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THE COPPER DIET

Recipes to Promote Standardization, Centralization, and Redundancy in a Digital Substation World

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Abstract

Much has been written on the use of IEC 61850, particularly about the protocol itself and networking. What has not been extensively written about is what to do with the "copper leftovers", the small amount of wiring left over to engineer once the decision to use process bus has been made.

This paper explores some details and examples of facilitating standardization of the copper leftovers, which decreases engineering time. Other topics that are explored include:

- Hybrid designs (mixtures of process bus and hardwire)
- Redundancy concepts
- Centralization

Introduction

"Begin with the end in mind."

This quote from a book by Steven Covey, The Seven Habits of Highly Effective People, can lend itself to electrical engineering in the Protection, Automation and Control (PAC) arena. We always strive to employ standard designs that are proven, economically implementable, and repeatable. By exploring how to create a standardized design at the beginning, will help the designer to end with a standard, repeatable design.

Designing digital substations is not exempt from the quest for standardization. With the possibility of eliminating many of the hardwires between the yard elements and the relay panels in the control house, opportunities for standardization are available. These yard elements include CTs, VTs, breakers, switches, and other input/output (I/O) associated with the primary apparatus. If the design is executed with a well-thought-out plan, it can lead to design, engineering, site construction, programming, and commissioning time and cost savings.

Review of Digital Substations

A digital substation involves the use the merging units (MUs) to connect to yard elements (CT, VT, 52, 89, and other), digitizing the data, then communicating with relays in the control house through fiberoptic cables. For this exploration, we are using a redundant network topology. The network where the digital data is transmitted is called the process bus. Redundant MUs, instrument transformers, the process bus networks, and the protection are employed for high reliability (99.9989%). Redundant protection systems are typically employed in transmission and (to a degree) in distribution. Analog data (sampled values; SV) as well as binary status and commands are included in the data. High-speed messaging (GOOSE) is used for commands and time-critical status.

Inter-relay information used for interlocking, breaker failure, protection modification, and other purposes is performed over a station bus network. Figure 1 shows a simplistic view of the arrangement described above.

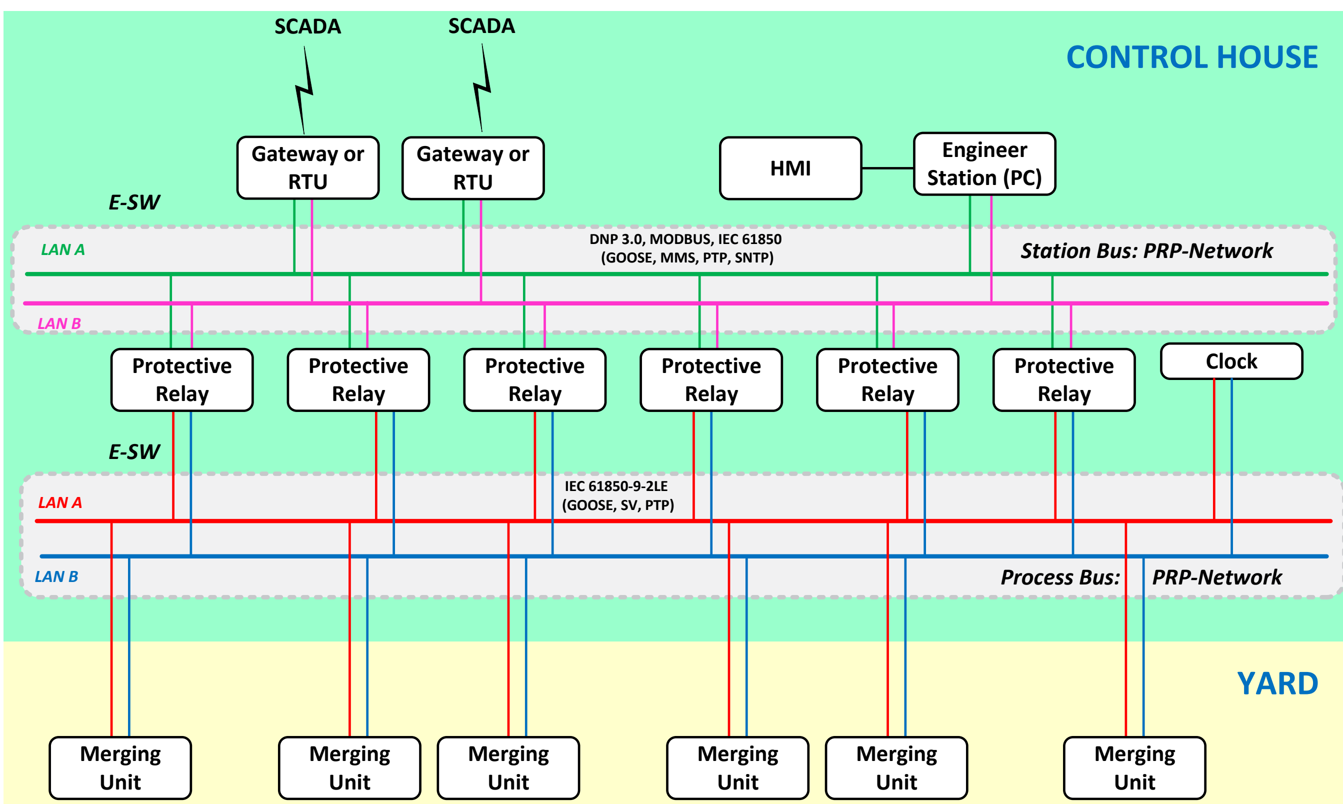


Fig. 1: Simple Block Diagram of a Digital Substation

There are some proponents of employing a limited amount of hardwired connection from the control house to the yard. These could be considered hybrid designs that employ both process bus and hardwired portions of the protection and control system. Reasons for this hybrid design may be incompatibility of the yard element with the process bus, or philosophical choices to have some hardwire to supplement the network connected yard elements.

What are the benefits of a digital substation?

- Opportunity for improved indices due to improved redundancy tactics
- Extends testing intervals (NERC PRC-005) and provides greater protection system visibility (OPEX)
- Improves safety
- Can improve commissioning practices and reduce costs (OPEX)
- Can improve maintenance practices and reduce costs (OPEX)
- Eliminates wiring runs from the yard elements to the relay panels situated in the control house (CAPEX, signal integrity)
- Decrease in wire, terminations, trenching, and conduit costs (CAPEX)
- Decrease in engineering and labor costs associated with above and relay panels (CAPEX)
- Large opportunity for standardization in design, reducing engineering hours (CAPEX)

Standardization of Single-Line Diagram (SLD) Design

Figure 2 is a SLD for a 115kV/13.8kV substation. It consists of three diagonal high voltage breakers and one-half (1.5CB) section, and a main-tie-main (M-T-M) medium voltage distribution section.

The first step is to redraw the SLD to show the placement of the instrument transformers. The MUs are then placed in strategic areas based on their I/O capability and distances to the yard elements that will be connected. One tries to maintain a balance of using an optimum number of MUs. This quantity and placement selection takes some factors into consideration:

- One could place MUs very close to every element requiring connection, but that would be costly as the number of MUs would be high.
- One could place all the MUs in an enclosure centrally in the yard. However, the length of the wiring that runs to that single enclosure could become large depending on the distances to all the yard elements.
- One can balance to amount of MUs for redundancy considerations, keeping the quantity to an acceptable number, and managing the distance and number of wires from the MUs to the yard elements.

In Figure 3, redundant MUs are applied on the 115kV section of the substation. The connectivity is breaker-oriented, meaning there is a set of MUs used to sense and control a given breaker and the yard elements associated with that breaker.

