The Benefits of IEC 61850 Based Transmission Line Protection

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KEYWORDS

IEC 61850, transmission line protection, benefits

1 INTRODUCTION

High-speed unit protection is an essential requirement for efficient operation of transmission and sub-transmission systems. In the event of a fault, the protection must isolate quickly the faulted circuit to prevent damage and enhance the stability of the system. For line protection, two types of main protection are common: current differential and distance protection. The former has a dedicated signaling channel carrying the special current vector messaging between line ends, while the latter traditionally relies on teleprotection equipment external to the main protection relays. For distance applications there is thus much scope for improving the unit protection performance, by allowing the relay to connect directly to the signaling channel available between line ends, rather than using conventional binary inputs and output contacts to signal via other intermediate equipment. However, communications devices are still widely used.

High-speed fault clearing for different faults on transmission lines can be achieved by advanced communications based protection schemes.

The paper describes as an example a directional comparison protection scheme and discusses possible implementations using high-speed peer-to-peer communications to achieve the accelerated protection scheme.

Direct relay-to-relay communications allow significant reduction in the overall cost of accelerated transmission line protection schemes. At the same time they reduce the total operating time of the protection for any fault within the zone of protection.

The paper discusses the impact of IEC 61850 and how the high-speed peer-to-peer GOOSE (Generic Object Oriented Substation Event) messages can be used to replace proprietary communications or the hard wiring between the different devices used in such distributed protection scheme. The overall performance of the protection system is analyzed and requirements and methods for testing are later discussed. Line differential protection is out-of-scope of this paper

2 ACCELERATED LINE PROTECTION SCHEMES

Conventional distance protection does not provide instantaneous tripping for all faults on the protected transmission line. Communications based accelerated schemes allow considerable improvement in the overall fault clearing time for any fault within the zone of protection, while at the same time they do not have the high-speed communication requirements that line differential protection has. This is due to the fact that in these schemes a signaling channel is used to transmit simple ON/OFF data (from a local protection device). This provides additional information to the remote end protection device that can be used to accelerate in-zone fault clearance or prevent operation for external faults. These teleprotection schemes can be grouped into three main operation modes. In each mode, the decision to send a command is made by a local protective relay operation:

In **Intertripping**, (direct or transfer tripping) applications, the command is not supervised at the receiving end by any protection function and simply causes a breaker trip operation. Since no checking of the received signal is performed, it is absolutely essential that any noise on the signaling channel isn't seen as being a valid signal. In other words, an intertripping channel must be very secure.

In **Permissive** applications, tripping is only permitted when the command coincides with a protection operation at the receiving end. Since this applies a second, independent check before tripping, the signaling channel for permissive schemes does not have to be as secure as for Intertripping channels.

In **Blocking** applications, tripping is only permitted when no signal is received, but a protection operation has occurred. In other words, when a command is transmitted, the receiving end device is blocked from operating even if a protection operation occurs. Since the signal is used to prevent tripping, it is clear that a signal is received whenever possible and as quickly as possible. In other words, a blocking channel must be fast and dependable.

The protection function that sends the permissive or blocking signal to the remote end determines the type of scheme used. If this is a distance element, we usually talk about Permissive Underreaching or Overreaching schemes, or Blocking schemes. If a directional element is used to initiate the transmission of a signal to the remote end of the protected line - we have Directional Comparison schemes. A directional comparison schemes can be Permissive or Blocking, with directional elements initiating the signal transmission and providing the supervision at the receiving end.

We can consider as an example of an accelerated transmission line protection scheme a Permissive Directional Comparison scheme commonly used to accelerate the clearing of all kinds of faults, including high-resistance faults that are not seen by the distance elements of the transmission line protection relays or line differential relays.

