Design and Implementation of IEC 61850 in Communication-Assisted Protection Strategy

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***Abstract*—This paper presents a design and implementation of communication-assisted protection strategy to clear faults on a section of 115 kV transmission lines in Otter Tail Power system. The existing step-distance relaying scheme takes more than 25 cycles (417 ms) to clear faults on this particular three terminal line. In order to reliably clear all faults in less than 20 cycles (333 ms), the transmission line terminals communicate with each other through Ethernet to isolate and clear a fault as fast as possible. Through IEC 61850 Generic Object Oriented Substation Events (GOOSE) Messaging, the communication-based Permissive Overreaching Transfer Trip (POTT) scheme is utilized to achieve a faster and reliable clearance of all faults. The proposed method has been verified with ASPEN software and implemented in hardware.**

Keywords—Communication; Ethernet; GOOSE Messaging; Protection; Relay;

I. Introduction

When a fault occurs on the transmission line, the protection system is designed to clear the fault as fast and reliably as possible. In a protection system, there are typically three main components: instrument transformers, relays, and circuit breakers. Instrument transformers, for example, voltage transformer (VT) and current transformer (CT), transform the high voltage and current on the power system down to the lower voltage and current that can be used for measurements. Then relays pick up the measurement, typically 120 V or 5 A, to protect a section of equipment from faults. And circuit breakers serve the connection between the source and the fault. There are different types of circuit breakers that use different methods to reduce the arc when the breaker opens. Oil or SF6 are common materials used to dampen arcs.

There are various relaying schemes that are used to determine if there is a fault on the system. A survey in 2009 reported 958 different schemes, due to the growing complexity of today's power systems [1]. Many schemes use a protection zone, which is the amount of transmission line that is protected. For example, Zone 1 typically encases 80-90% of the line that needs protection. Zone 2 usually covers the whole line and then 25% beyond that. This zone is typically delayed for 20 – 30 cycles (333 – 500 ms) from Zone 1. Zone 3 covers 50% in the reverse direction. Also, sometimes a Zone 4 is used, which is the whole line and then 100% of the next line. Protection schemes use these zones in different ways based on certain schemes. For example, step–distance, current differential, POTT, Permissive Underreach Transfer Trip, Direct Underreach Transfer Trip, Directional Comparison Unblocking Scheme, Directional Comparison Blocking Scheme, Direct Transfer Trip, and etc. By sharing the common and differentiating their own characteristics, there are also many different hybrid combinations of these schemes.

In order to make the system more reliable and faster, protection schemes are used with the assistance of communications. Communication-assisted protection schemes have been applied in power systems using different channels, such as, power line carrier, optical fiber, microwave, radio, dedicated telephone line, and etc. For example, some protection systems use the POTT scheme with optical fiber, or DCUB with power line carrier. Also, most relays have the ability to connect and communicate with computers using standard protocols through serial cables for data acquisition and configuration settings. In [2-3], the communication-based strategy is developed for microgrid protection. Real-time Ethernet has been applied in power system automation [4]. Also in [5], GOOSE messages over an Ethernet LAN/WAN has been implemented in a protective relaying scheme.

In this paper, a communication-assisted protection strategy is designed to clear faults quickly and reliably on a section of 115 kV transmission lines. Ethernet is provided as the communication channel for the signals and protocols. The communication-based POTT scheme is implemented through Layer 2 GOOSE messaging to multicast the message in the network. The proposed method has been verified with ASPEN software and implemented in hardware. The results demonstrate that the proposed communication-assisted protection scheme ensures a reliable tripping and efficiently decreases the tripping time when a fault happens.

II. Project Background

This project aimed to provide a solution to an existing relaying problem in Otter Tail Power (OTP) company. OTP, located in Fergus Falls, MN, has a 115 kV transmission line that connects three different substations, labeled as Substation 1, Substation 2, and Substation 3. Figure 1 shows an illustration of the 115 kV system. OTP uses different numerical relays in this system: some are distance relays using the

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impedance as the variable to determine if a fault occurs, and others are multipurpose relays that use voltage, current, and impedance as variables to determine if a fault occurs. These relays can also be used as backup to primary relays, which OTP uses in its system.