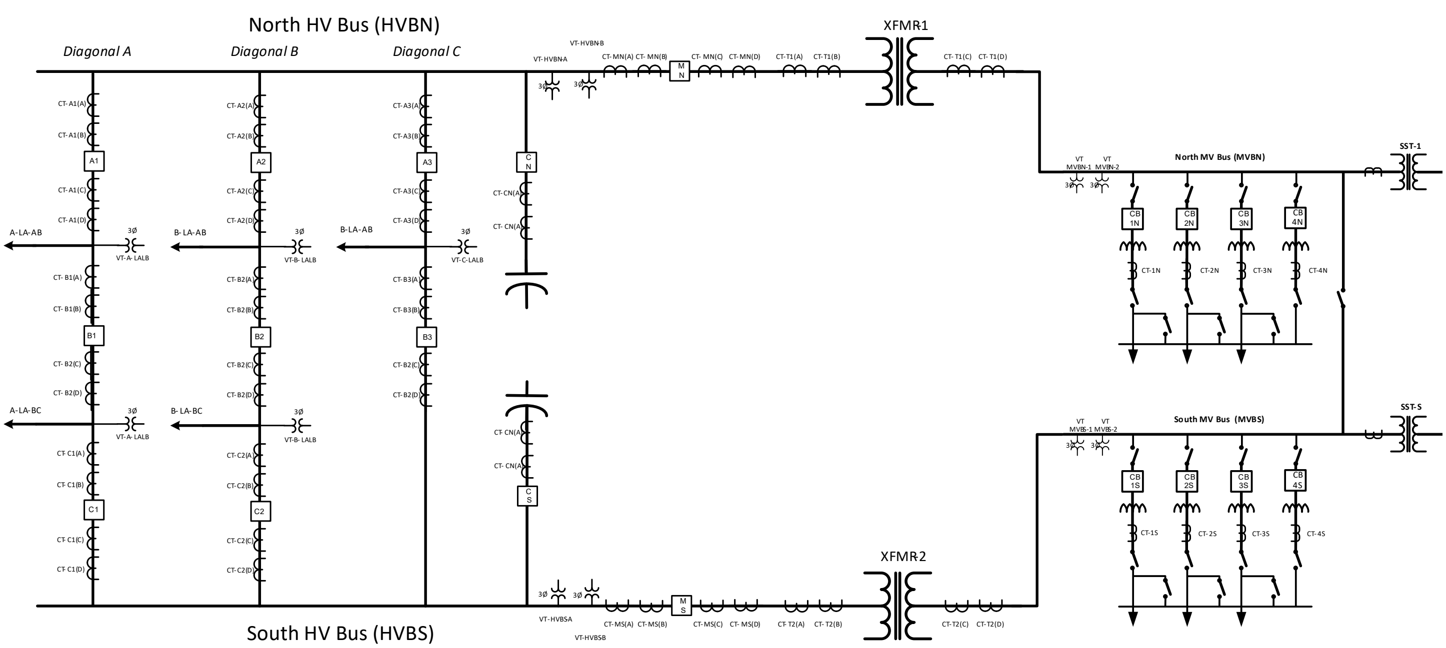


Fig. 2: SLD of a 115kV/13.8kV Substation

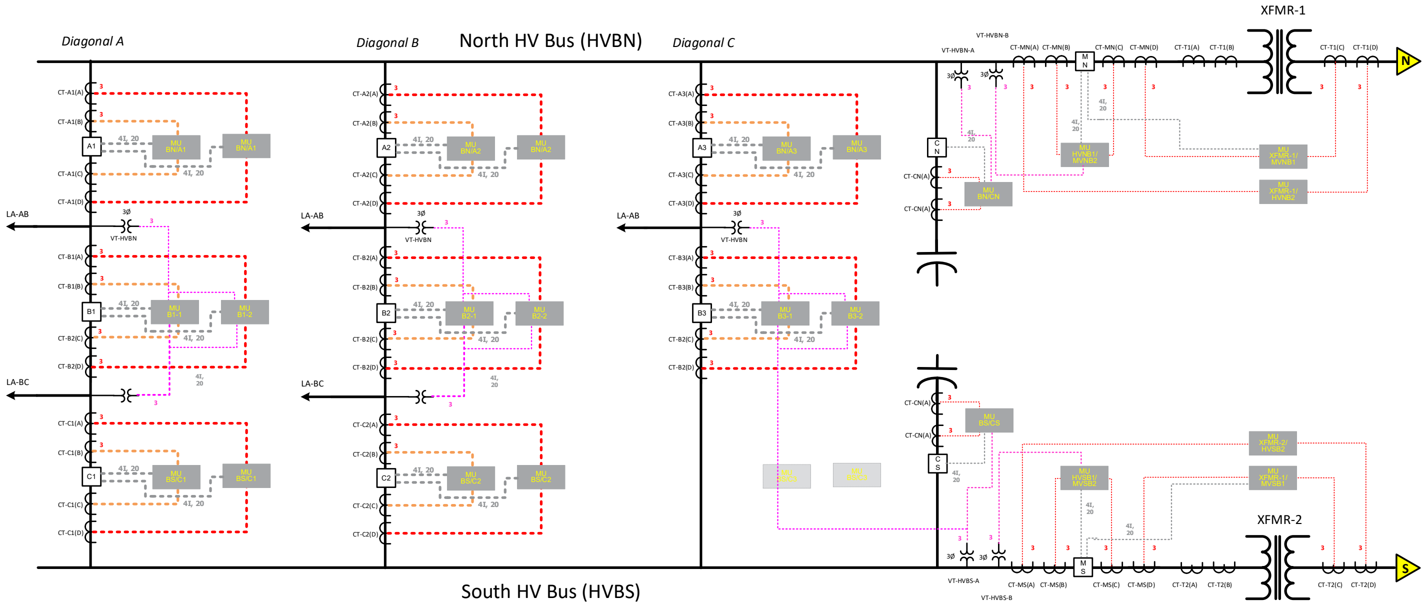


Fig. 3: SLD of a 115kV/13.8kV Substation

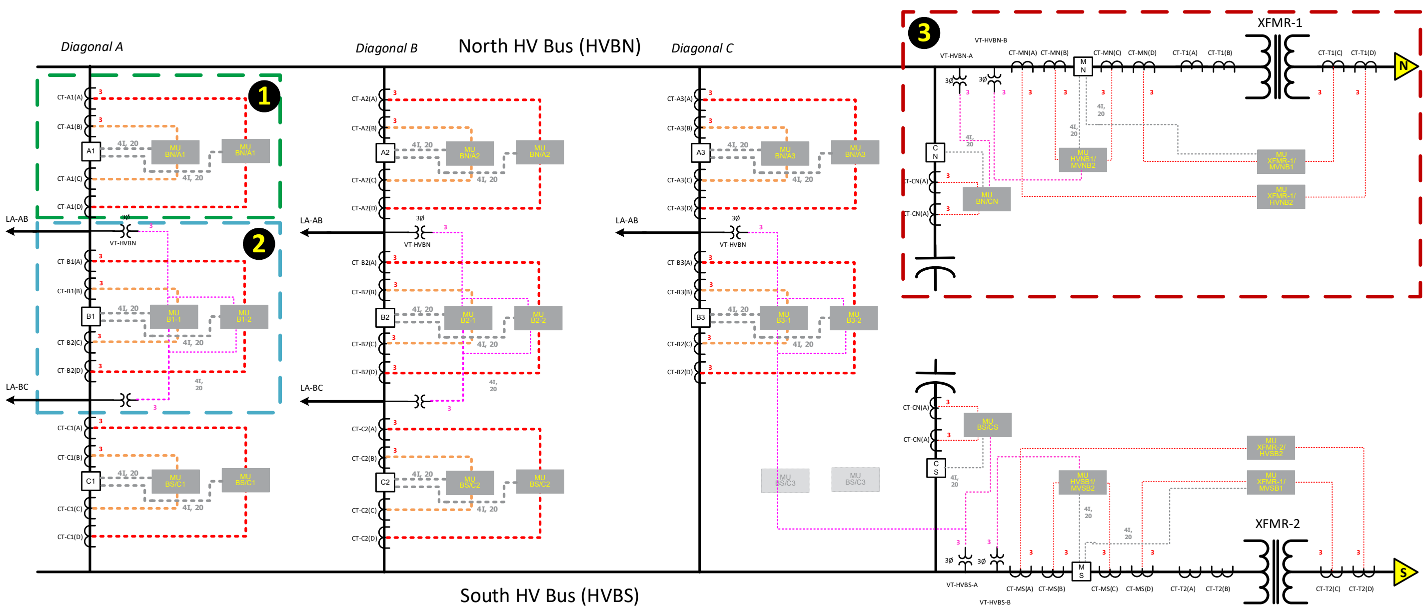


Fig. 4: High Voltage Section for Deeper Examination

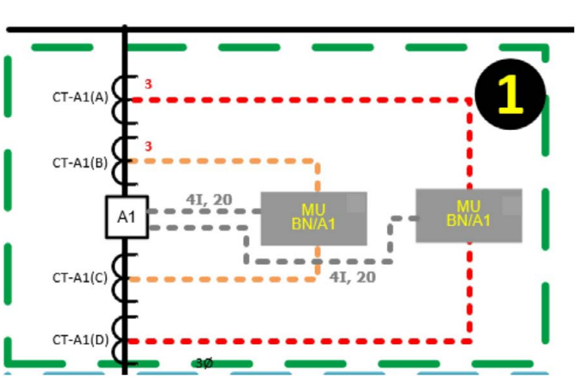


Fig. 5: MU Connectivity for Breakers Off Bus

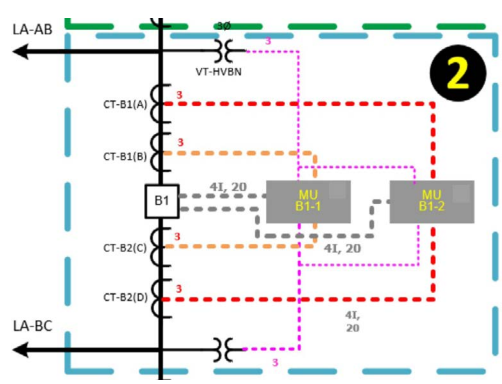


Fig. 6: MU Connectivity for a Center Breaker

Figure 4 shows the three areas to be explored in detail.

