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WHITE PAPER

An SEL Approach to Modifying Transformer Protection for Nuclear Stations

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Introduction

While much of the protective relaying on the electric utility grid has been updated to modern standards using microprocessor-based relays, nuclear power generating stations have lagged behind because of the unique challenges they face in making design changes. As nuclear plants age, plant personnel face the need to upgrade their protective relaying due to concerns with the maintainability and obsolescence of existing equipment, as well as the need for additional functions that have become required since the original plant design. This white paper addresses modifying one part of that protective relaying—the protection of the generator step-up (GSU) transformer, unit-auxiliary transformer (UAT), and station-service transformer (SST). It discusses design considerations for modifying transformer protection at an existing nuclear station and the SEL equipment that can be used to implement that design.

General Design Considerations

Typically, transmission line protection is applied using dual-redundant schemes. A dual-redundant scheme provides a high degree of dependability (tripping when required) and reduced security (not tripping when not required) as compared with a single relay. The transmission system generally has redundant paths for power flow. Therefore, the transmission provider usually has a greater concern for dependability than security. When upgrading protection at nuclear stations, engineers typically have greater concern for security and the elimination of single-point vulnerabilities than for dependability, for various reasons. Therefore, a redundant two-out-of-three voting scheme may be considered for increased security. One study says that, for transformer protection, a redundant two-out-of-three voting scheme increases security over the dual-redundant scheme by about 200 percent and decreases dependability by about 40 percent [1]. Although this type of voting scheme has about a 25 percent higher cost than a dual-redundant scheme, this is immaterial when compared with the other costs and considerations associated with modifying nuclear station transformer protection. For that reason, this white paper only addresses two-out-of-three voting schemes for transformer protection. The wiring of a simple dual-redundant scheme is intuitive, and many of the points described in this paper apply to that scheme as well.[1]

SEL generally recommends using a single model of transformer relay in any redundant scheme for the following reasons [1] [2] [3]:

- Using a single model results in lower settings labor, higher settings reliability, and a lower incidence of human error (the primary cause of unintended operations).
- Common designs, algorithms, and settings ensure optimum protection coordination.

[1] Some nuclear units use a double two-out-of-two scheme that provides symmetry with the batteries, current transformers, and other redundant equipment. This scheme eliminates single-point vulnerabilities and is worth consideration.

- Common automation and integration simplify architecture and reduce cost.
- A common operator interface makes system operators more comfortable.
- Personnel can analyze data with the same skills and tools.
- Personnel can train in depth on one relay instead of having to learn how to use two or three relays for the same purpose.
- Troubleshooting is simpler because it is easier for users to compare the reports of two or three identical relays for the same fault.

These reasons far outweigh the very small increases in dependability (~0 percent) and security (~5 percent) that one study says are gained by using different relay types [1].

Relay Selection

SEL offers four different families of transformer protection relays with different features, form factors, and price points. Typically, modifications to large generating stations employ the SEL-487E Transformer Protection Relay because it is the fastest, most secure, and most full-featured transformer protection relay that SEL offers. A one-line diagram highlighting the available functions of the SEL-487E is shown in Figure 1. The functions are defined in Table 1.