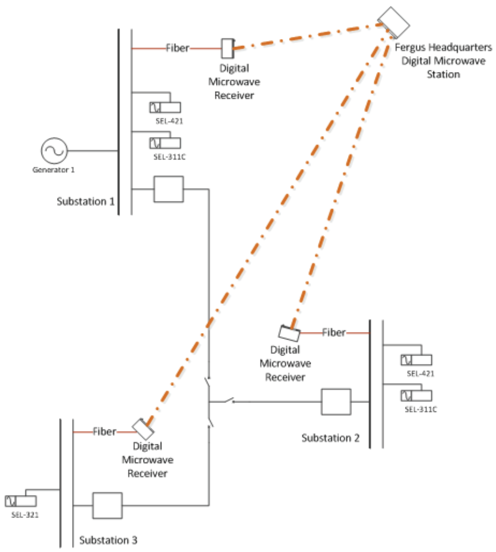

Fig. 1. Otter Tail Power 115 kV system

Currently, OTP uses step-distance protection without communications. According to OTP, it takes a maximum of 417 ms (25 cycles) to trip the circuit breakers, which is a very long time that current will increase if a fault happens. Besides, a large generator is connected to the 230 kV system which is connected to the 115 kV system at Substation 1. When there is a fault on this 115 kV line, opening the circuit breakers quickly is critical in preventing instability in the system and the generator. The instability may cause tripping of breakers on other parts of the transmission system, including the generator.

Therefore, a reliable and fast communication system is desired to increase the reliability of the system by isolating the fault and tripping the necessary breakers. Also, clearing faults quickly will minimize the damage done by the overcurrent in the fault, such as damage to structures or injuries to people near the fault. These goals were achieved by adopting a well-designed communication-assisted protection scheme. The following sections provide design details.

III. Technical Design

There are two stages to design the communication-assisted protection system. The first is to determine proper parameters of the communication-based POTT scheme for decreasing tripping time. The second stage is to utilize the Ethernet network and design the relay communication method when sending and receiving trip signals.

A. Design POTT parameters

POTT scheme is a communication-based protection scheme that uses distance relays to coordinate with each other to determine whether a fault is occurring inside the protected zone. As shown in Fig. 2, the logic diagram on the left shows that POTT will operate only when overreaching zone (RO) detects a fault and trip signals are received from all other relays. The mho diagram on the right shows the operation of a distance relay. It will only trip when the impedance is within the mho circle.

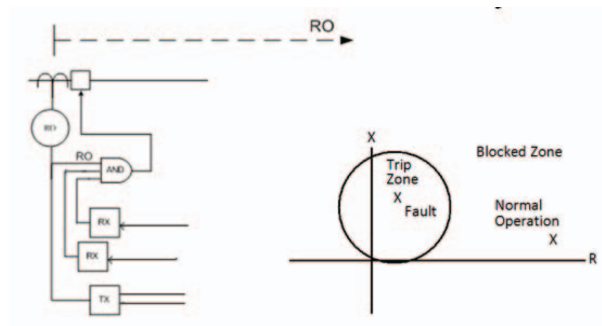

Fig. 2. POTT scheme theory

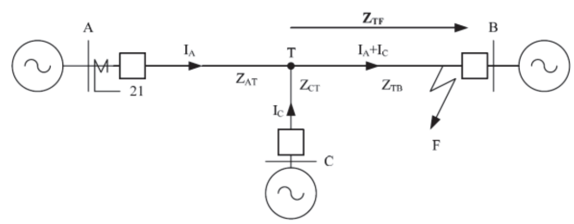

Fig. 3. Illustration of infeed effect [6]