Figure 5 shows a typical MU connectivity diagram for a 1.5CB breaker connected off either bus. The connectivity of MU BN/A1 is identical to MU BN/A2. The numerals near the connection paths indicate the number of circuits, not conductors.

- “3” in the CT connection indicates A, B, and C phases; the wiring would be 4-conductor A, B, C, and N
- 4I in the breaker control circuit indicates four status connections (a, b, TCM, and CCM); the wiring would be 4x 2- conductor
- 2O in the breaker control circuit indicates two control connections (trip and close); the wiring would be 2x 2-conductor

The connectivity requirements are subject to the situation at the breaker:

- Use of single or dual trip/close coils
- Associated items such as motorized disconnect switches that may be used in some designs

Figure 6 shows a typical MU connectivity diagram for a 1.5CB breaker connected between the bus breakers and associated with the two lines in the diagonal. The connectivity of MU B1-1 is identical to MU B1-2. The numerals near the connection paths indicate the number of circuits, not conductors.

- “3” in the CT connection indicates A, B, and C phases; the wiring would be 4-conductor A, B, C, and N
- “3” in the VT connection indicates A, B, and C phases; the wiring would be 4-conductor A, B, C, and N
- 4I in the breaker control circuit indicates four status connections (a, b, TCM, and CCM); the wiring would be 4x 2- conductor
- 2O in the breaker control circuit indicates two control connections (trip and close); the wiring would be 2x 2-conductor

The connectivity requirements are subject to the situation at the breaker:

- Use of single or dual trip/close coils
- Associated items such as motorized disconnect switches that may be used in some designs

Figure 6 shows a typical MU connectivity diagram for a transformer connecting the high voltage and medium voltage sections of the substation. One can see the MU connectivity is not identical to the four MUs involved in the zone.

The chart in the Figure 7 shows the connectivity of the various MUs to the voltages and current involved with protecting the zone. There are backup MUs for potential failures of a given MU that can supply the protection used with the required current and/or voltages as applicable.

- “3” in the CT connection indicates A, B, and C phases; the wiring would be 4-conductor A, B, C, and N
- “3” in the VT connection indicates A, B, and C phases; the wiring would be 4-conductor A, B, C, and N
- 4I in the breaker control circuit indicates four status connections (a, b, TCM, and CCM); the wiring would be 4x 2- conductor
- 2O in the breaker control circuit indicates two control connections (trip and close); the wiring would be 2x 2-conductor

By examining the shaded areas in Figure 8, we can see the following:

- The design of the MU connectivity about the breakers in the 1.5CB diagonals is identical, except the tagging (light green shading)
- The design of the MU connectivity about the middle breakers in the 1.5CB diagonals is identical, except for the tagging (light yellow shading)
- The design of the MU connectivity about the capacitors that support each bus are identical, except for the tagging (light blue shading)

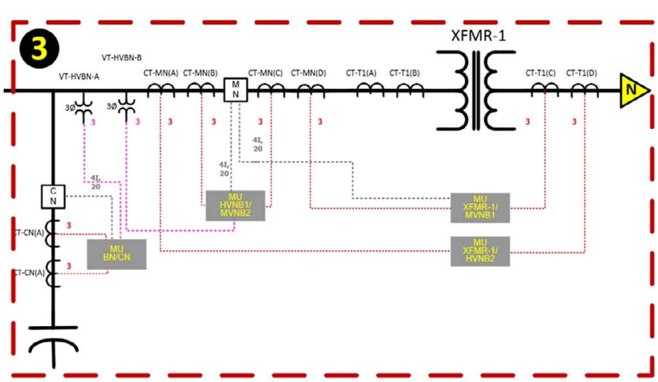


Fig. 7: MU Connectivity for a Transformer

MU COVERAGE

Zone	MU Tag	MU Tag
XFMR-1 PRI Current	HVNB-1/HVNB-2	XFMR-1/NVNB-2
XFMR-1 SEC Current	XFMR-1/MVNB-1	XFMR-1/HVNB-2
XFMR-1 PRI Voltage	HVNB-1/MVNB-2	BN/CN
Breaker MN	HVNB-1/MVNB-2	XFMR-1/MVNB-1

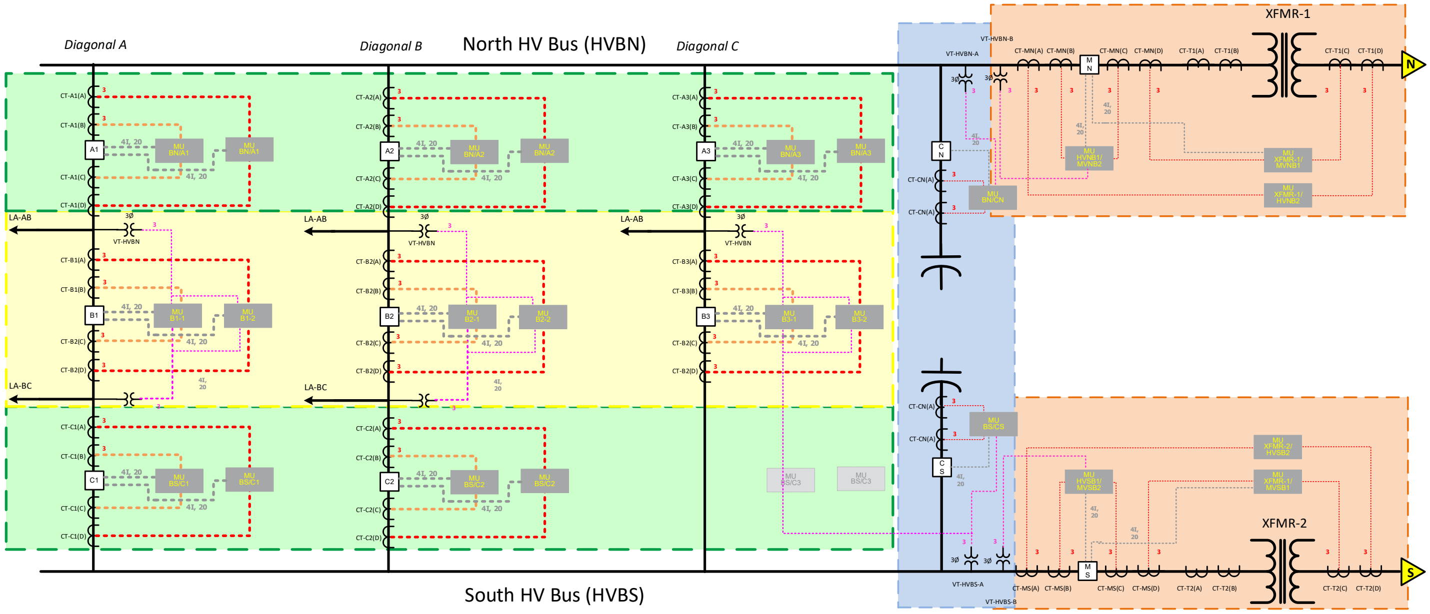


Fig. 8: Identical Yard-to-MU Connectivity Zones

- The design of the MU connectivity about the transformer that connect the high voltage and medium sections of the substation are identical, except for the tagging (light orange shading)

In Figure 9, non-redundant MUs are applied on the 13.8kV medium voltage section of the substation. The MU connectivity is shared for two breakers, that is, one MU is used to sense and control a given breaker and the yard elements associated with that breaker.