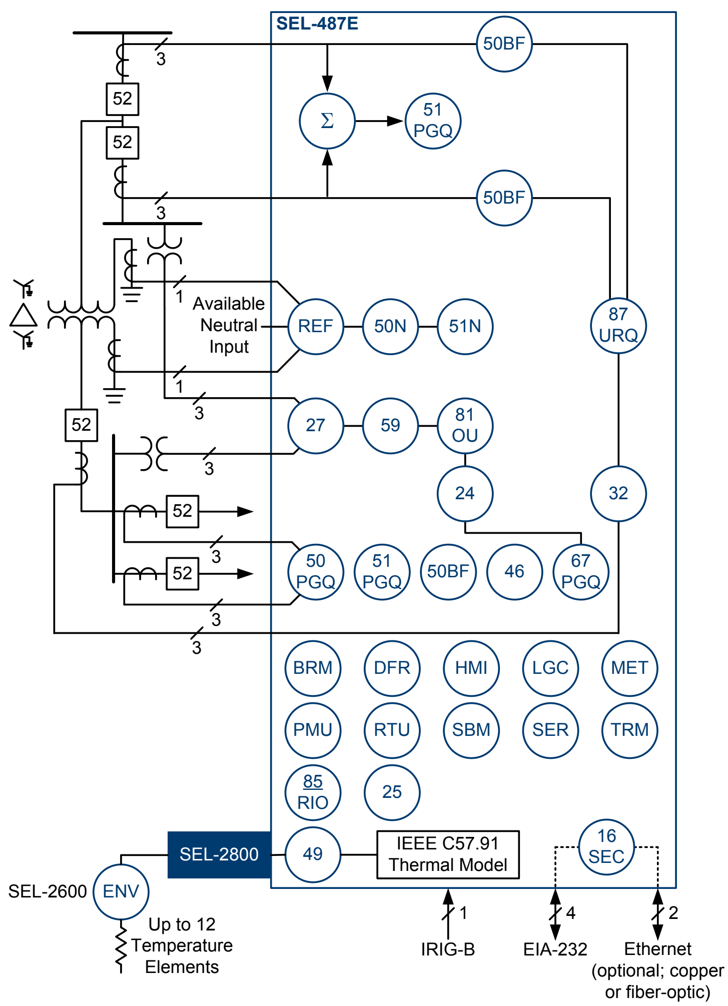

Figure 1 SEL-487E Functional Overview

Table 1 SEL-487E Functions

ANSI Number/Acronym	Function
16 SEC	Access security (serial, Ethernet)
24	Volts/Hertz
25	Synchronism check
27	Undervoltage
32	Directional power
46	Current unbalance
49	Thermal
50BF	Breaker failure overcurrent
50N	Neutral overcurrent
50 (P,G,Q)	Overcurrent (phase, ground, negative sequence)
51N	Neutral time-overcurrent
51 (P,G,Q)	Time-overcurrent (phase, ground, negative sequence)
59	Overvoltage
67 (P,G,Q)	Directional overcurrent (phase, ground, negative sequence)
81 (O,U)	Overfrequency/underfrequency
85 (RIO)	SEL MIRRORED® BITS communications
87 (U,R,Q)	Transformer differential (unrestrained, restrained, negative sequence)
DFR	Event reports
ENV	SEL-2600 RTD Module
HMI	Operator interface
LGC	Expanded SELOGIC® control equations
MET	High-accuracy metering
PMU	Synchrophasors
REF	Restricted earth fault
RTU	Remote terminal unit
SER	Sequential Events Recorder
BRM	Breaker wear monitor
LDP	Load data profiling
SBM	Station battery monitor
TRM	Transformer monitor

The relay offers up to five restraint inputs and three neutral inputs. The five restraint inputs make the relay ideal for protecting a GSU transformer and an isolated phase bus feeding up to three UATs. The three neutral inputs make it ideal for protecting the typically resistance-grounded secondary windings of multiwinding transformers that are sometimes used for UATs or SSTs.

Function Selection

Nuclear station personnel sometimes make only one-for-one replacements of electromechanical relays and do not take advantage of the full features provided by the SEL-487E. The existing relaying typically includes differential relaying (87), backup overcurrent protection (50/51), and transformer neutral overcurrent protection (51N). This covers the basics. However, other valuable features of the SEL-487E that engineers may want to consider for this application include the following:

