COMPARATIVE PERFORMANCE ANALYSIS OF IDENTICAL PROTECTION FUNCTIONS IN THE SAME IED FED BY CONVENTIONAL AND PROCESS BUS CONNECTED ANALOG QUANTITIES

Mike Kockott
Hitachi Energy, USA

Galina Antonova
Hitachi Energy, Canada

I INTRODUCTION

In digital substation applications based on IEC 61850 technology, protection Intelligent Electronic Devices (IEDs) obtain analog quantities and binary signals via Ethernet communication. The digitized analog quantities are published as Sampled Values (SVs), and binary signals as GOOSE messages, with the IEDs that need these quantities/signals subscribing to receive them.

In conventional substation applications, IEDs obtain analog quantities via copper wires that connect the CT/PT secondaries to the IED's analog inputs, and binary signals via copper wires that connect the signal source to the IED's binary inputs.

All protection personnel are well accustomed to connecting CT and PT secondary analog quantities in the conventional way to their protection IEDs. With the continued evolution of digital technologies, and the coming to fruition of the IEC 61869-9 standard for instrument transformers with digital outputs that encompass the IEC 61850-9-2 process bus standard, the wired connection of the secondary analog quantities to the protection IEDs is no longer the only method by which these devices can receive these quantities. A question that now arises is whether the performance of the protection functions remain unchanged irrespective of the way in which the analog quantities are connected to the IED, or whether performance differences arise? This is one of the questions a project was set up to answer. The procedure adopted was to connect to the same IED the same analog quantities in the conventional way (i.e. connected to the IED via a traditional copper wire interface) as well as via process bus (i.e. connected to the IED via a fiber interface as sampled values), and then internally to connect each input type to identical protection functions (in the same IED), with identical settings, and to compare their performance.

II APPLICATION DETAILS

The pilot project was installed on a parallel, series compensated 525kV line with length of 225 miles. The bus layout at the line end where the pilot is installed is 1½ CB. Note that the line protection IED installed for this pilot project does not trip the circuit breakers, i.e. does not replace the in-service protection on the line.

Conventional analog quantities:

- Bus and tie-side CTs
- PT (CVT) on the line-side of the series capacitor and shunt reactor

The secondary-side currents and voltages are connected via conventional copper wires to the TRM (transformer input module) inputs of the IED.

Process bus (SV) analog quantities:

- Current values come from two fiber optic current sensors (FOCS), one mounted on the bus-side CB and the other on the tie-side CB. The fiber optic current sensors essentially perform the same function as CTs but use a completely different technology. They have associated merging units (FOCS_MU) that output sampled values according to IEC 61850-9-2 LE.
- Voltage values come from a classical merging unit (MU) that outputs sampled values according to IEC 61850-9-2 LE. The PT secondary-side voltages are connected as inputs to the MU via copper wires, in parallel with the connections to the IED.

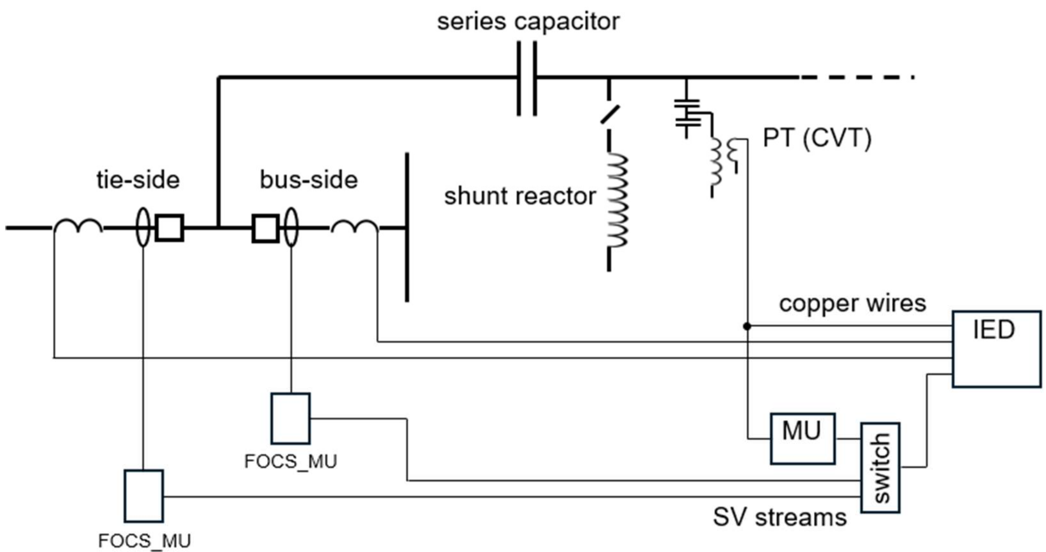


Figure 1: simplified sketch of primary and secondary equipment layout for the pilot installation

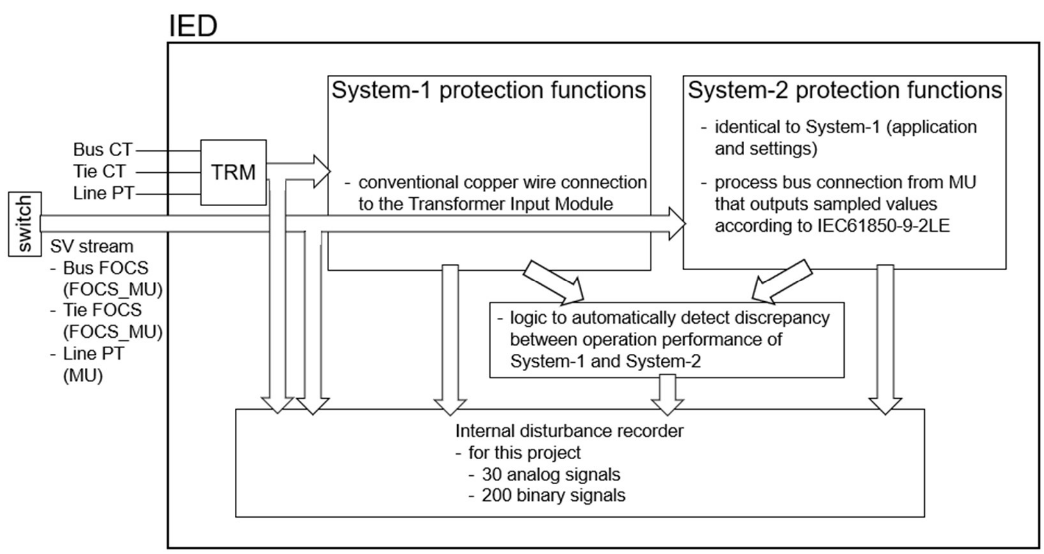


Figure 2: simplified overview of the IED engineering

III SIGNALS ON WHICH THE CONVENTIONAL VS. PROCESS BUS PROTECTION PERFORMANCE COMPARISON WILL BE MADE

The settings for the -1 and -2 protection functions are identical. The -1 functions receive their analog inputs via copper wire interface (TRM-connected functions), while the -2 functions receive their analog inputs as SV streams (MU-connected functions). A comparative performance is made between all outputs shown below for all -1 and -2 functions.

21 – distance protection

All settings for the 21 functions were calculated and applied as if the 21 functions were the in-service distance protection on the line. Mho characteristic was selected for all phase-phase loop measurements, and quadrilateral characteristic was selected for all phase-ground loop measurements.

The inputs shown as XXX, YYY and ZZZ represent the connections required for normal application of the 21 function, such as:

- blocking input for fuse failure detected
- blocking input for power swing detected
- blocking release input for fault during power swing

For the 21-1 function, the connected signals come from the fuse failure detection function and power swing blocking function that are TRM-connected, whereas for the 21-2 function the connected signals come from the fuse failure detection function and power swing blocking function that are MU-connected.