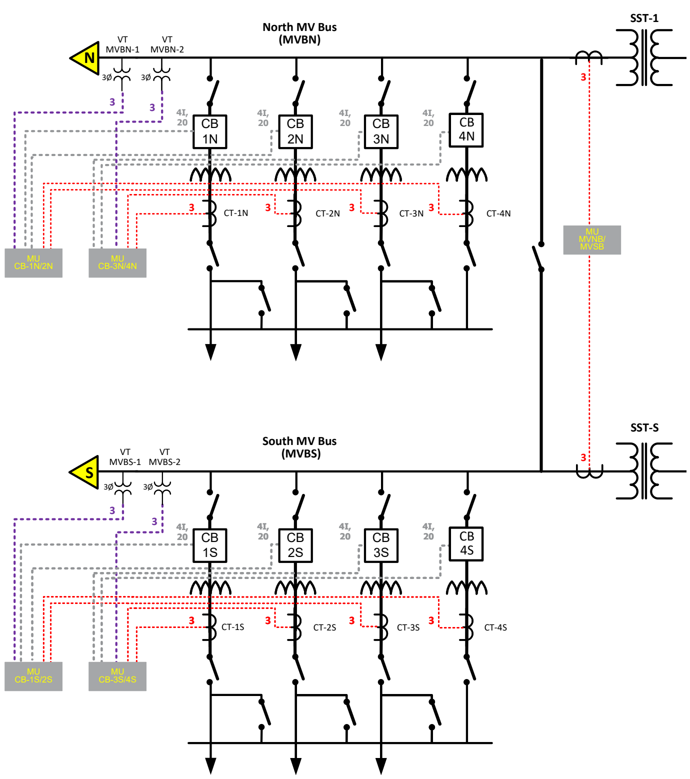


Fig. 9: Medium Voltage Section for Deeper Examination

Figure 10 shows a typical MU connectivity diagram for the medium voltage north bus feeders of the substation. In this application, non-redundant MUs (single MU per feeder) are applied. The connectivity to MU CB 1N/2N is identical to the connectivity of MU CB 3N/4N.

- “3” in the CT connection indicates A, B, and C phases; the wiring would be 4-conductor A, B, C, and N
- “3” in the VT connection indicates A, B, and C phases; the wiring would be 4-conductor A, B, C, and N
- 4I in the breaker control circuit indicates four status connections (a, b, TCM, and CCM); the wiring would be 4x 2- conductor
- 2O in the breaker control circuit indicates two control connections (trip and close); the wiring would be 2x 2- conductor

By examining the shaded areas in Figure 11, we can see the following:

- The design of the MU connectivity for the north bus breakers and the south bus breakers is identical

Now that we have explored the MU connectivity of the entire station, we can see how using standard connectivity facilitates the development of SLD diagrams. As we will explore in the next section, the standardization flows into the development of standardized design of the AC 3-line diagrams and the DC elementary diagrams.

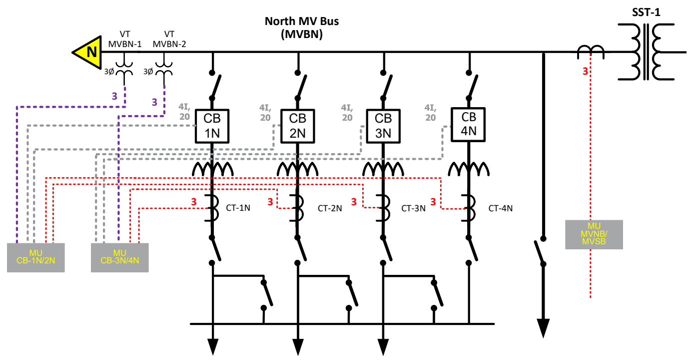


Fig. 10: MU Connectivity for North Bus Feeders

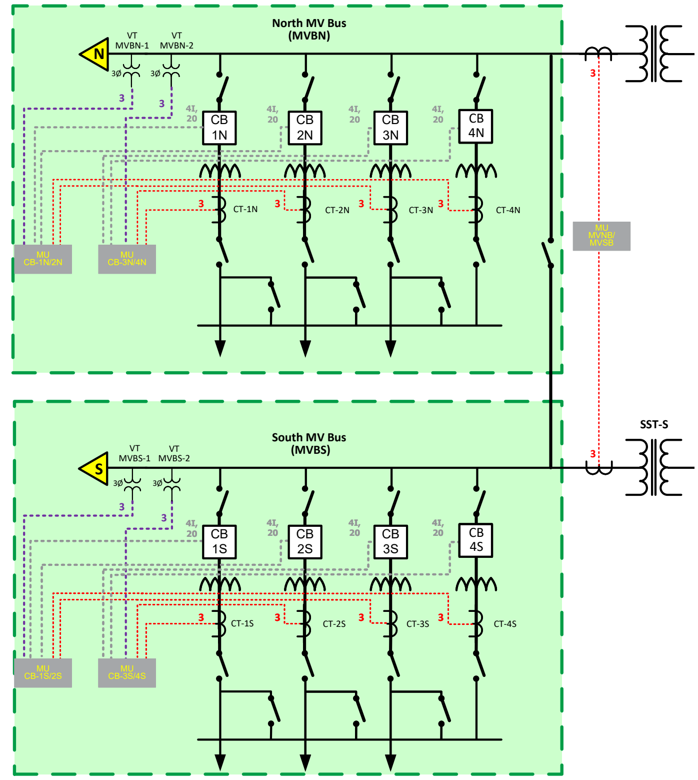


Fig. 11: Identical Yard-to-MU Connectivity

MU Enclosure Grouping and Placement

Figures 12 and 13 show the grouping of MUs into enclosures. This follows the optimization of MU use with respect to redundancy requirements, connectivity requirements, and locational requirements to ensure short wiring runs and a smaller MU enclosure footprint.

We have three identical MU enclosure designs for the high voltage 1.5CB diagonal sections: one enclosure for the transformer and capacitor area and one enclosure for the medium voltage buses.