Since the system is a three terminal line, an infeed effect was considered, as shown in Fig. 3. For example, if a fault were to occur at location F, the impedance seen by the relay at bus A would not be the line impedance from bus A to the fault. The current contribution from Bus C actually increases the voltage between point T and the fault. This relationship is shown in (1):

$$Z_{app} = Z_{AF} + \frac{I_C Z_{TF}}{I_A} \tag{1}$$

As (1) shows, the apparent impedance Z_{app} seen by the relay is actually larger than the actual impedance from the relay to the fault. To determine the relay parameters, the apparent impedance is calculated for each relay assuming a fault occurred at the substation furthest away. For example, in Fig. 3, to calculate the relay parameter for substation A, a fault was assumed to occur at substation B, since substation B is farther than substation C from substation A. This ensures the entire transmission section is covered. The first step in this process is to find the Thévenin equivalent for positive, negative, and zero sequence networks. The Thévenin equivalents are then connected in series to find the sequence currents and calculate the phase currents using the A matrix. Once the fault currents are known, current division in the sequence domain is used to find the currents in each branch. Using these currents and transmission impedances, the apparent impedances are calculated for each substation. These values are multiplied by 110% to assure the relay covers the whole line due to errors.

B. Ethernet Communication

Typical pilot protection relays use serial connections. There are different protocol options, such as, MIRRORED BITS, DNP3, IEC 61850, Modbus, and IEEE 802.1. IEC 61850 GOOSE messaging is selected to limit extra hardware additions or modifications to existing infrastructure. The relay software programs are used to design and program the relays for GOOSE messaging. One is used to design and map the GOOSE messages for each relay, and the other is used to directly embed the desired data into data packets framed, so that only the desired relays can read the messages. The process to design and map the GOOSE messages are described in the following five steps.

- Step 1: Set up relays

IEC 61850 is a protocol supported by all power system protection companies. Based on a complete mapping, three relays were set up with their IP Address and Subnet Mask entered to match the settings of the Ethernet ports on the relay.

- Step 2: Create the Dataset

The Dataset contain the actual bits of data that each relay will send and receive to each other in GOOSE messages. A new Dataset was created to include the bits needed to communicate POTT scheme information. In order to transmit the permissive signal, a status information bit was included in the new Dataset. Specifically, this dataset contains a logic value 1 if the relay has an active KEY signal, otherwise a logic value 0. The KEY signal is an internal relay bit associated with the POTT logic when the communication-assisted trip scheme is enabled.

- Step 3: Set up the transmit of GOOSE messages

Each relay is needed to be assigned which messages it would transmit. These transmitting messages are encoded with the media access control (MAC) address, so that multiple relays could receive the message at the same time. It helps to cut down unnecessary network traffic of sending the same message to designated sites. Only one Dataset may be assigned to each transmitting message. To avoid sending multiple messages from each relay to cause network latency, all desired data to be sent should be incorporated in the same Dataset. Moreover, if the relays are to be integrated into a Local Area Network (LAN) with existing data traffic, VLAN priority tags can be re-interpreted in Class of Service (CoS) and provide priority to the GOOSE messages. By segregating certain portions of Ethernet switches, it will decrease the latency associated with the GOOSE messages.

- Step 4: Set up the receiving of GOOSE messages

The messages that each relay receives and the location that information are stored on the relay are set in this step. Each message quality bit and status value bit are assigned to remote bits on the desired relay to be used in the trip logic later. The quality bit ensures that each message is sent without corruption. If the quality bit is flagged, the GOOSE message with failed quality will be recorded and an alarm will be provided to alert operators of failure. The status value bit from each message is either logic 1 or 0 from the permissive KEY signal described earlier. Also, the bits from each message can be encoded to three different locations on the relays, to virtual remote bits, to breaker closed bit, or to breaker open bit. Virtual remote bits are used in this project.