In Figure 3, Z1 = zone 1, Z2 = zone 2, ZRV = reverse zone, ND = non-directional, TD = time domain element, and PhSel = phase selection.

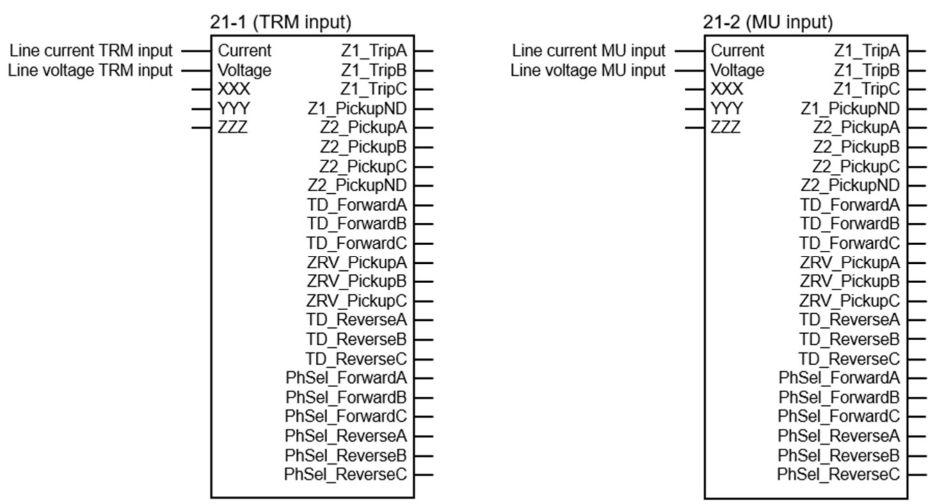


Figure 3: distance protection (21) – output signals for performance comparison

Outputs labeled “Trip” apply to those elements where the trip outputs have no added time delay (e.g. zone 1), i.e. the “Trip” outputs are issued immediately following operation (pickup) of the element. Outputs labeled “Pickup” apply to those elements where the trip outputs have added time delay (e.g. zone 2, zone RV). For these elements, the “Pickup” outputs are issued immediately following operation (pickup) of the element. For outputs not labeled as “Trip” or “Pickup”, e.g. “TD_ForwardA”, the outputs are issued immediately on operation (pickup) of the element.

Switch-on-to-fault

The SOTF functionality is setup to operate solely on the connected currents and voltages. Detection of the deadline (to arm SOTF) is based solely on undercurrent and undervoltage measurement. When the line is re-energized, the deadline condition is removed, and the dropout timing of the SOTF window is started. Any SOTF trip during the timing of the SOTF window is based solely on the measured current and voltage – from the deadline condition to either a healthy line (healthy voltage with or without current – no SOTF trip) or a faulted line (current without healthy voltage – SOTF trip). No pickup signals from any protection elements were included to give a SOTF trip if they operated during the timing of the SOTF window.

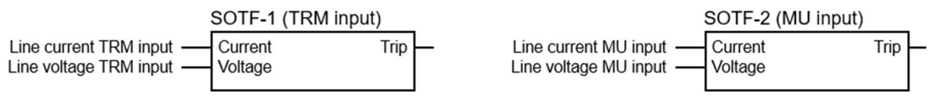


Figure 4: SOTF protection – output signal for performance comparison

68 – power swing blocking

The settings for the 68 functions were calculated and applied as if the 68 functions were the in-service power swing blocking on the line. The inputs shown as XXX, YYY and ZZZ represent the connections required for normal application of the 68 function, such as

- blocking input for fuse failure detected
- power swing blocking release input for ground fault detected during power swing
- single-pole trip input to enable power swing blocking release for single-pole autoreclose on to a persistent fault if the initial fault and trip caused a power swing in the other two phases

The 68-1 function receives the fuse failure detected and ground fault detected inputs from TRM-connected functions, and the 68-2 function from MU-connected functions.

In Figure 5, Pickup = power swing detected blocking signal, ZOUT = apparent impedance measured to be inside the outer power swing blocking characteristic.

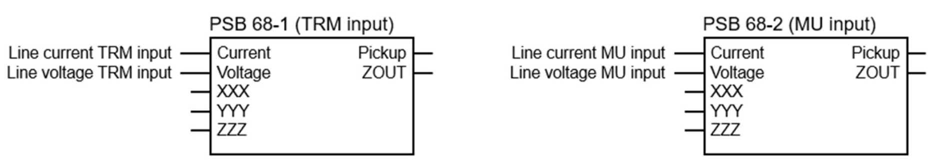


Figure 5: power swing blocking (68) – output signals for performance comparison

Fuse failure detection

The settings for the fuse failure detection functions were applied as if the fuse failure functions were the in-service fuse failure detection on the line (zero-sequence and delta-quantity based). The inputs shown as XXX and YYY represent the connections required for normal application of the fuse failure detection function, such as:

- blocking for any open phase detected
- blocking following a trip command

The any open phase detected signal for both fuse failure detection functions comes from TRM-connected overcurrent and overvoltage functions (no pickup of overcurrent [0.1 per unit pickup threshold] and no pickup of overvoltage [0.7 per unit pickup threshold], per phase).

For this project there is no trip command signal, as the pilot IED is not setup to issue any trip. Therefore, the trip command signals for connection to the fuse failure detection functions were obtained as follows:

- 21-1 zone 1 trip or zone 2 pickup connected to the FuseFail-1 function (input from TRM-connected 21 function)
- 21-2 zone 1 trip or zone 2 pickup connected to the FuseFail-2 function (input from MU-connected 21 function)

In Figure 6, Pickup = fuse failure detected.

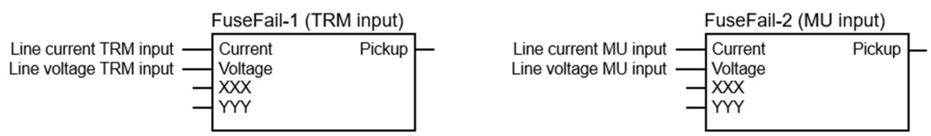


Figure 6: fuse failure detection – output signal for performance comparison

50 – instantaneous phase overcurrent protection

The 50 functions were set to operate for overcurrent in one or more phases. The pickup threshold was set at 100% IBase, where IBase = 2000A (CT ratio = 2000/5); pickup threshold = 2000A.

In Figure 7, Trip = immediate pickup of the function for phase current measured above the pickup threshold in the indicated phase – no added time delay to issue the trip outputs.

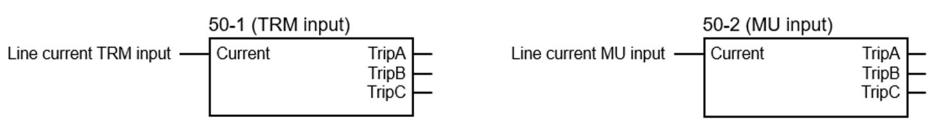


Figure 7: instantaneous phase overcurrent protection (50) – output signals for performance comparison

50N – instantaneous residual (ground fault) overcurrent protection

The 50N functions were set with pickup threshold of 10% IBase, where IBase = 2000A (CT ratio = 2000/5); pickup threshold = 200A. The input shown as XXX represents the connection required for normal application of the 50N function, i.e.

- blocking for any open phase detected

In Figure 8, Trip = immediate pickup of the function for residual current measured above the pickup threshold – no added time delay to issue the trip output.

