet the needs of the application
- the selector switch functions (select to trip, auto transfer on/off) can be traditionally wired switches, or implemented via protective relay faceplate programmable pushbuttons, eliminating components and installation costs
- an interlocking (bus protection) with downstream and upstream relays, trip-zone interlocking to reduce arc-flash hazard can be accomplished with IEC 61850 GOOSE messaging
- the scheme alarms when either protective relay is off-line or not communicating
- the reconfiguration of scheme without the time and expense of additional wiring.

The benefits to the PCIC conference attendees are:

- the knowledge of IEC 61850 GOOSE peer-to-peer communication between IEDs through Ethernet
- the knowledge of how IEC 61850 GOOSE can play an important role of relay to relay communications for different applications related to bus-transfer schemes
- the knowledge of how IEC 61850 GOOSE can reduce number of components and hard wire connection to save cost in bus-transfer schemes in substations
- the knowledge of how IEC 61850 GOOSE can be used in different substation configurations for communication-assisted relay schemes
- the reduced costs for bus-transfer schemes for different configurations and implementation of other communication-assisted relay applications all together.

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