- Combining harmonic blocking and restraint functions in parallel to provide secure operation and an optimum operating speed for the transformer differential element during inrush conditions [4] [5].
- Using the waveform-based inrush detection method to augment the harmonic restraint and blocking functions to prevent differential element operation during an inrush condition with low second-harmonic content. This may become particularly critical if the transformer is replaced with a new transformer having an improved core type that exhibits less harmonic content on inrush [6].
- Using the negative-sequence differential element for turn-to-turn fault protection. Previously, only a sudden pressure relay (SPR) could detect turn-to-turn faults. SPRs are prone to unintended operation due to external faults and other nonfault events and are often a source of single-point vulnerabilities for nuclear stations [7]. Testing has shown that the negative-sequence differential element is sensitive enough to detect turn-to-turn faults involving less than 2 percent of the winding. It is also secure for external faults, irrespective of current transformer (CT) saturation [5].
- Using the restricted earth fault (REF) element for internal ground fault protection for the transformer. This method is much faster and more secure than the simple neutral time-overcurrent relay (51N) that is typically employed. The time-overcurrent element can still be used for backup transmission protection if desired.
- Using the asset management features of the relay. These include a thermal element that indicates when the transformer is in danger of excessive insulation aging or loss of life (when combined with the SEL-2600), a through-fault monitor that calculates the cumulative mechanical stress on the transformer windings due to through faults, and a circuit breaker monitor that can help maintenance personnel determine the extent of a developing circuit breaker problem.
- Using the reporting functions of the relay, such as the digital fault recorder (DFR) and the Sequential Events Recorder (SER). Engineers needs to take special care to select adequate analog and digital points for recording. As a general rule, any digital point that is part of an algorithm that causes a trip should be recorded by both the DFR and SER. This makes forensic analysis much easier and more thorough.
- Detecting geomagnetically induced currents (GICs). GICs can stress a transformer via induced vibrations and localized heating due to magnetic flux flowing through alternative paths, such as clamping devices and the transformer tank. The accompanying geomagnetically induced half-cycle transformer saturation causes a resulting excitation current to be composed of high even and odd harmonics. The SEL-487E directly measures the magnitudes of the second, fourth, and fifth harmonics and can be used for monitoring the presence of GICs [8].

- Using the volts/hertz element (24) to protect the transformer and isolated phase bus either for (1) a unit with an open generator breaker or (2) when the generator braids are removed during an outage on a unit-connected generator. During these conditions, the 24 element typically applied in the generator relay is not available. Also, the 24 element in the SEL-487E has a user-defined curve that can be used to closely match the overexcitation characteristic of the GSU transformer.
- Using the zero-sequence overvoltage element (59N) to protect the transformer and isolated phase bus either for (1) a unit with an open generator breaker or (2) when the generator braids are removed during an outage on a unit-connected generator. During these conditions, the isolated phase bus and delta winding of the GSU transformer no longer have any ground protection. Using the 59N element in the transformer relay provides that protection.

This is not to say that all of the functions shown in Figure 1 should be applied, which is a common error in applying microprocessor-based relays. It is up to the engineer to pick those features that are appropriate to the application.

AC Wiring Design

The ac wiring design is limited primarily by the number of CTs and their location. It is best if each relay has its own dedicated phase and neutral CTs; however, that is unlikely. It is desirable to have the CTs wrap a differential zone with circuit breakers on either side, but that may also not be the case.

An example GSU transformer protection one-line diagram is shown in Figure 2. This setup could be for a GSU transformer on a unit-connected plant. It is also possible that there could be a unit or overall differential that connects to the CTs shown on the breaker and that the transformer differential only connects to the bushing CTs on the transformer. If there are two phase CTs available, the SEL-487E Relays could be split, with one CT feeding one relay and the other CT feeding two. Both this possibility and the design shown in Figure 2 introduce a single-point vulnerability caused by the number of CTs.

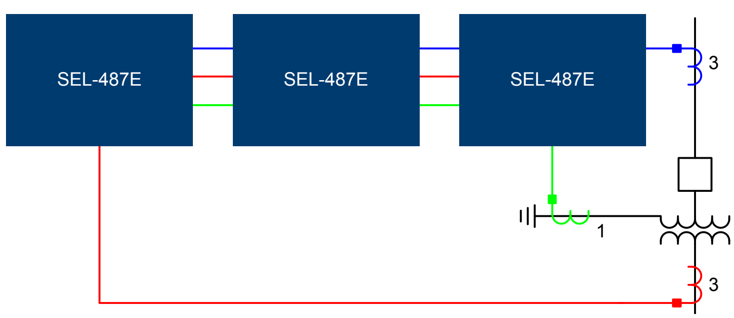

Figure 2 Proposed GSU Transformer Protection One-Line Diagram

Note that the CTs shown in Figure 2 are connected in wye. This is recommended so that currents measured at the relay will not include the increased magnitude and phase shift caused by delta-connected CTs. Connecting all CTs in wye simplifies the settings of overcurrent elements, the reading of DFR data, and metering. However, it is likely that one of the existing sets of CTs is connected in delta because this was required by the electromechanical relays. While this connection can be accommodated in the relay settings, it is not preferred. Reconnecting the existing CTs in wye should be considered, if practicable.