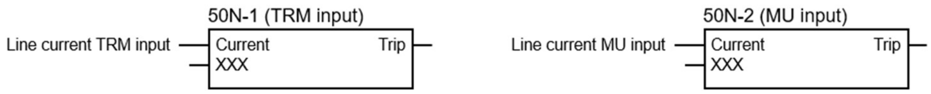


Figure 8: instantaneous residual (ground fault) overcurrent protection (50N) – output signal for performance comparison

<u>46 – negative-sequence overcurrent protection</u>

The 46 functions were set with pickup threshold of 10% IBase, where IBase = 2000A (CT ratio = 2000/5); pickup threshold = 200A. The input shown as XXX represents the connection required for normal application of the 46 function, i.e.

- blocking for any open phase detected

In Figure 9, Pickup = immediate pickup of the function for negative-sequence current measured above the pickup threshold – Pickup is used as this function would normally have an added time delay to issue the trip output.

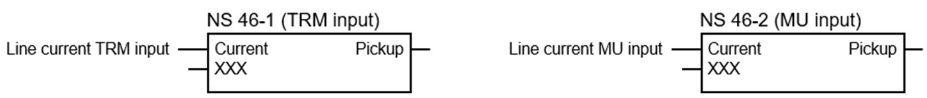


Figure 9: negative-sequence overcurrent protection (46) – output signal for performance comparison

<u>71 – current delta supervision</u>

The 71 functions were set to operate on the instantaneous difference between the present sample and the sample one cycle back. Operation occurs when the absolute value of the difference exceeds the pickup threshold for three consecutive samples. The pickup threshold was set at 150% IBase, where IBase = 2000A (CT ratio = 2000/5); pickup threshold = 3000A.

In Figure 10, Pickup = function operated in the indicated phase.

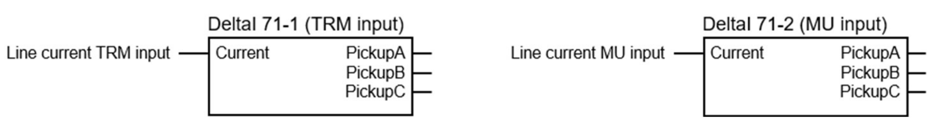


Figure 10: current delta supervision (71) – output signals for performance comparison

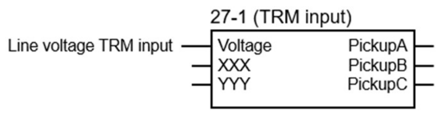
<u>27 – phase undervoltage protection</u>

The 27 functions were set with pickup threshold of 60% VBase phase-ground, where VBase phase-phase = 525kV (PT ratio = 525kV/116.667V); pickup threshold = 181.9kV phase-ground. Pickup is blocked for measured phase-ground voltage less than 10% VBase phase-ground. The inputs shown as XXX and YYY represent the connections required for normal application of the 27 function, such as

- blocking for fuse failure detected
- blocking for any open phase detected

The 27-1 function receives the fuse failure detected input from the TRM-connected fuse failure detection function, and the 27-2 function from the MU-connected function.

In Figure 11, Pickup = immediate pickup of the function for phase voltage measured below the pickup threshold in the indicated phase – Pickup is used as this function would normally have an added time delay to issue the trip outputs.



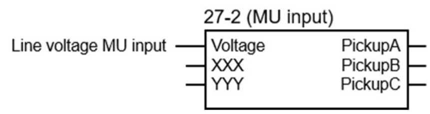


Figure 11: phase undervoltage protection (27) – output signals for performance comparison

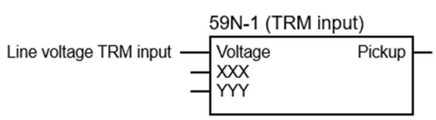
59N – residual overvoltage protection

The 59N functions were set with pickup threshold of 10% VBase phase-ground, where VBase phase-phase = 525kV (PT ratio = 525kV/116.667V); pickup threshold = 30.3kV phase-ground. The inputs shown as XXX and YYY represent the connections required for normal application of the 59N function, such as

- blocking for fuse failure detected
- blocking for any open phase detected

The 59N-1 function receives the fuse failure detected input from the TRM-connected fuse failure detection function, and the 59N-2 function from the MU-connected function.

In Figure 12, Pickup = immediate pickup of the function for residual voltage measured above the pickup threshold – Pickup is used as this function would normally have an added time delay to issue the trip output.



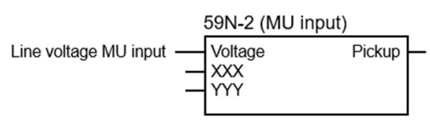


Figure 12: residual overvoltage protection (59N) – output signal for performance comparison

59NS – negative-sequence overvoltage protection

The 59NS functions were set with pickup threshold of 10% VBase phase-ground, where VBase phase-phase = 525kV (PT ratio = 525kV/116.667V); pickup threshold = 30.3kV phase-ground. The inputs shown as XXX and YYY represent the connections required for normal application of the 59NS function, such as

- blocking for fuse failure detected
- blocking for any open phase detected

The 59NS-1 function receives the fuse failure detected input from the TRM-connected fuse failure detection function, and the 59NS-2 function from the MU-connected function.

In Figure 13, Pickup = immediate pickup of the function for negative-sequence voltage measured above the pickup threshold – Pickup is used as this function would normally have an added time delay to issue the trip output.

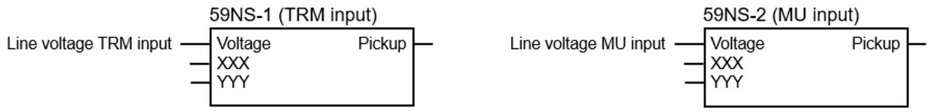


Figure 13: negative-sequence overvoltage protection (59NS) – output signal for performance comparison

<u>78V – voltage delta supervision</u>

The 78V functions were set to operate on the instantaneous difference between the present sample and the sample one cycle back. Operation occurs when the absolute value of the difference exceeds the pickup threshold for three consecutive samples. The pickup threshold was set at 50% VBase phase-ground, where VBase phase-phase = 525kV (PT ratio = 525kV/116.667V); pickup threshold = 151.6kV phase-ground. The input shown as XXX represents the connection required for normal application of the 78V function, i.e.

- blocking for fuse failure detected.

The 78V-1 function receives the fuse failure detected input from the TRM-connected fuse failure detection function, and the 78V-2 function from the MU-connected function.

In Figure 14, Pickup = function operated in the indicated phase.

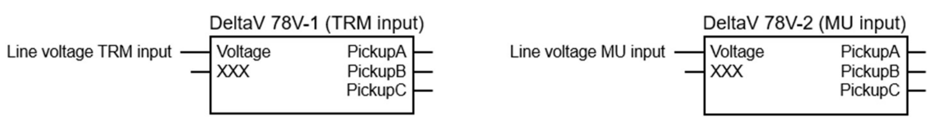


Figure 14: voltage delta supervision (78V) – output signals for performance comparison

IV COMPARATIVE PERFORMANCE METHOD: OPERATION OF CONVENTIONAL VS. PROCESS BUS CONNECTED FUNCTIONS

The logic used for the performance comparison is shown in Figure 15.