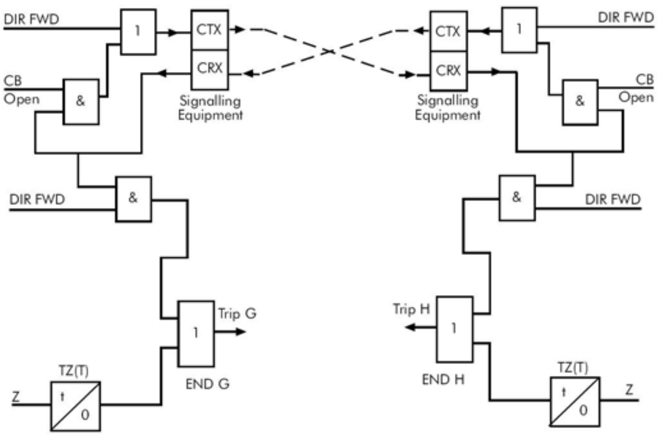

Figure 1: Permissive Directional Comparison Scheme

The channel for a directional comparison Permissive scheme is keyed by operation of the forward looking elements of the relay. If the remote relay has also detected a forward fault upon receipt of this signal, the relay will operate. Such schemes offer some significant advantages, especially when high-speed directional detection methods based on superimposed current and voltage components are used.

Permissive schemes tend to be more secure than blocking schemes because forward directional decisions must be made at both ends of the line before tripping is allowed. Failure of the signaling channel will not result in unwanted tripping, because no signal is going to be received and the relay does not trip based on a forward directional detection only.

If the source at either end of the line is weak, the directional comparison permissive scheme uses Weak Infeed logic.

Current reversal guard logic is used to prevent healthy line protection maloperation for the high speed current reversals experienced in double circuit lines, caused by sequential opening of circuit breakers.

If the signaling channel fails, Basic distance scheme tripping will be usually available.

3 IEC 61850 GOOSE

The peer-to-peer communications in IEC 61850 integrated substation protection and control system are based on what is defined as a GOOSE messages. They use multicast Ethernet communications and represent the asynchronous reporting of an IED’s functional element change of state to other peer devices enrolled to receive it during the configuration stages of the substation integration process. GOOSE messages are used to replace the hard wired control signals exchanged between IEDs for interlocking and protection purposes and, consequently, are mission sensitive, time critical and must be highly reliable. It is important to understand that the GOOSE message is not a command in the sense that it does not tell any receiving device what to do. It just indicates that a new event has occurred, what that event is and the time when it happened.

The IEDs receiving the message use the contained information to determine what the appropriate response is for the given change of state. The decision of the required action to GOOSE messages and what to do should a message times out due to a communication failure is determined by local intelligence in the IED receiving the GOOSE message.

The high speed peer-to-peer communications are defined as interface IF8 in the standard: direct data exchange between the bays especially for fast functions like interlocking or protection.

Considering the importance of the functions performed using GOOSE messages, IEC61850 defines very strict performance requirements. The idea is that the implementation of high-speed peer-to-peer communications should be equal to or better than what is achievable by existing technology. Thus the total peer-to-peer time should not exceed 4 ms. This is the total time between the functional element in the publishing device and the one using the information in the subscribing device.

Another important requirement for the GOOSE messages is very high reliability. Since the messages are not confirmed, but multicasted, and considering the importance of a message such as Breaker Failure Protection Operate or Fault in Reverse Direction, there has to be a mechanism to ensure that the receiving IEDs will receive the message and operate as expected.

To achieve a high level of reliability, messages are repeated as long as the state persists. To maximize dependability and security, a message will have a time to live which will be known as “hold time”. After the hold time expires, the message (status) will expire unless the same status message is repeated or a new message is received prior to the expiration of the hold time.

The repeat time for the initial GOOSE message is short – a few milliseconds - and subsequent messages have an increase in repeat and hold times until a maximum is reached. The GOOSE message contains information that allows the receiving IED to know that a message has been missed, a status has changed and the time since the last status change.

In order to achieve high speed performance and at the same time reduce the network traffic during severe fault conditions, the GOOSE message has been designed based on the idea to have a single message that conveys all required protection scheme information regarding an individual protection IED. It represents a state machine that reports the status of the IED to its peers. High-speed peer-to-peer communications can be implemented in different kinds of distributed protection schemes as a function of the substation configuration and the type of protected element.