- Step 5: Set up the relay trip logic

Finally, the information assigned to remote bits and received by each relay is integrated in the relay trip logic. Two remote bits are logically AND together in the permissive trip 1 equation (PT1). Internally, PT1 is logically AND with the communications-assisted trip conditions, which are the relay reach parameters. Other settings on the relays can also be changed, such as turning off features not needed for the scope of hardware tests. Also, the relay Ethernet port parameters are configured to support IEC 61850 GOOSE messages, as well as assigning other various port parameters and relay settings.

IV. HARDWARE MODEL DESIGN

The hardware model, as shown in Fig. 4, was designed to test the viability of GOOSE messaging and to determine the total trip time using the proposed communication method. Inductor banks and Automatic Load Banks (ALBs) were used to emulate the fault impedance that relays at each substation would see. OTP system is scaled down to the lab system with 208 V line-to-line voltage, which achieved the maximum current rating of 30 A in the lab. The generators (source) were connected to a 3Ø load with a small amount of current (0.2 A) to emulate a normal load flow. In this way, relays detected a normal current outside the mho circle, and did not trip.

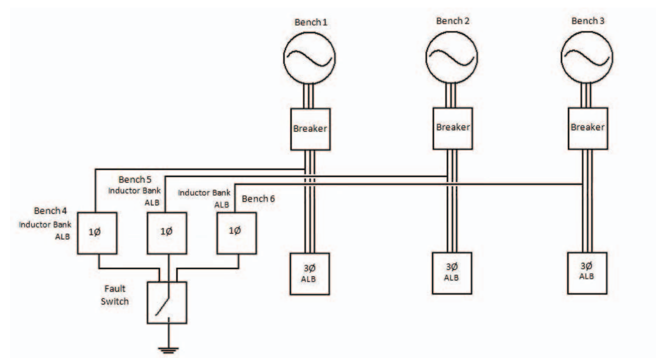

Fig. 4. Overall hardware model

From the source, a shunt trip breaker was connected. This breaker was then connected to the 3Ø ALBs, which were used to emulate normal load flow. Right after the breaker, a single phase line was connected, which was designated for the fault line. This line was connected to a series combination of 1Ø inductor banks and ALBs, which were set to different impedances depending on the location of the fault in OTP's system. From here, a 3Ø switch is connected so that all three 1Ø lines could be closed at exactly the same time, emulating a fault on a three terminal line. A detailed diagram of the components at one of the three terminals, including the VT, CT, and relay, is shown in Fig. 5.

The variacs in the lab were used as VTs to transform the voltage down for the relays. CTs of 1:1 ratio were used to produce large enough current for relays to pick up. The connection between the shunt trip breaker and the relay is also shown in the diagram. When the relay detects a fault, it trips by closing a predetermined output contact, which is then connected to the shunt trip breaker and causes it to trip. The Ethernet switch was used to connect all three relays together for their communication. A personal computer was connected to this switch for debugging purposes. This diagram also shows the wire sizes used throughout the setup. A 10 AWG wire was used to connect the main components such as the source and the ALBs and the inductor banks. An 8 AWG wire was used to connect the fault phases to the fault switch. A 14 AWG wire was used to connect all of the control circuit components such as the VT, CT, and shunt trip wires. Ethernet cords were used to connect the relays to the Ethernet switch.

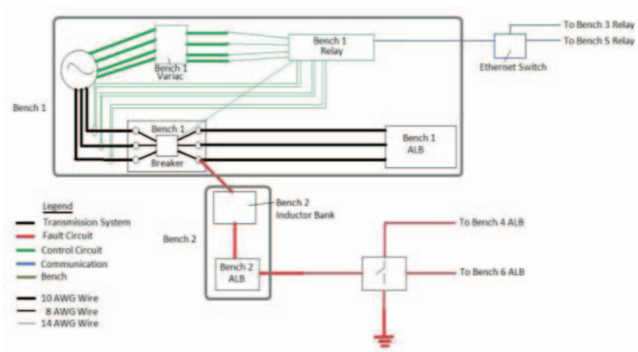

Fig. 5. Detailed hardware diagram of one terminal

The final step was to select the locations to run tests and determine the impedances for each location. The selected fault locations are shown in Fig. 6. Faults 1-4 are located inside the system and faults 6-7 are located outside the system. It was anticipated that the relays trip for faults at 1, 2, 3, and 4, but not trip for faults at 5, 6, and 7.