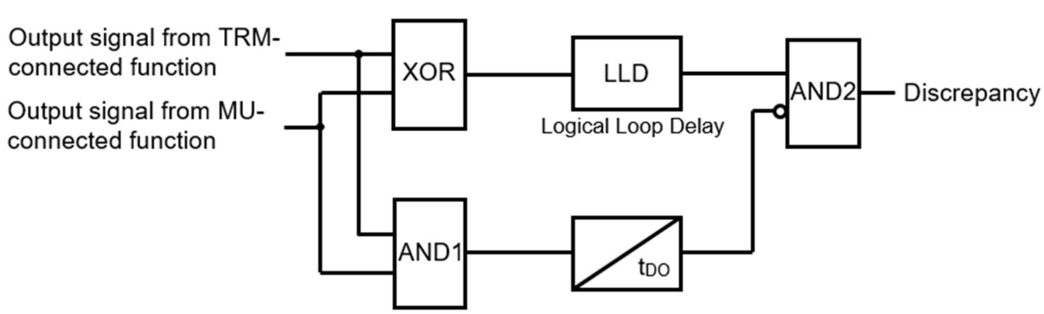


Figure 15: performance comparison logic

Each pair of output signals (one from a TRM-connected function and one from the identical MU-connected function) are connected to an XOR-gate (exclusive OR-gate) and to an AND-gate (AND1).

The output of the XOR-gate will become logic 1 if one input signal is logic 0 and the other logic 1. If both input signals are logic 0 or logic 1, the output of the XOR-gate will be logic 0.

If both input signals become logic 1 from logic 0 at the same time (within the execution of the same processing cycle), the output of the XOR-gate will remain logic 0, and the output of the AND1-gate will become logic 1. A logic 1 on the output of the AND1-gate will block a discrepancy from being declared.

If one input signal becomes logic 1 and not the other input signal (within the execution of the same processing cycle), the output of the XOR-gate will become logic 1, and the output of the AND1-gate will remain logic 0 (so will not block a discrepancy from being declared). However, because of the logical loop delay, the discrepancy will not be declared immediately when the XOR-gate becomes logic 1, as the AND2-gate will only see the logic 1 on its input within the execution of the next processing cycle. The output of the LLD-gate follows its input, but with a delay of one processing cycle, i.e. if the input becomes logic 1, the output will only become logic 1 during the execution of the next processing cycle.

If the other input signal also becomes logic 1 within the execution of the next processing cycle, the output of the XOR-gate will return to logic 0, and the output of the AND1-gate will become logic 1 (from logic 0), blocking any discrepancy from being declared, even though the output of the LLD-gate will now also be logic 1 for this processing cycle due to the logic 1 on its input from the previous processing cycle.

If the other input signal does not become logic 1 within the execution of the next processing cycle, the output of the XOR-gate will remain logic 1, the output of the AND1-gate will remain logic 0, and so the logic will declare a discrepancy in the operate performance between the TRM-connected function and the MU-connected function.

Note, for no discrepancy to be declared, the functions must issue operate signals not more than one processing cycle apart. The drop out timer ensures a discrepancy is not declared during signal reset.

43 performance comparisons are made as shown in Figure 15. The 43 output signals subject to this performance comparison are those shown in Figures 3 to 14.

The output signals from all functions undergoing the above performance comparison, plus the Discrepancy signal for each, are connected to the IED’s disturbance recorder. Hence, for this performance comparison, all compared protection operate signals, for both conventionally connected and process bus connected functions, originate within the same IED, and are connected to the same disturbance recorder, as opposed to comparing the functional performance in one IED with conventional connections vs. a second IED with process bus connection.

V COMPARATIVE PERFORMANCE METHOD: CONVENTIONAL ANALOG QUANTITIES VS. PROCESS BUS ANALOG QUANTITIES

This was done to capture any discrepancy that might occur between the analog quantities connected to the IED. The phasor difference between a TRM-connected analog quantity and the same MU-connected analog quantity is connected to a low set function. Pickup of the low set function would indicate a difference between the analog quantities greater than the low set threshold.

50D and 50ND – instantaneous phase current difference and instantaneous residual current difference overcurrent protection

The 50D function was set to operate for overcurrent in one or more phases. The pickup threshold was set at 5% IBase, where IBase = 2000A; pickup threshold = 100A.

The 50ND function was also set with a pickup threshold of 5% IBase, where IBase = 2000A; pickup threshold = 100A.

In Figure 16, Trip = immediate pickup of the 50D function for phase current measured above the pickup threshold in the indicated phase, or immediate pickup of the 50ND function for residual current measured above the pickup threshold – no added time delay to issue the trip output/s.

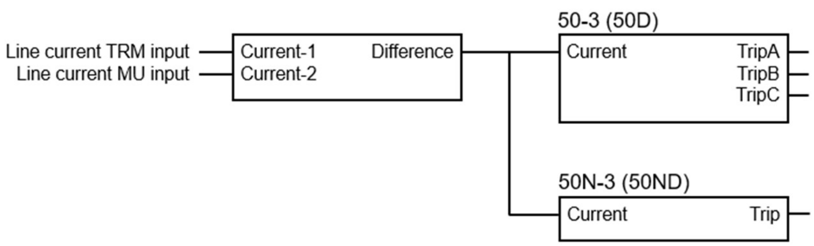


Figure 16: instantaneous phase and residual current difference overcurrent protection (50D and 50ND)

50D – instantaneous phase current difference overcurrent protection (separately for bus-side and tie-side currents)

As the bus layout is 1½ CB, the line currents are the sum of the bus-side and tie-side currents. Up to now, the line currents have been connected to all functions. This comparison looks for any TRM vs. MU (FOCS_MU) difference separately for bus- and tie-side currents.

Both 50D functions were set with a pickup threshold of 5% IBase, where IBase = 2000A; pickup threshold = 100A.

In Figure 17, Any_Ph_Trip = immediate pickup of the function for any phase current measured above the pickup threshold – no added time delay to issue the trip outputs.

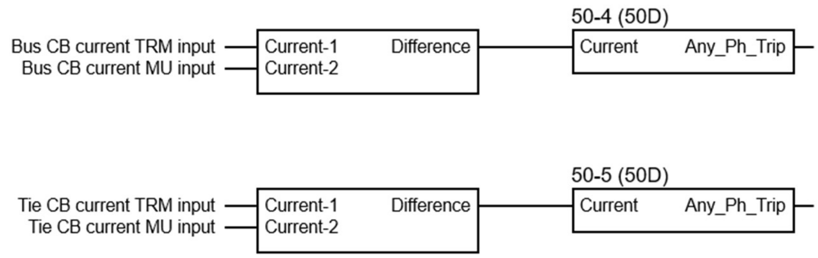


Figure 17: instantaneous phase current difference overcurrent protection (50D), separately for bus- and tie-side currents

59D and 59ND – phase and residual voltage difference overvoltage protection

The 59D function was set to operate for overvoltage in one or more phases. The pickup threshold was set at 5% VBase phase-ground, where VBase phase to phase = 525kV; pickup threshold = 15.2kV phase-ground.

The 59ND function was also set with a pickup threshold of 5% VBase phase-ground, where VBase phase-phase = 525kV; pickup threshold = 15.2kV phase-ground.

The input XXX shown for the 59D function represents the connection required for application of the 59D function, i.e.

- blocking for fuse failure detected

The inputs shown as XXX and YYY for the 59ND function represent the connections required for application of the 59ND function, such as

- blocking for fuse failure detected
- blocking for any open phase detected

Note that for both the 59D and 59ND functions the fuse failure detected signals come from the FuseFail-1 TRM-connected fuse failure detection function.

In Figure 18, Pickup = immediate pickup of the 59D function for phase voltage measured above the pickup threshold in the indicated phase, or immediate pickup of the 59ND function for residual voltage measured above the pickup threshold – Pickup is used as these functions would normally have an added time delay to issue the trip output/s.