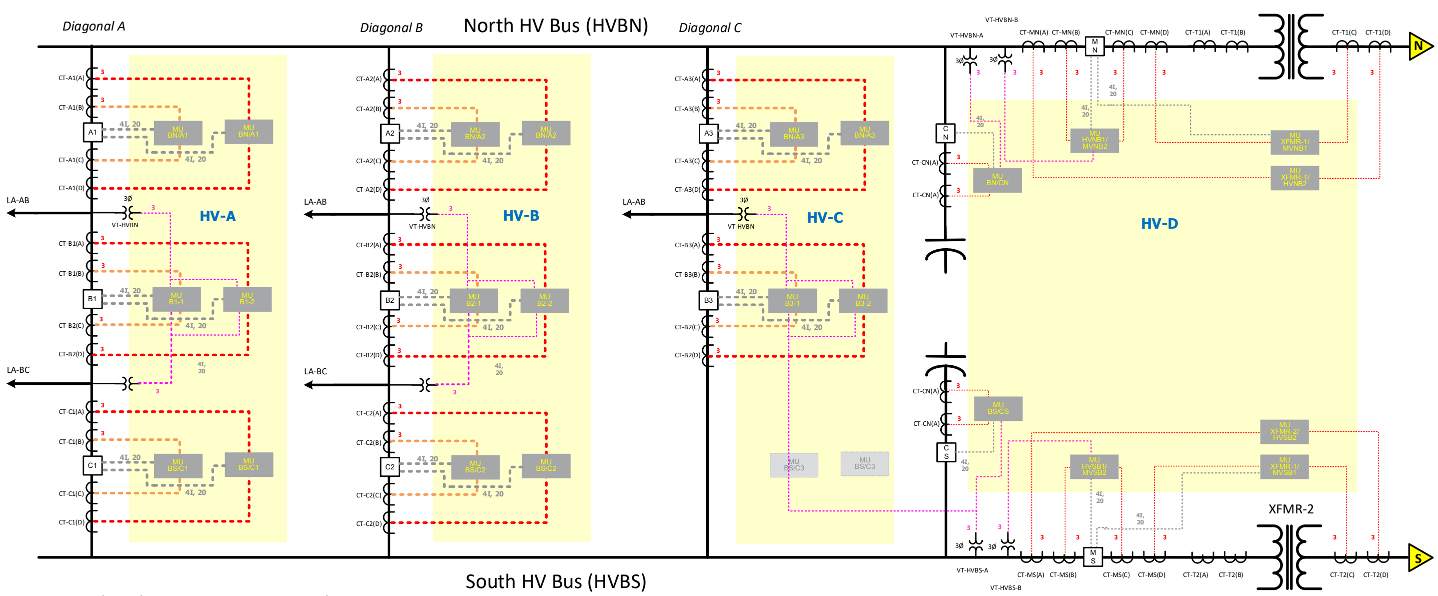


Fig. 12: High Voltage Section MU Enclosure Grouping

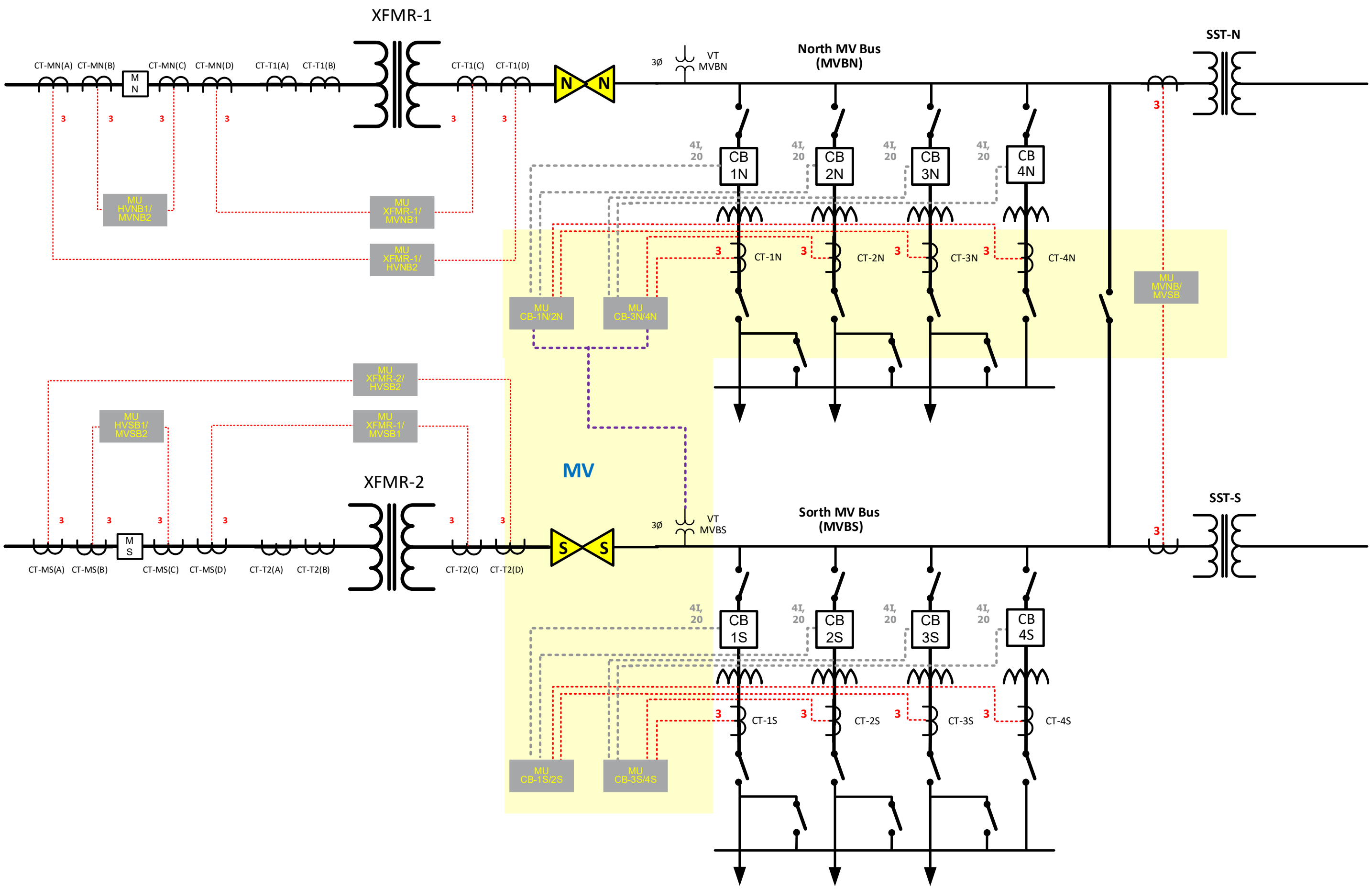


Fig. 13: Medium Voltage Section MU Enclosure Grouping

Enclosure Tag	MUs in Enclosure	Description
HV-A	6	MUs for Diagonal 1
HV-B	6	MUs for Diagonal 2
HV-C	6	MUs for Diagonal 3
HV-D	8	MUs for the Transformers and Capacitor Banks
MV	5	MUs for North and South Buses/Feeders

Standardization of AC 3-Line and DC Elementary Diagrams

Using the SLD developed in Section 4, we can now turn to the design of the actual point-to-point wiring from the yard elements to the MUs. By following standard designs, not only is the engineering of the MU enclosures reduced, but their fabrication becomes identical. It is possible, depending on the grouping of the MUs into enclosures, to have a few standard MU enclosures to design and fabricate. This leads to decreased engineering and fabrication costs.

Figure 14 shows a single MU with FT type test switches connected to a single CT set and a single VT set.

Note how the six wires (A-N, B-N, C-N) for the instrument transformers are reduced to four wires in the yard equipment cabinet (breaker cabinet for CTs and VT terminal box for VTs). The four wires are the yard-to-MU connectivity for each of these circuits. With the proper MU enclosure placement, these runs of wire may be short (between 20 feet and 50 feet) depending on air insulated substation clearances and substation arrangement. In the case of SF6 or metal-clad switchgear substation designs, these wiring runs may be very short (between 5 feet and 15 feet).