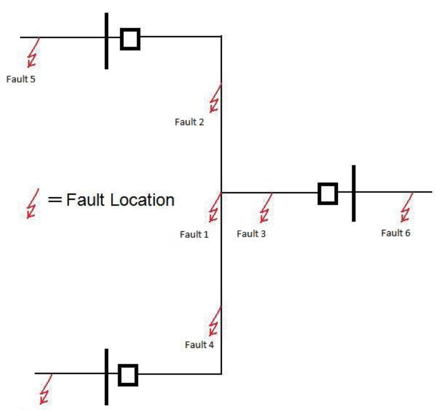

Fig. 6. Different fault locations

To calculate the impedance at each location that relays will see, the first step is to obtain the current transmission line impedance, including the positive, negative, and zero sequence impedances. The impedance for Fault 1 is the impedance of the transmission line from each respective relay to the fault. The impedance for Faults 2, 3, and 4 are calculated using the apparent impedance, according to (1). These impedances were set to secondary ohms by multiplying the current ratio and dividing by the voltage ratio. Since the ALBs were set using power instead of resistance, the current was calculated for all apparent impedances. Thus, the inductor banks were set to the calculated reactance and the ALBs were set to the calculated current. For fault location, the ALBs and inductor banks were set according to the reactance and currents calculated for their respective fault. In order to determine accurate trip times, shunt trip breakers were used so that the relays could trip the breakers whenever a fault was detected. Therefore, output contacts were programed within the relay settings to close when a trip signal is detected. Using a 120 V source and having the relay contacts closed caused the breaker to trip.

V. Test Results

A. Software Model Test

All faults in this project are assumed to be single phase line-to-ground faults, which cover over 90% of all types of faults [7]. All seven faults were simulated using step-distance and POTT schemes in ASPEN. For Fault 1, the result of each associated breaker's operating time using step-distance scheme and POTT scheme are shown in Fig. 7 and Fig. 8, respectively. It can be seen that the breaker trip time using POTT scheme is smaller than using step-distance scheme.

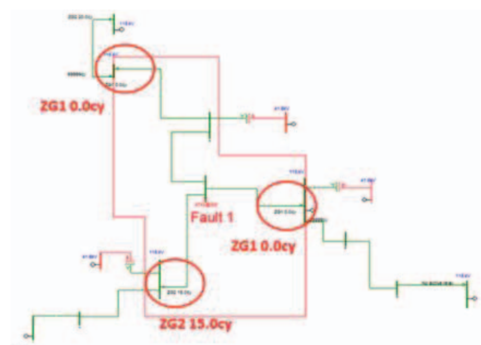

Fig. 7. Modeled OTP system using step-distance

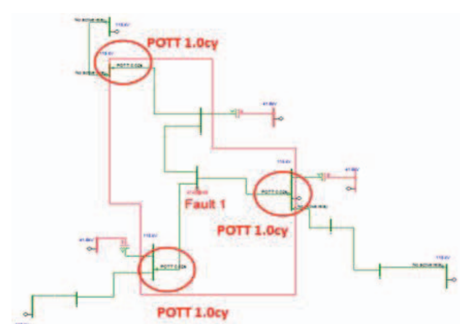

Fig. 8. Modeled OTP system using POTT

The comparison of results for all faults inside the system is shown in Table I. It is shown that the step-distance delay times vary from 0 to 20 cycles (0-333 ms), depending on the fault location. This complies with the time given from OTP of 25 cycles (417 ms), including the relay and breaker time. The POTT scheme reduces the time to 1 cycle (16.7 ms) for all faults, and will not over trip due to faults outside the protected system. POTT is faster and more secure than step–distance.