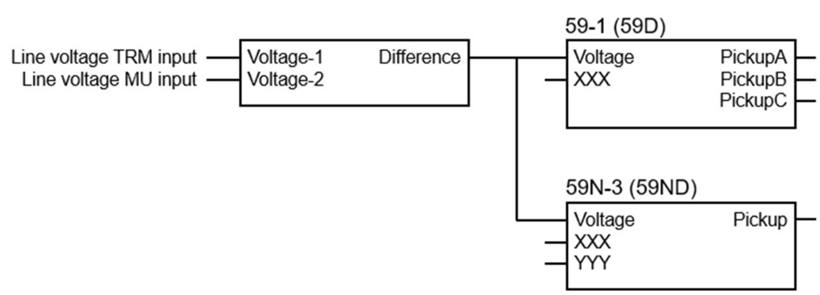


Figure 18: phase and residual voltage difference overvoltage protection (59D and 59ND)

The output signals from all the above functions measuring the difference between the analog quantities are connected to the IED's disturbance recorder. Operation of any of these functions indicates a difference between the two same-source analog quantities connected to the IED.

VI COMPARISON OF MEASURED VALUES

Comparison of measured values is made by taking the value of the TRM-connected function as the reference, and then determining whether the value of the MU-connected function is within a plus/minus percentage band around the reference. If yes, no discrepancy signal will be given. However, if the value of the MU-connected function falls outside the no discrepancy plus/minus percentage band around the reference, a discrepancy signal will be given.

Current

As a discrepancy between the measured values will be given when the discrepancy band is exceeded, and as this band is a percentage of the reference value, a single percentage difference cannot be used for the full range of measured current. For example, if a 5% band was set, and 2000A (= 1 per unit) is flowing (and measured as such by the TRM-connected reference), a discrepancy will be given if the value of the MU-connected function differs by more than 100A. However, for the same set 5% band with 200A (= 0.1 per unit) flowing (and measured as such by the TRM-connected reference), a discrepancy will be given if the value of the MU-connected function differs by more than just 10A. Therefore, to avoid unwanted discrepancies being given, different percentage values have been applied to different ranges of current. For reference current values less than 200A (= 0.1 per unit) no discrepancy evaluation will be made. Furthermore, no discrepancy will be given for a current difference value less than 100A (= 0.05 per unit).

The evaluation is performed separately in each phase.

Table 1 shows the values that define the characteristic, and Figure 19 shows the characteristic graphically. Operation will occur (discrepancy declared) when the magnitude of the difference between the measured current values is above the characteristic.

Reference current range (TRM-connected function)	± % difference of MU-connected function to TRM-connected function to get discrepancy in the measured value	± current value difference between MU-connected function and TRM-connected function to get discrepancy in the measured value
≤ 200A	No evaluation	No evaluation
200-400A	50%	100-200A
400-800A	25%	100-200A
800-1600A	12.5%	100-200A
≥ 1600A	6.25%	100A+

Table 1: values that define the measured current discrepancy characteristic

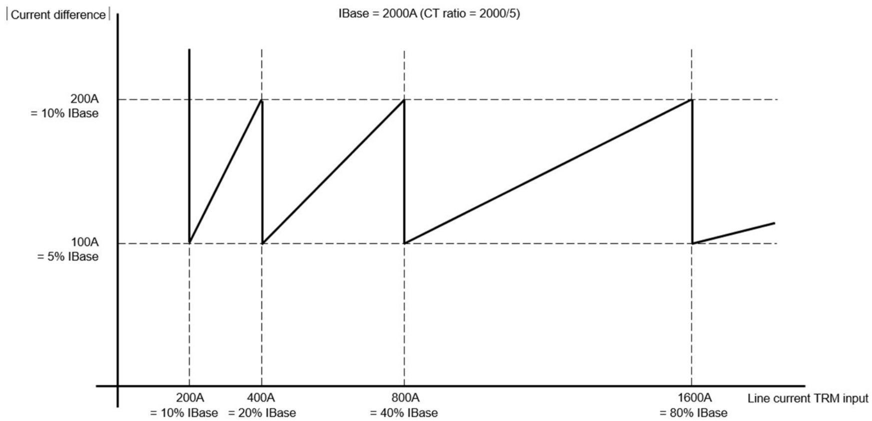


Figure 19: measured current discrepancy characteristic

P and Q

As the measured values for P and Q can vary over a wide range, a similar approach was adopted here as for the current measurement.

Voltage

Normal measured voltage should, under healthy system conditions, be around 1 – 1.05 per unit. For reference voltage values less than 242.5kV phase-ground (= 0.8 per unit) no discrepancy evaluation will be made. Furthermore, no discrepancy will be given for a voltage difference value less than 15.2kV phase-ground (= 0.05 per unit).

The +/- % difference of MU-connected function to TRM-connected function (reference) to get a discrepancy in the measured voltage value is 6.25%. At 242.5kV phase-ground, a 6.25% difference is 15.2kV phase-ground, which = 0.05 per unit.

The evaluation is performed separately in each phase.

Figure 20 shows the characteristic graphically. Operation will occur (discrepancy declared) when the magnitude of the difference between the measured voltage values is above the characteristic.

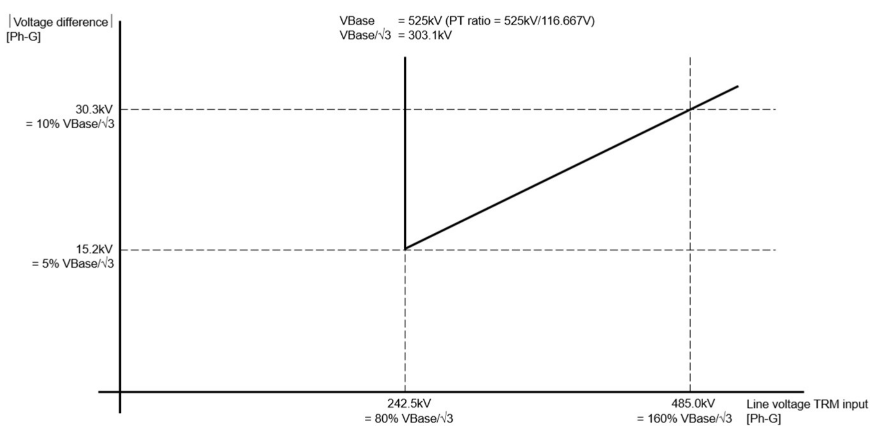


Figure 20: measured voltage discrepancy characteristic

Frequency

A similar approach was adopted here as for the voltage measurement. Normal measured frequency should be at, or very close to, 1 per unit (= 60Hz). No discrepancy evaluation will be made when the frequency measured by the TRM-connected function (reference) is less than 50Hz. Furthermore, no discrepancy will be given for a frequency difference value less than 3Hz (= 0.05 per unit).

The +/- % difference of MU-connected function to TRM-connected function (reference) to get a discrepancy in the measured frequency value is 6%. At a frequency of 50Hz, a 6% difference is 3Hz, which = 0.05 per unit (of 60Hz).

The output signals from all the above discrepancy evaluations are connected to the IED's disturbance recorder. To further prevent the possibility of records being triggered too often, each of the above signals has a 3sec pickup delay added.

VII ANALYSIS OF SYSTEM EVENTS

1) Phase A to ground fault in zone 2 (on May 17, 2024, at 3:18am)

This fault was successfully cleared in 49.999ms following operation of the in-service protection and opening of the Phase A pole of the bus and tie circuit breakers.