If the REF element is to be used, the neutral CT terminal pointing toward the ground needs to be connected to the polarity side of the relay input, as is shown in Figure 2. Note that the phase CTs on the protected winding must be connected in wye to use the REF element.

The relay accepts voltage transformer (VT) inputs, but none are shown in Figure 2. The voltage-based functions shown in Figure 1 are likely to be implemented elsewhere. However, if available, VT inputs to the relays aid in forensic analysis when using a DFR. Also, using the 24 or 59N functions should be considered, as described in the Function Selection section of this paper.

From its inception, SEL has not recommended the use of test switches. This is because regular current injection tests are not needed for maintenance [9]. Eliminating the test switches and associated wiring can improve the cost and reliability of protection, metering, and control systems [10]. However, test switches are still commonly applied on transmission line and generating station relaying.

The ac wiring for UAT or SST protection is very similar to Figure 2, with the CT inputs wired to the available phase and neutral CTs and the phase CTs connected in wye wherever possible.

DC WIRING DESIGN

DC power is typically provided by two station batteries. This can make powering the relays for a two-out-of-three voting scheme a bit awkward; i.e., powering one relay off of one battery and two off of another. That design makes the failure of the battery powering two relays a single-point vulnerability. This issue can be overcome by applying a small, industrial control-cabinet type uninterruptable power source (UPS), typically with a 24 Vdc or 48 Vdc output. Alternatively, 120 Vac UPS power can be applied.

One channel of tripping is shown in Figure 3. Each output shown is assigned to the tripping logic within the relay. There is no reason to segregate protective elements to different contacts. A lockout relay (86T1) is shown. However, it may not be required because the SEL-487E can be ordered with up to 24 outputs (as shown in Figure 4), and contact multiplication may not be needed. The relay logic can seal in the outputs and serve in place of a lockout relay. Most engineers still choose to use a lockout relay because of familiarity, although this does reduce dependability slightly. IN103 is shown monitoring the state of 86T1, and IN104 is shown monitoring the coil continuity of 86T1. This assumes that IN101 is used to monitor the breaker position (52a), and IN102 is used to monitor the breaker trip coil continuity in a similar manner.

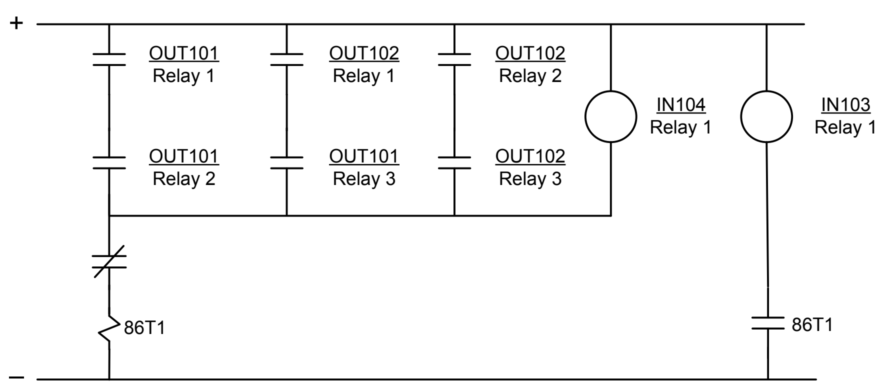

Figure 3 Tripping Channel 86T1

Figure 4 I/O Connections to the SEL-487E

A second channel of tripping is shown in Figure 5.