TABLE I. OTP SYSTEM DELAY COMPARISON

Fault Location	Fault Detected	Sub 1 Delay (cycles)		Sub 2 Delay (cycles)		Sub 3 Delay (cycles)	
		Step-Distance	POTT	Step-Distance	POTT	Step-Distance	POTT
Fault 1	Yes	0	1	0	1	15	1
Fault 2	Yes	0	1	20	1	15	1
Fault 3	Yes	20	1	0	1	15	1
Fault 4	Yes	20	1	20	1	0	1

B. Hardware Model Test

All faults simulated in the software model were tested in the hardware model. The software model of lab system with Fault 1 is shown in Fig. 9. In order to measure the trip time in hardware, current probes were used on the oscilloscopes and set to trigger when a fault current was detected.

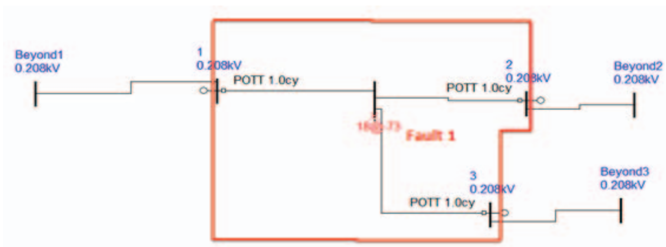

Fig. 9. Lab system software model

As shown in Table II, all faults within the protected system were detected and tripped with the time of 1 cycle (16.7 ms) in software simulation, and relays didn't operate (NOP) for any faults outside the protected system. It is proven that Ethernet can be used as a very fast method of relay communication. It is also shown that the trip times vary from 1.752 to 2.676 cycles in hardware compared to the 1 cycle simulated in software. The reason for the difference is the oscilloscope measures the coordination time as well as the operating time of relay and breaker, while the software only measures the coordination time. Also, the time varies for each situation. It is because the oscilloscope starts to trigger when the current waveform reaches zero, so the times will be slightly different depending on where the waveform is and when the fault occurs.

TABLE II. COMPARISON OF LAB SOFTWARE AND HARDWARE RESULTS

Fault Location	Fault Detected	Trip Delay Time (cycles)					
		Sub #1 Relay		Sub #2 Relay		Sub #3 Relay	
		Soft ware	Hard ware	Soft ware	Hard ware	Soft ware	Hard ware
Fault 1	Yes	1	2.136	1	1.752	1	2.268
Fault 2	Yes	1	2.424	1	2.4	1	1.944
Fault 3	Yes	1	2.1	1	1.98	1	2.412
Fault 4	Yes	1	1.8	1	2.304	1	2.676
Fault 5	No	NOP	NOP	NOP	NOP	NOP	NOP
Fault 6	No	NOP	NOP	NOP	NOP	NOP	NOP
Fault 7	No	NOP	NOP	NOP	NOP	NOP	NOP

VI. CONCLUSION

In this paper, the communication-assisted protection strategy is developed and tested to provide reliable and fast tripping of faulted lines. It is shown that POTT is faster than step-distance by up to 19 cycles (317 ms). Also, a method is developed for the relays to communicate trip signals amongst each other through GOOSE messaging, which can be implemented in OTP's existing communication network. The test results show a trip time of about 3 cycles (50 ms) using the proposed method. If the communication delay is less than 17 cycles (283 ms), it is recommended to use the communication-assisted protection scheme to clear all faults within 20 cycles (333 ms). If the communication channel is disrupted, the existing step–distance scheme should be used to increase the reliability of the system. However, the respective zone delay times need to be increased to allow time for the POTT scheme to operate first. Moreover, this Ethernet-and-GOOSE-message based protection system can be applied in other utilities as long as Ethernet and the required relays are available. In future work, VLN's and priority tagging to segregate ports on the network for GOOSE message traffic will be investigated to decrease the latency.

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