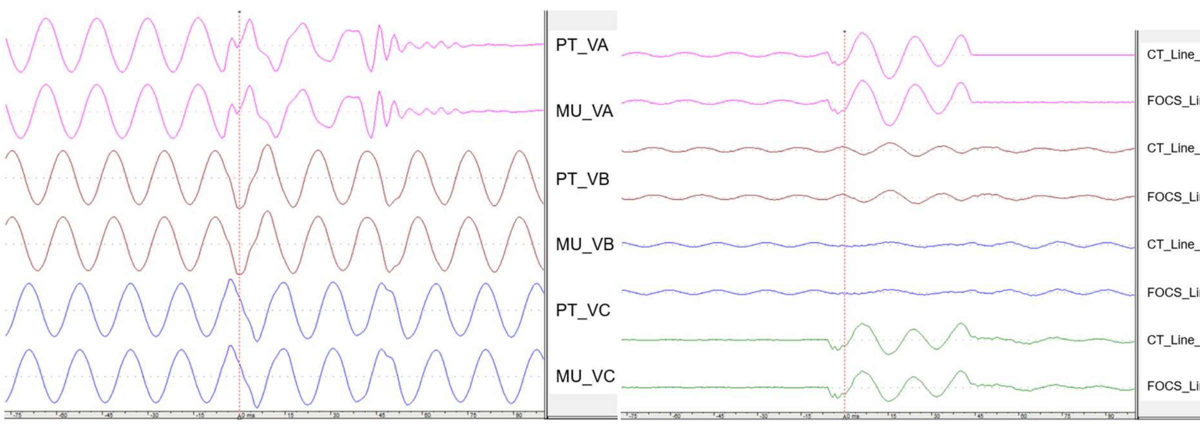
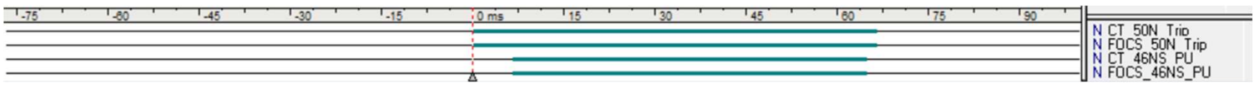


Figure 21: recorded line voltages and currents

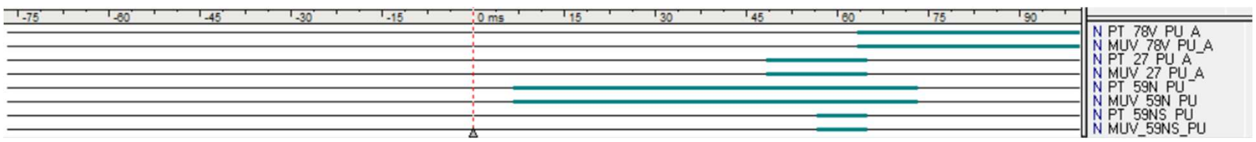
Figure 22 shows the recorded binary signals. The comparative performance of all the shown signal pairs was evaluated using the logic shown in Figure 15. CT, PT or CT/PT = signals from TRM-connected functions, whereas FOCS, MUV of FOCS/MU = signals from MU-connected (process bus-connected) functions. As can be seen, the TRM-connected functions and MU-connected functions operated at the same time, showing no performance difference, other than for zone 2 pickup, where the TRM-connected zone 2 element operated one processing time interval after the MU-connected zone 2 element. As the TRM-connected zone 2 element operated not more than one processing time interval later, no discrepancy was declared. Note that the TRM-connected 21 function elements consistently reset 6.667ms slower than the same MU-connected 21 function elements. The dropout timer in the logic shown in Figure 15 prevents a discrepancy being declared for this.

(a): zone 2 pickup Ph A, zone 2 pickup non-directional, time domain element pickup forward Ph A, phase selection forward Ph A

(b): ZOUT pickup



(c): 50N residual overcurrent trip, 46 negative-sequence overcurrent pickup



(d): 78V delta voltage pickup Ph A, 27 phase undervoltage pickup Ph A, 59N residual overvoltage pickup, 59NS negative-sequence overvoltage pickup

Figure 22: binary signal recording showing comparative performance of the distance, power swing, current and voltage functions

2) *Phase A to ground fault in zone 2 (on June 27, 2024, at 4:35am)*

This fault was successfully cleared in 50ms following operation of the in-service protection and opening of the Phase A pole of the bus and tie circuit breakers.

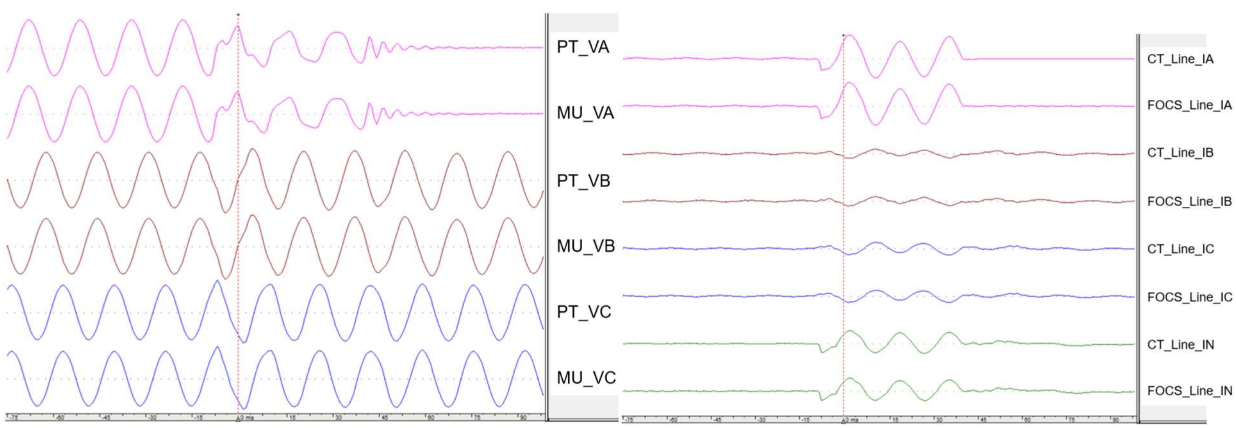
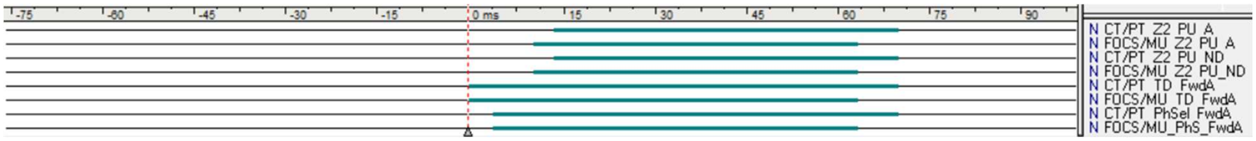


Figure 23: recorded line voltages and currents

Figure 24 shows the recorded binary signals. As before, the TRM-connected functions and MU-connected functions operated at the same time, showing no performance difference, other than (this time) for both the directional and non-directional zone 2 pickup, where the TRM-connected zone 2 element operated one processing time interval after the MU-connected zone 2 element. As the TRM-connected zone 2 element operated not more than one processing time interval later, no discrepancy was declared. Note again that the TRM-connected 21 function elements consistently reset 6.667ms slower than the same MU-connected 21 function elements.



(a): zone 2 pickup Ph A, zone 2 pickup non-directional, time domain element pickup forward Ph A, phase selection forward Ph A

(b): ZOUT pickup

(c): 50N residual overcurrent trip, 46 negative-sequence overcurrent pickup

(d): 78V delta voltage pickup Ph A, 27 phase undervoltage pickup Ph A, 59N residual overvoltage pickup, 59NS negative-sequence overvoltage pickup

Figure 24: binary signal recording showing comparative performance of the distance, power swing, current and voltage functions

3) Phase C to ground fault in zone 1 (on September 16, 2024, at 7:17pm)

This fault was successfully cleared in 41.666ms following operation of the in-service protection and opening of the Phase C pole of the bus and tie circuit breakers.