To further improve security and the performance of protection schemes over the substation local area network GOOSE messages use some of the advanced features of later versions of Ethernet. The Virtual Local Area Network (VLAN) protocol on Ethernet networks permits insertion of an identifier, or "tag", into the Ethernet frame format to identify the VLAN to which the frame belongs. It allows frames from devices to be assigned to logical groups and provides various benefits such as enhancing network security, Refer to IEEE standard 802.1Q for definition of the VLAN protocol. The IEEE 802.3ac standard defines only the implementation details of the VLAN protocol that are specific to Ethernet.

When present, the 4-byte VLAN tag is inserted into the Ethernet frame between the Source MAC Address field and the Length/Type field. The first 2-bytes of the VLAN tag consist of the "802.1Q Tag Type" and are always set to a value of 0x8100. The 0x8100 value is actually a reserved Length/Type field assignment that indicates the presence of the VLAN tag, and signals that the traditional Length/Type field can be found at an offset of 4-bytes further into the frame. The last 2-bytes of the VLAN tag contain the following information:

- The first 3-bits are a User Priority Field that may be used to assign a priority level to the Ethernet frame.
- The next 1-bit is a Canonical Format Indicator (CFI) used in Ethernet frames to indicate the presence of a Routing Information Field (RIF).
- The last 12-bits are the VLAN Identifier (VID) which uniquely identifies the VLAN to which the Ethernet frame belongs.

The use of higher priority for GOOSE messages allows the improvement of the overall performance of a distributed protection scheme, especially at times of high network traffic that may be expected when a fault occurs,

Improved security of implementation of distributed schemes can be achieved using VLAN identifiers.

4 IMPLEMENTATION OF ACCELERATED SCHEMES

The implementation of accelerated transmission line protection schemes depends on the requirements of the application, the available communications channel and the substation communications protocol.

Electromechanical, solid state and early microprocessor based relays used intermediate equipment to transmit the permissive or blocking signal to the relay at a remote end of the protected line. To achieve that at the sending end an output contact of the protection relay is wired to an input of the teleprotection device. An output of the communication device receiving the signal in the remote substation is wired to an input of the relay receiving the accelerating signal used by the transmission line protection scheme. This conventional implementation of an accelerated scheme is shown in Figure 2.

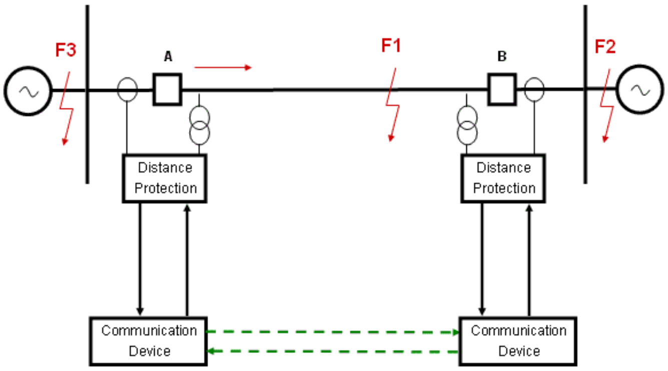

Figure 2: Conventional implementation of accelerated scheme

The availability of serial communications interface in later versions of microprocessor based transmission line protection relays allowed the implementation of accelerated schemes without the use of intermediate teleprotection devices.

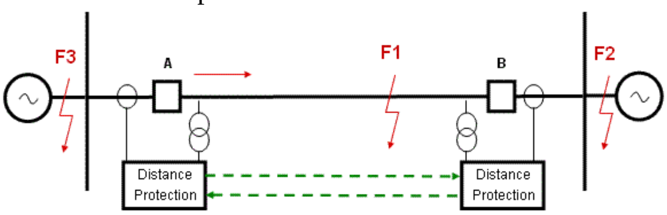

Figure 3: Accelerated scheme using serial communications

The exchange of permissive or blocking signal in this case is using a proprietary communications protocol between the relays at the ends of the protected transmission line. This implementation has advantages over the classical one described above due to improvements in performance and reliability by eliminating the hard wired interface between the relays and teleprotection devices at the sending and receiving ends of the distributed application.