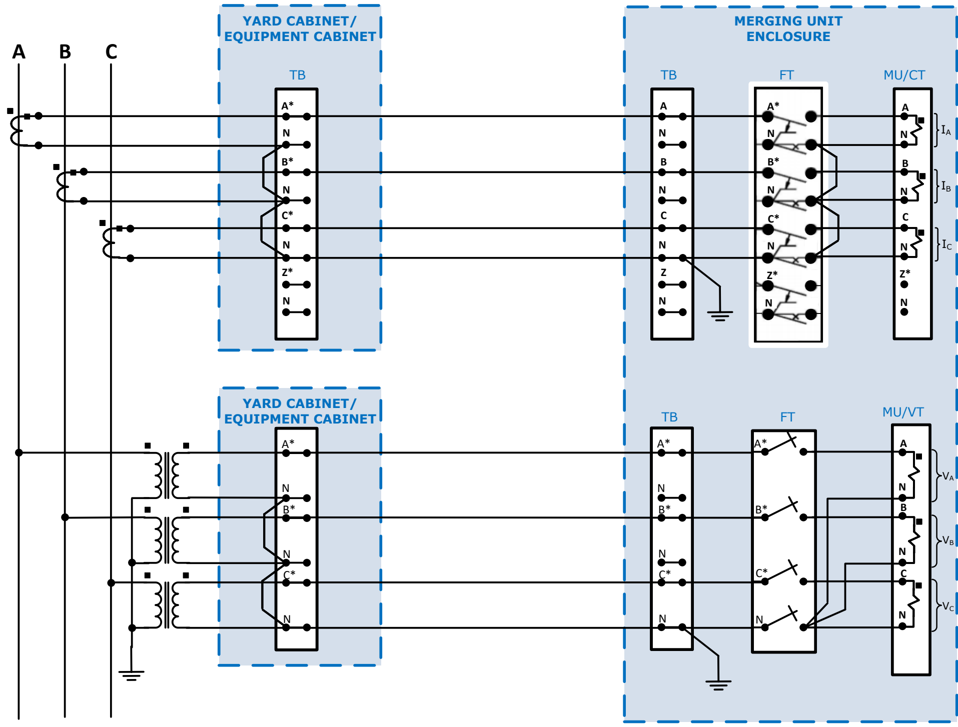


Fig. 14: AC 3-Line for One MU with FT Switches, a VT Set, and a CT Set

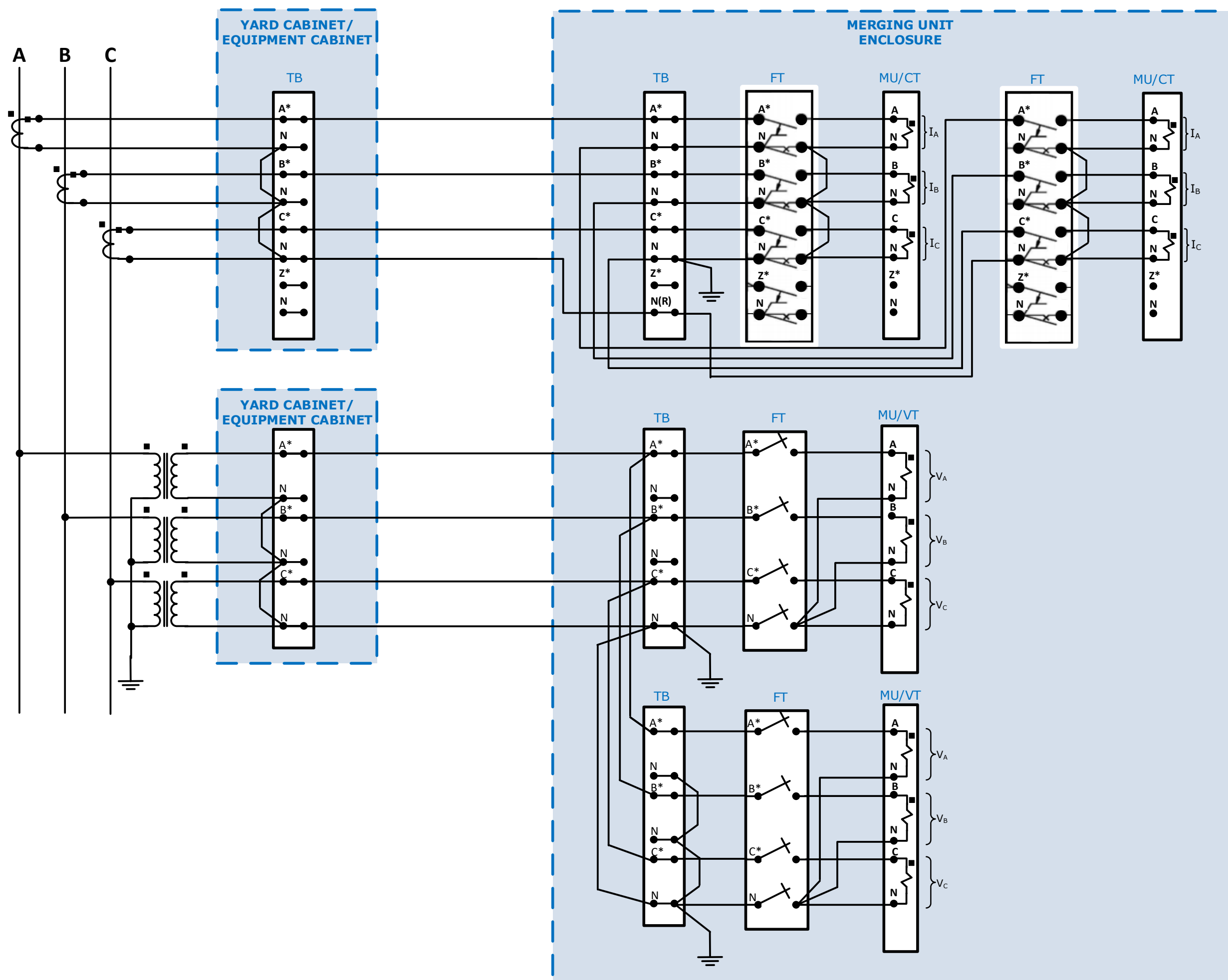


Fig. 15: AC 3-Line for Two MUs with FT Switches, a VT Set, and a CT Set

Figure 15 shows two MUs with FT switches connected to a single CT set and a single VT set.

Use of two MUs would support redundant connectivity for the CT set and VT set. The design of the wiring from the instrument transformers to the MU enclosure terminal blocks are identical to those in Figure 14. Inside the MU cabinet, the CT wiring is a series loop to provide current to the two MUs and their associated FT switches. The VT wiring is a parallel connection to provide voltages to the two MUs and their associated FT switches. Note that each connection from the MU terminal block to the respective FT/MU inputs is identical, and identical to that of Figure 14.

Figure 16 shows two MUs with FT switches connected two CT sets and a single VT set.

Use of two MUs would support redundant connectivity for a CT set and a VT set. The design of the wiring from the instrument transformers to the MU enclosure terminal blocks are identical to those in Figure 14. Inside the MU cabinet, the CT wiring is a series loop to provide current to the two MUs and their associated FT switches. The VT wiring is a parallel connection to provide voltages to the two MUs and their associated FT switches. Note that each connection from the MU terminal block to the respective FT/MU inputs is identical, and identical to that of Figure 14.

One could envision other standard arrangements for other CT, VT, and redundancy requirements. The concept is to develop the standards needed for a given project or application and reduce the engineering and fabrication costs.

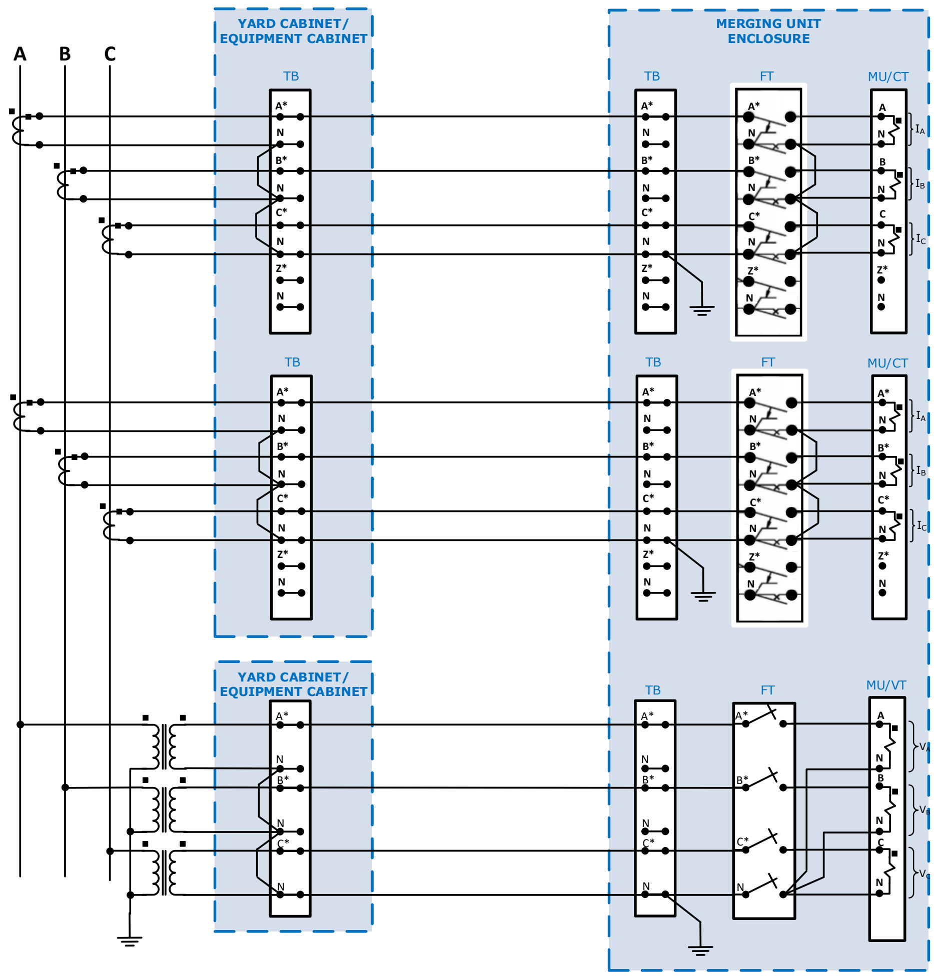


Fig. 16: AC 3-Line for Two MUs with FT Switches, a Single VT Set, and Two CT Sets

Standardization of DC Elementary Diagrams

Using the same general guidance as in Section 6 and the SLD developed in Section 4, we can now develop the DC elementary diagrams.

Figure 17 shows a single MU with FT switches connected to a single battery and single trip/close circuit breaker.