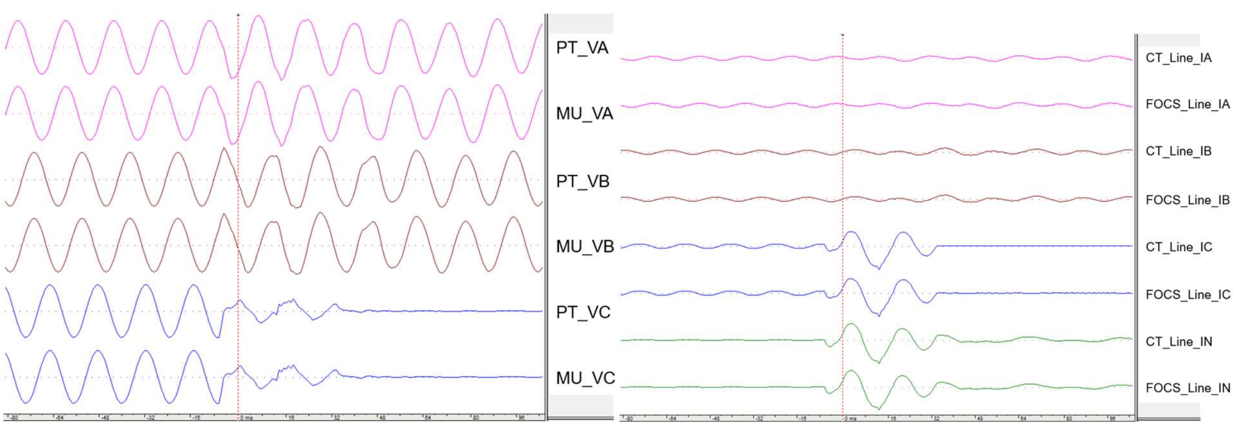
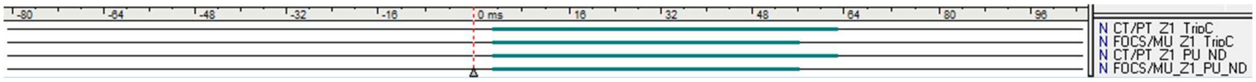
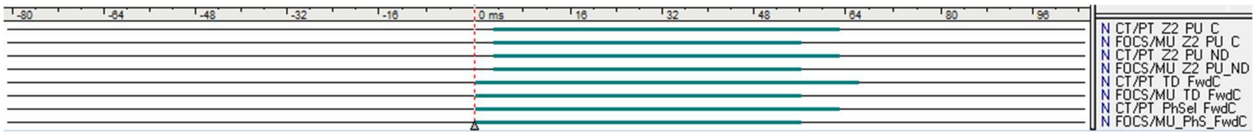


Figure 25: recorded line voltages and currents

Figure 26 shows the recorded binary signals. As before, the TRM-connected functions and MU-connected functions operated at the same time, showing no performance difference, and hence no discrepancy was declared. Note again that the TRM-connected 21 function elements consistently reset 6.667ms slower than the same MU-connected 21 function elements (10ms slower for the Phase C forward TD element).

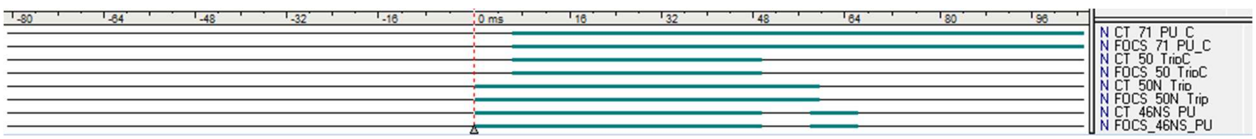


(a): zone 1 trip Ph C, zone 1 pickup non-directional

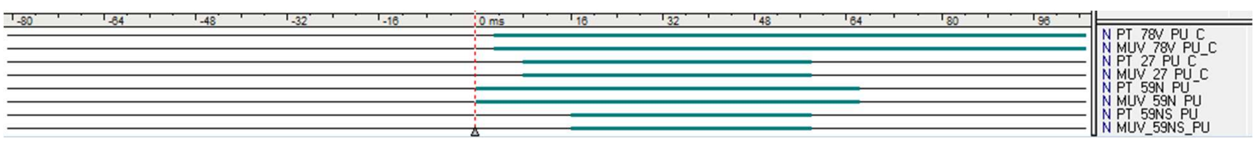


(b): zone 2 pickup Ph C, zone 2 pickup non-directional, time domain element pickup forward Ph C, phase selection forward Ph C

(c): ZOUT pickup



(d): 71 delta current pickup Ph C, 50 phase overcurrent trip Ph C, 50N residual overcurrent trip, 46 negative-sequence overcurrent pickup



(e): 78V delta voltage pickup Ph C, 27 phase undervoltage pickup Ph C, 59N residual overvoltage pickup, 59NS negative-sequence overvoltage pickup

Figure 26: binary signal recording showing comparative performance of the distance, power swing, current and voltage functions

<u>4) 59N pickup</u>

Over 50 disturbance records have been triggered since the beginning of February 2024 by 59N pickup. The incident analyzed here occurred on May 8, 2024, at 8:35am.

Figure 28 shows the RMS values of the phase-ground voltages over a 5-cycle window that covers the pickup of the 59N functions (new RMS values of the phase-ground voltages were calculated after every 4 samples = 0.2 per unit of a cycle).

This transient in the voltage occurred when a bus reactor (closest to the line with the installed pilot) was switched out.

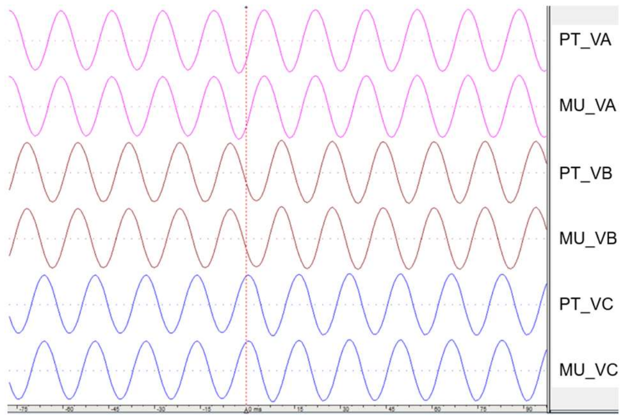


Figure 27: Recorded line voltages

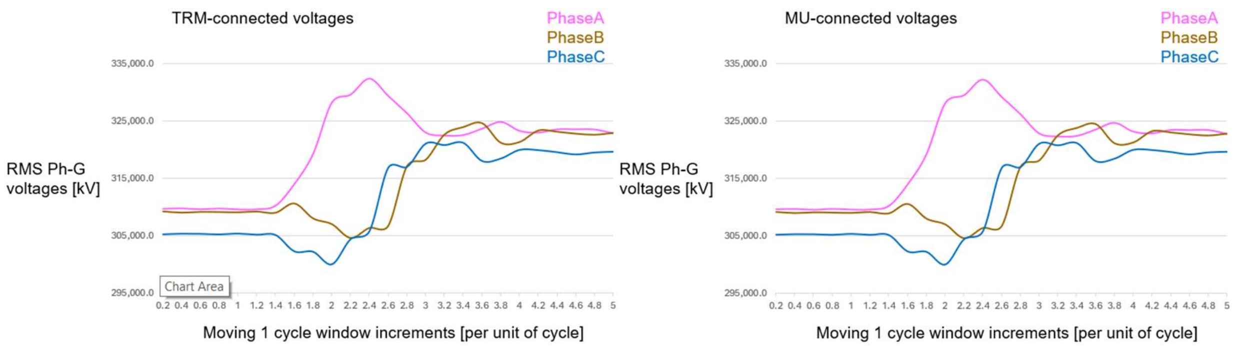


Figure 28: RMS values of the phase-ground voltages

Figure 29 shows the RMS value of the 3V0 voltage calculated from the TRM-connected phase-ground voltages, and the 3V0 voltage calculated from the MU-connected phase-ground voltages (both calculated from their respective RMS values shown in Figure 28).