An accelerated scheme implementation using direct serial communications between the relays at both ends of the protected transmission line is shown in Figure 3.

The introduction of IEC 61850 as an international standard for substation communications and the significant increase in the availability of fiber optic cables between substations allows a new way of implementation of accelerated schemes that offers some important benefits. The specifics of each implementation still are determined by the communications available between the substations at the ends of the protected line.

If power line carrier signaling equipment is available for communications between the substations, the system will logically be similar to the one shown in Fig. 3, but the hard wiring between the relay outputs of the protection devices and the inputs of the communications device are replaced with the virtual connections using GOOSE messages. Several GOOSE messages will be required depending on the selected scheme as described below.

If we consider as an example the permissive directional comparison scheme in Figure 1, and if the implementation of the monitoring of the status of the breaker is in a dedicated breaker control IED, the following GOOSE messages will have to be used:

- Change of breaker status should be published by the breaker control IED to indicate to the protection IED if it should use the Echo logic in the accelerated protection scheme
- Receiving of a Permissive signal from the remote end should be published by the communication IED. The protection IED uses this message to make a decision if the fault is within the zone of protection
- Change of state of the directional element should be published by the transmission line protection IED to indicate to the communications device to send over the power line carrier the permissive signal to the remote end
- Directional comparison scheme operation should be published by the protection relay to indicate to the breaker control device that is should trip the breaker

In case of implementation of the breaker control and monitoring function within the protection device (which is the typical case at this stage of use of IEC 61850) the number of required GOOSE messages is limited to the following:

- Receiving of a Permissive signal from the remote end should be published by the communication IED. The protection IED uses this message to make a decision if the fault is within the zone of protection
- Change of state of the directional element should be published by the transmission line protection IED to indicate to the communications device to send over the power line carrier the permissive signal to the remote end

Figure 4 shows this case of implementation of the permissive directional comparison scheme. RDIR is the logical node representing the directional element in each relay.

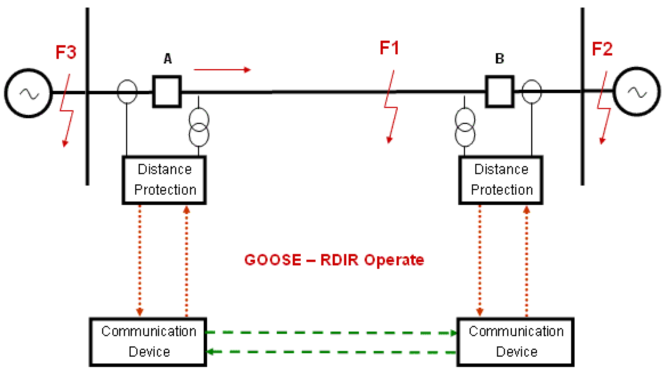

Figure 4: Accelerated scheme using GOOSE messages between substation IEDs

The implementation of the directional comparison blocking scheme requires a little different set of GOOSE messages:

- Receiving of a Blocking signal from the remote end should be published by the communication IED. The protection IED uses this message to make a decision if the fault is within or outside the zone of protection
- Change of the state of the power line carrier channel will be published by the communications IED. The protection IED uses this signal to avoid misoperation in the case of power line carrier failure.
- Change of state of the directional element should be published by the transmission line protection IED to indicate to the communications device to send over the power line carrier the blocking signal to the remote end
- Directional comparison scheme operation should be published by the protection relay to indicate to the breaker control device that is should trip the breaker

Like many other cases protection engineers sometimes push the technology beyond its intended application. The availability of fiber optic cables or SONET rings with Ethernet allows the use of GOOSE messages for direct exchange of directional information between the protection devices implementing the accelerated scheme. In this case permissive schemes become the preferred choice due to the fact that they do not have to wait to receive a blocking signal from the remote end, while there is no concern that the permissive signal is not going to get through a faulted phase.