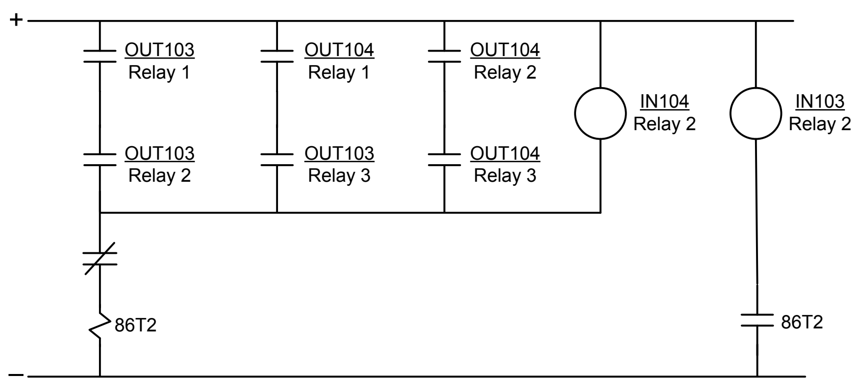

Figure 5 Tripping Channel 86T2

Cutout switches can be applied in the dc circuits to block the trip path. However, they are not needed. Functions can be blocked in the logic using front-panel pushbuttons or the local control screens that appear as switches on the SEL-487E human-machine interface (HMI), as shown in Figure 6. These features provide for the function of the cutout switch without the added complexity and diminished reliability of external switches [10].

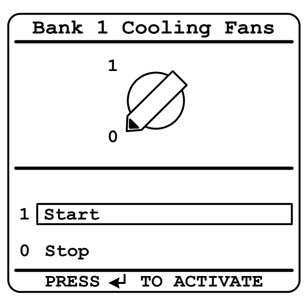

Figure 6 Local Control Screen

Engineers often do not take full advantage of the flexibility of microprocessor-based relays and needlessly leave switches, lights, and auxiliary relays in the dc circuits. This reduces the reliability of those circuits. It is recommended that engineers consider how the circuit can be simplified by using lights, pushbuttons, local control switches, and displayed text on the relay HMI (as shown in Figure 7) and, most importantly, by using digital I/O and internal logic to replace timers and other auxiliary relays.

Figure 7 SEL-487E Front-Panel HMI

An SPR can be wired into the SEL-487E, and the logic in the relay can be used to seal in and trip. SPRs have proven to be susceptible to misoperation because of surges on the dc supply arcing over the normally open microswitch contact (63) [7]. For this reason, it is common practice that both a normally open and a normally closed 63 contact be monitored and that they only trip when both contacts change state, as shown in Figure 8. SEL MIRRORED BITS communications (see the Communications section of this paper) can be used to communicate the state of the 63 contacts to other relays used in the two-out-of-three voting scheme so that the relays can perform the logic in parallel with the relay connected to the SPR.

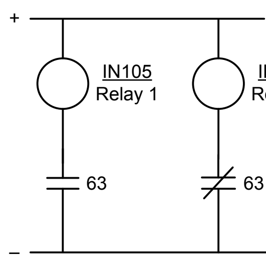

Figure 8 SPR DC Wiring

In some transformer designs, SPRs have a tendency to operate on high-current through faults. SEL has developed a method to block the operation of the SPR using a high-speed SEL-751A Feeder Protection Relay [11].

A critical part of the dc wiring design is alarm contact monitoring, particularly if there are no communications between the relay and the plant control system. This alarm contact alerts the operator to relay failures and warns the operator if someone is accessing the relay settings or control functions.

INSTALLATION

Using microprocessor-based relays simplifies installation and greatly reduces wiring as compared with discrete relays because hardwired logic is replaced with programmable logic. Even though the SEL-487E is quite large (a maximum of 12.22 inches high by 19 inches wide by 8.5 inches deep for rack-mounted relays), the three relays in a two-out-of-three voting scheme, along with test switches, should be able to fit in one door of a relay panel. SEL provides both full replacement panels and prewired replacement doors to make upgrades easier. An example panel with two SEL-487E Relays and two SEL-421 Protection, Automation, and Control Systems installed is shown in Figure 9.

Figure 9 Example Transformer and Line Protection Relay Panel

COMMUNICATIONS

Modern microprocessor-based relays offer a wide range of communications protocols and media, both serial and Ethernet. Two that might be considered for the SEL-487E in the application described in this paper include SEL MIRRORED BITS communications and Ethernet.