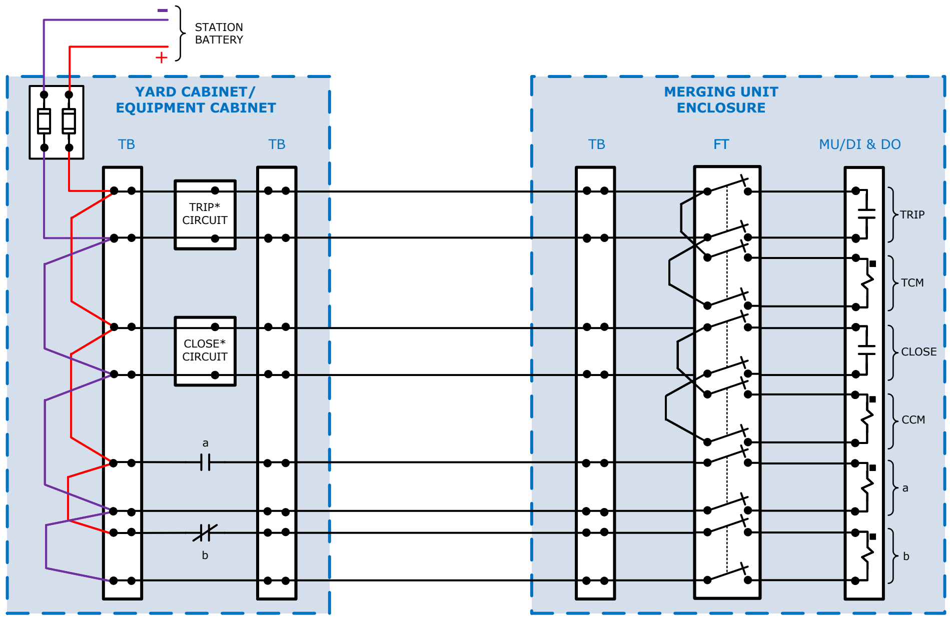


Fig. 17: DC Elementary Diagram for a Single MU, Single Battery, and Single Trip/Close Circuit Breaker

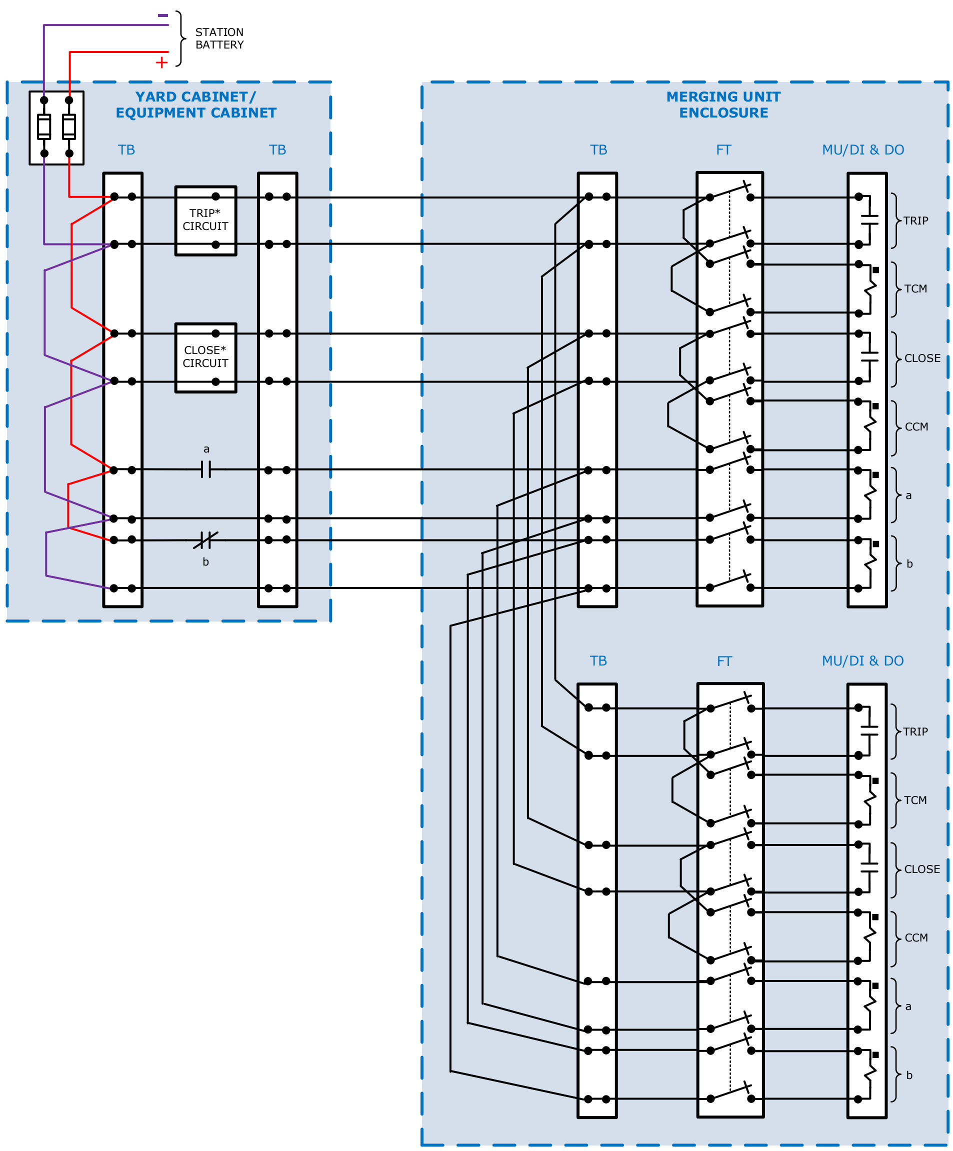


Fig. 18: DC Elementary Diagram for Two MU, Single Battery, Single Trip/Close Circuit Breakers

Note the trip circuit monitoring (TCM) and the closed-circuit monitoring (CCM) inputs are connected in parallel with the trip and close contacts at the MU. This eliminates having to run two additional two-conductor cables to the breaker for interface.

Figure 18 shows two MUs with FT switches connected to a single battery and single trip/close circuit breaker. The circuits to the two MUs are duplicates.

Note the TCM and CCM inputs are connected in parallel with the trip and close contacts at the two MUs. This eliminates having to run four additional two-conductor cables to the breaker for interface.

Figure 19 shows two MUs with FT switches connected to a dual battery and dual trip/close circuit breaker. The circuits to the two MUs are duplicates.

Note the TCM and CCM inputs are paralleled with the trip and close contacts at the two MUs. This eliminates having to run four additional two-conductor cables to the breaker for interface.