This implementation is achieved by actually extending the substation LAN to the remote substation. Since substation-to-substation communications have been considered out of scope of IEC 61850 Edition 1and there are no specific security features available, it is important to analyze the potential threats to such implementation. Using VLAN to improve security and proper processing of the data available in the GOOSE messages received by the subscribing protection relays make it very difficult for an intruder to cause an operation of the directional comparison or any other accelerated scheme. The fact that there is also local supervision and detection of a fault condition required for the scheme to operate further reduces the chance for success of an intruder.

Figure 5 shows the accelerated scheme implementation using direct exchange of GOOSE messages between the two protection devices. To simplify the diagrams the Ethernet switches are not shown.

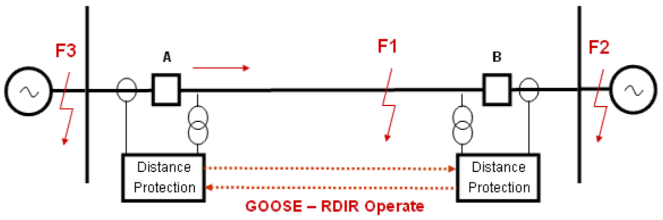

Figure 5: Direct GOOSE exchange

The tripping of the breaker again can be achieved directly by the relay when the accelerated scheme operates, or by publishing a GOOSE message that will be received by the breaker control device which will trip the breaker(s).

One of the advantages of this implementation is that in the case of primary and backup protection schemes both devices at the receiving end can be accelerated, thus improving the reliability of the scheme when one of the sending devices fails.

5 COMPARISON BETWEEN THE PERFORMANCE OF HARD WIRED AND GOOSE BASED ACCELERATED SCHEMES

Numerous tests performed by different relay manufacturers and test companies show that GOOSE based distributed applications consistently outperform hard wired schemes with the same functionality. This may look strange at the beginning, but as can be seen from the careful analysis of the factors that determine the overall operating time of a distributed protection function it is what should be expected.

If we consider that the breaker tripping and the communications exchange between the two ends of the protected line is performed in the same manner by the IEDs in both cases, we will have to analyze the time from the operation of the directional element in the sending relay and the resulting detection of the operation of the opto input of the communications device at the sending end of the line, as well as the time from the receiving of the accelerating signal and its resulting detection by the relay at the receiving end.

In the conventional hard wired scheme this will include the operating time of two output relays (each about 3 ms) plus the two detections of the energization of opto inputs (depending on the availability or lack of filtering and the scanning of the opto inputs this time for each can be from 2 to 8 ms).

If we assume an average time of opto input with filtering of about 5 ms, the total time at each end for the hard wired interface between the relay and communication device will be about 8 ms, giving us a total of about 16 ms for both ends.

If we look at the time between the directional element output and the communication device detection of the GOOSE message, according to IEC 61850 it should be less than 4 ms at each end of the line, giving us a total of about 8 ms for both ends. If we are not using communication devices but direct Ethernet interface between the two ends, than the time goes down to 4-5 ms.

When we compare the two solutions, we see that the GOOSE based scheme will be about 8-12 ms (half a cycle or more) faster than the hard wired equivalent.

All of the above has to be proven using testing of the accelerated protection scheme, which in the case of IEC 61850 based implementations will require some new tools compared with the conventional scheme testing.

6 TESTING OF IEC 61850 BASED ACCELERATED SCHEMES

The testing of accelerated protection schemes is the final step in the testing of a distance relay and is based on the assumption that all individual protection elements – distance, directional, faulted phase selection, etc. have already been tested and proven to be operating correctly.

The conventional test process requires the programming of the test system to perform pre-fault, fault and post-fault steps simulating the changing power system conditions to evaluate the performance of the selected transmission line protection scheme logic.