MIRRORED BITS Communications

SEL developed MIRRORED BITS communications to provide simple, high-speed, secure, relay-to-relay communication of real or virtual contact-status bits. The SEL-487E has two channels of MIRRORED BITS communications connected serially that can each continuously send and receive the status of eight different status bits. Sending digital status bits over a MIRRORED BITS channel is more reliable than hardwiring because of the structure of the MIRRORED BITS packet and the fact that it is continuously error-checked and verified to be coming from the proper transmit source. This allows relays in redundant schemes to securely share information and to perform logic decisions based on that shared information. An example of this is the communication of the state of the SPR, as described in the DC Wiring Design section of this paper.

Ethernet

Traditionally, there was a reluctance to use Ethernet in a nuclear station control network because commercial-grade hardware was too fragile and Ethernet is nondeterministic. Also, cybersecurity is a concern. However, SEL manufactures Ethernet switches, communications processors, and Ethernet security gateways that meet the same hardened standards as SEL protective relays. These devices also provide methods for making Ethernet more deterministic through the use of virtual local-area networks (VLANs). Redundant ring topologies, fiber-optic communications, and fail-over ports on the SEL-487E are also available to increase the reliability of Ethernet communications.

The SEL-487E is available with combinations of copper and fiber-optic media connections on each of its two ports. Multiple sessions of both engineering and control system data access are available over these ports. Ethernet protocols for the SEL-487E include SEL ASCII, SEL Fast Messaging, File Transfer Protocol (FTP), Telnet, DNP3 LAN/WAN, IEC 61850 GOOSE, and IEEE C37.118 synchrophasors. Note however, that Modbus® TCP is not native to the SEL-487E. Communication via Modbus requires the addition of a single SEL-3530-4 Real-Time Automation Controller (Figure 10) along with a single SEL-2730U Unmanaged 24-Port Ethernet Switch (Figure 11) to communicate with the SEL-487E Relays. Other arrangements can be used for more sophisticated Ethernet topologies and to meet cybersecurity requirements.

Figure 10 SEL-3530-4 Real-Time Automation Controller

Figure 11 SEL-2730U Unmanaged 24-Port Ethernet Switch

MAINTENANCE

As stated previously, after initial commissioning, current injection tests are not necessary for routine maintenance of microprocessor-based relays. This is because all calculations are performed in firmware and cannot drift over time. The relay continuously monitors itself and can report on the health of most relay components. The only components not monitored by self-tests are logic inputs, contact outputs, and analog (voltage and current) inputs. For this reason, periodic maintenance for SEL relays is greatly simplified as compared with electromechanical or solid-state protective relays. No specialized relay test equipment or training is required.

The following describe SEL's recommended approach to relay testing and best practices [9]:

- Perform comprehensive commissioning testing at the time of installation.
- Monitor the relay self-test alarm contact in real time, and take immediate steps to repair, replace, or take corrective action for an alarmed relay.

- Monitor potential relay failures not detected by self-tests. Periodically pulse outputs, activate inputs, and verify analog metering against other instruments.
- Analyze event reports to root cause, verify logic inputs, and verify output contact operation.
- Observe and act on all product service bulletins.

CONCLUSIONS

More and more, nuclear station personnel are faced with the need to replace their protective relaying as the stations age. This gives them the opportunity to increase the reliability of their protective relaying systems by increasing security and eliminating single-point vulnerabilities. They also have the opportunity to use more modern relay elements and algorithms to better protect their equipment. Forensic data available from SEL relays, such as DFR and SER data, help plant engineers to better understand an event after its occurrence. Asset management features help with diagnosing aging and wear on protected equipment. Secure communications paths provide engineering access and data to the plant control system. Relay maintenance requirements are reduced considerably.

All of these features and benefits are available by upgrading existing nuclear plant transformer protection with the SEL-487E. This is just one area that can be improved. Similar benefits can be realized in all areas of the plant by updating existing relay systems with SEL protection and communications products.

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BIOGRAPHY

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