Figure 29 also shows the set 59N pickup threshold. The two 3V0 voltages overlay "identically".

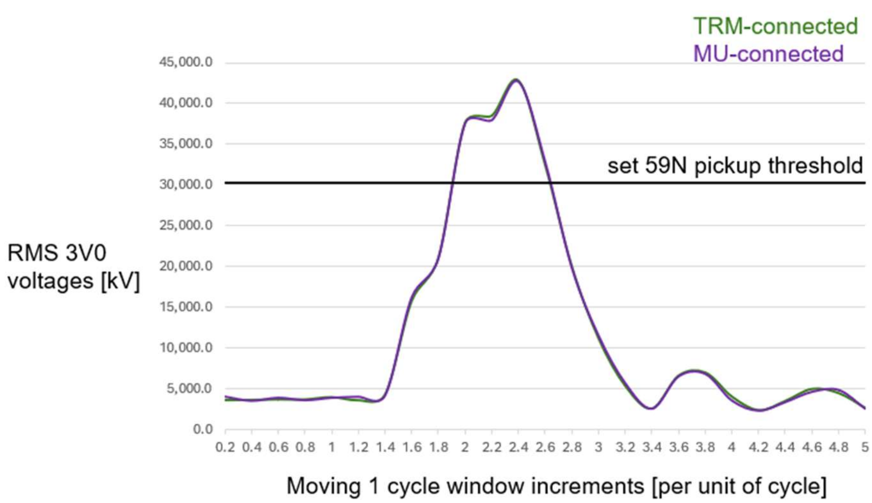


Figure 29: RMS values of the 3V0 voltages

The operational performance of both the TRM-connected and MU-connected 59N functions is also identical, with no discrepancy. This is shown in Figure 30.

59N residual overvoltage pickup

Figure 30: binary signal recording showing comparative performance of the 59N functions

5) Forward TD (time-domain) element operation

More than 10 disturbance records have been triggered since the beginning of February 2024 by forward time domain element operation without there being a fault. The incident analyzed here occurred on May 7, 2024, at 10:50am.

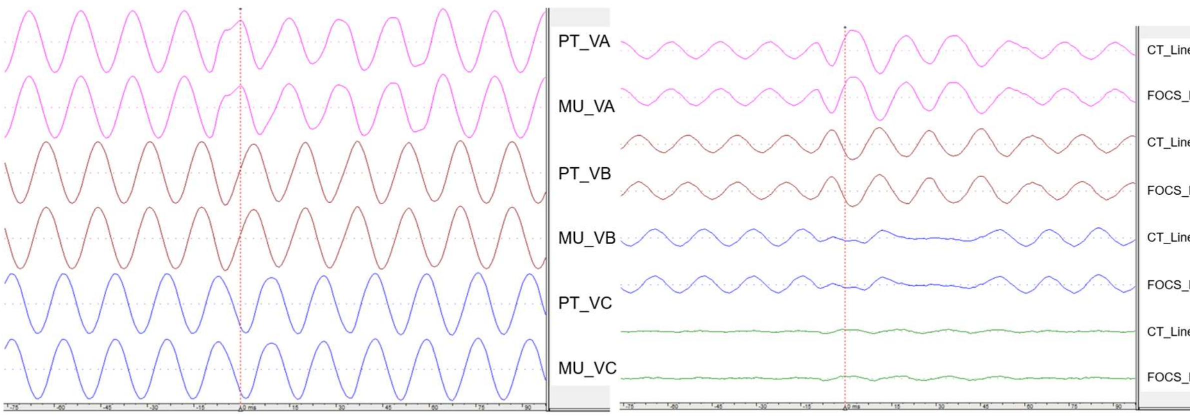
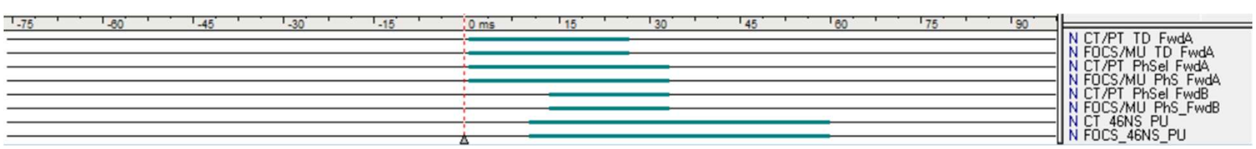


Figure 31: Recorded line voltages and currents

The reason for the transients in the voltages and currents is not known. However, the customer did see that their 525kV and 230kV recorders were triggered. There was no operation of any HV equipment at the time.

Figure 32 shows the signals recorded by the IED's disturbance recorder. The TRM-connected functions and MU-connected functions operated at the same time, showing no performance difference (discrepancy).



TD time domain element pickup forward Ph A, phase selection forward Ph A, phase selection forward Ph B, 46 negative-sequence overcurrent pickup

Figure 32: binary signal recording showing comparative performance of distance functions (TD elements and phase selection) and negative-sequence overcurrent functions

Interesting to note in this case is that the TRM-connected 21 function elements (TD FwdA, PhSel FwdA and PhSel FwdB) reset at the same time as the corresponding MU-connected 21 function elements, which is different from the behavior observed during the faults.

VIII CONCLUSIONS

This project was setup to perform a thorough evaluation of the performance of conventionally connected functions vs. process bus connected functions. So far there have been three single-phase faults, as well as other transients that have caused the protection functions to react. The evidence to date substantiates that the performance of the protection functions is the same for conventional and process bus method of connecting the analog quantities to the IED.

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[2] George Gresko, PECO; Steve Kunsman, Samuel Morbin, Mike Kockott, ABB Inc; Smart Substation: Design, Installation, Testing, and Training Experience; 44th annual Western Protective Relay Conference, Spokane, WA

AUTHORS

Mike Kockott
Mike is a Senior Technical Consultant at Hitachi Energy. He joined Hitachi Energy (formally ABB Inc.) in November 2011 in Raleigh, North Carolina as a Senior Applications / Product Specialist. Prior to relocating to North America, Mike worked as a Senior Applications Specialist / Senior Regional Technical Manager for 12 years at the SA Product factory in Västerås, Sweden. Before joining ABB AB in January 2000 in Sweden, Mike was Senior Consultant, Protection (Transmission) at Eskom (national power utility, South Africa). Mike joined Eskom as an engineer-in-training in 1983 and rose to Protection Design Manager (Line Protection), before switching to Senior Consultant. Mike graduated from the University of Cape Town with a BSc (electrical engineering) degree (with honors) in 1980. Mike is active in IEEE PSRC where he is currently chair of one working group, and vice-chair of another. Mike has also previously been active in Cigré (study committee B5).

Galina S. Antonova
Galina serves as a Technical Sales Engineer with Hitachi Energy in North America since 2010. She has over 20 years of experience in the area of electrical engineering, data communications and time synchronization, which she applied to the electrical power industry. In her current role Galina is applying her expertise to substation automation and protective relay applications. Galina received her M.Sc. Degree with Honors in 1993 and a Ph.D. in 1997 in Electrical Engineering and Data Communications from the State University of Telecommunications, St. Petersburg, Russia, and spent one year at University of British Columbia (UBC) on a scholarship from the Russian President. She is actively involved with IEEE PSRC, PSCC and is a Canadian member of the IEC TC57 WG10.