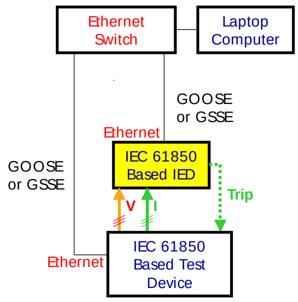

Figure 6: Testing of accelerated scheme in IEC 61850 protection IED

In the case of a directional comparison scheme that we are using as an example in this paper we will have to test the scheme for different applications – single line with strong and weak sources, three terminal line or double circuit line with mutual coupling and possible current reversal, or any other different from the just listed applications.

Different types of faults and fault locations, within or outside of the zone of protection will need to be included in the test plan. Considering that superimposed components based directional detection is superior from the point of view of speed of operation and no need for polarizing quantity, in order to properly test the directional comparison scheme transient simulation will be the preferred method.

The testing tool also should properly simulate the pre-fault power flow through the protected line, as well as the current reversal that may occur as a result of sequential tripping of breakers on a double circuit line.

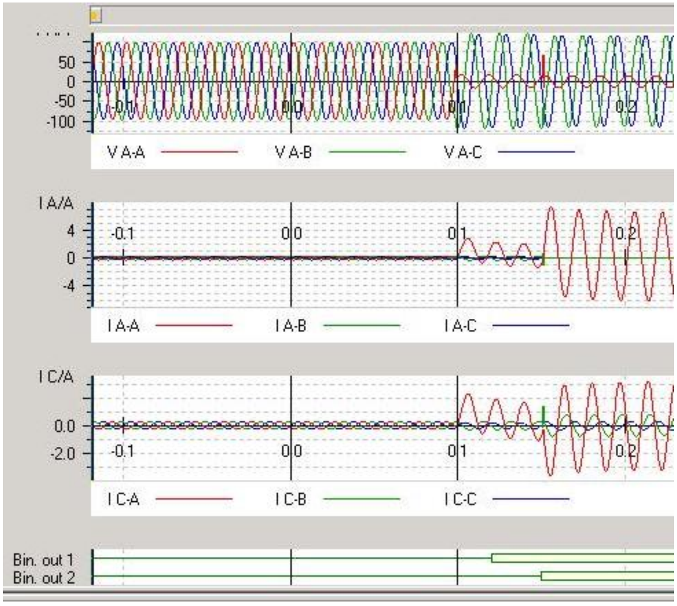

Figure 7: Current reversal simulation for fault on double circuit line

The test equipment also will have to act both as a GOOSE publisher or subscriber. This will depend on the type of testing being performed – commissioning, maintenance or end-to-end testing. This will define the directional comparison (or other accelerated scheme) scheme boundary and what signals need to be simulated or monitored.

Figure 6 shows the test setup of a transmission line relay with an accelerated scheme implemented based on GOOSE exchange with the communications device. The test device in this case needs to simulate the permissive signal received through a GOOSE message from the communications device and monitor the GOOSE messages from the tested relay indicating the operation of the directional element and the accelerated scheme.

Figure 7 shows the simulation of a fault on a double circuit line with current reversal and operation of protection relays.

7 CONCLUSIONS

Implementations of accelerated protection schemes in IEC 61850 based substation automation systems offers some significant advantages over conventional hard wired schemes.

The continuous repetition of GOOSE messages by the protection and communications devices provides reliable indication about the status of that interface, something that can be achieved in conventional schemes only through scheduled testing or when the scheme fails to operate.

The analysis of the different factor that determine the overall operating time of the protection scheme show that it should be expected GOOSE based implementations to be faster than the conventional hard wired solutions.

Testing of accelerated protection schemes implemented in IEC 61850 based substation automation systems requires the availability of a new generation of protection tools that can not only realistically simulated the changes in the electric power system when a fault occurs, but also can perform as both GOOSE publishers and subscribers, depending on the type of implementation and test being executed.