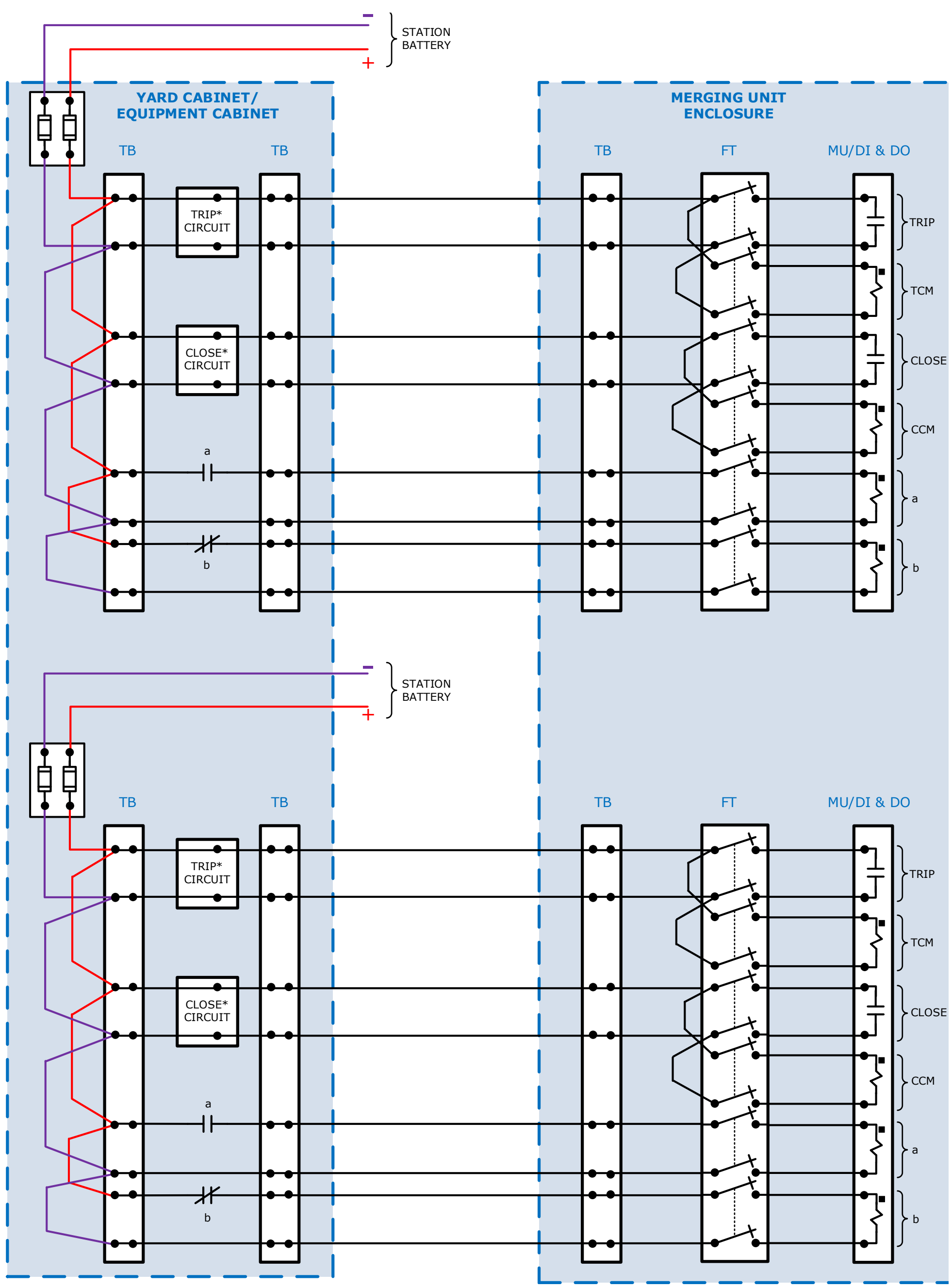


Fig. 18: DC Elementary Diagram for Two MU, Single Battery, Single Trip/Close Circuit Breakers

Distributed Lockout Function

In hardwired substations, we typically employ electromechanical lockout relays (LOR) for the lockout function (LOF). With a digital substation design, a LOF can be created in a distributed style using the MUs.

Per C37.2, "IEEE Standard Electrical Power System Device Function Numbers, Acronyms, and Contact Designations," the standard reference position for a LOR is reset. This is opposite of how we usually define standard reference as a device in the open or low position.

To meet the standard reference with MU LOF:

- The lockout trip contact should be open (non-trip)
- The lockout close permissive contact should be closed (allowing continuity)

To show an "a" contact in an operational state, including standard reference, as closed, we use a dual-headed arrow to indicate the "a" is closed. To show "b" contact in an operational state, including standard reference, as open, we use a dashed circle to indicate the "b" is open. In the LOF developments, we only use "a" contacts in the MU. Figure 20 shows an MU-based LOF in standard reference.

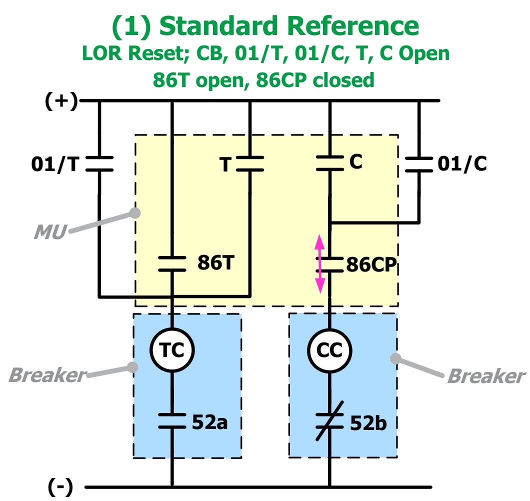
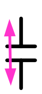


Fig. 20: MU-based LOF in Standard Reference

 *"a" contact that is closed in scenario*

 *"b" contact that is open in scenario*

86T *Lockout function "a" contact used in breaker trip circuit to trip the breaker*

86CP *Lockout function "a" contact used in breaker close circuit as close permissive*

43T, 43C *Manual trip, manual close (not controlled by lockout function)*

T *Non-lockout trip contact(s) from relays, SCADA, other*

C *Close contact(s) from relays, SCADA, other, that use LOR Close Permissive*

TC, CC *Trip coil, Close coil*

Figure 21 shows three states of the LOF.

Standard reference has already been discussed.

CB Closed/86 Reset has the close permissive closed, and the closed breaker "a" and "b" contacts indicating closed and open, respectively.

CB Closed/86 Lockout has the close permissive opened, and the still closed breaker "a" and "b" contacts indicating closed and open, respectively (the breaker has not yet tripped, the LOF trip contact has just closed).

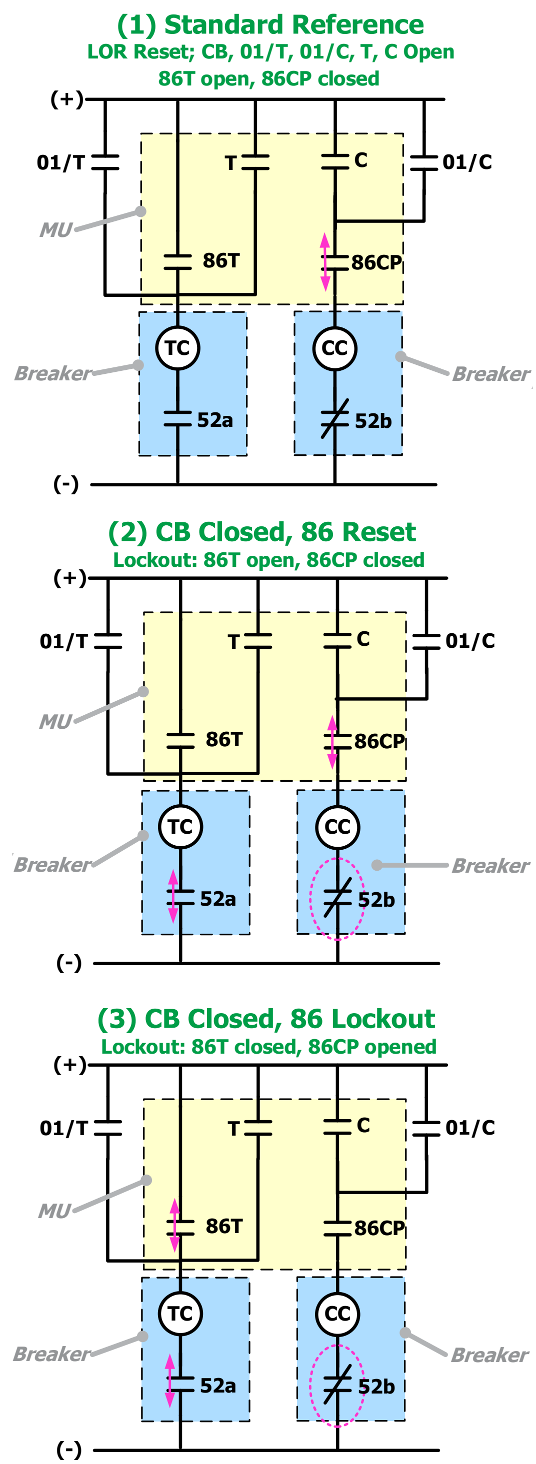


Fig. 21: MU-based LOF in Standard Reference, CB Closed/86 Reset and CB Closed/86 Lockout Conditions

Figure 22 shows three states of the LOF.

CB Opened/86 Lockout has the close permissive opened, the LOF trip closed, and tripped breaker "a" and "b" contacts indicating opened and open, respectively.

CB Closed/86 Lockout has the close permissive opened and the closed breaker "a" and "b" contacts indicating closed and opened and closed, respectively (the breaker has tripped from the LOF trip contact closing).

With a power or communications failure to the MU, all LOF contacts open. The breaker remains in its last state. Upon repowering or reestablishment of communications, the MU will either enter a lockout state or normal non-lockout state depending on commands from the relays that use the given MU for lockout purposes.

- If the power or communications failure occurs while the breaker was in lockout, upon reestablishment of power or communications, the trip permissive would remain open, and the lockout trip contact would again close.
- If the power or communications failure occurs while the breaker was not locked out, upon reestablishment of power or communications, the trip permissive would close, and the lockout trip contact would remain open.

Figure 23 shows three states of the LOF like Figure 20.

Figure 24 shows three states of the LOF like Figure 21.

What has been added in Figures 22 and 23 are 43M/A and 01/T-C switches that are hardwired from the control house to the MUs. In a brownfield application, where the wires already exist, one can employ combinations of process bus and hardwire if desired.

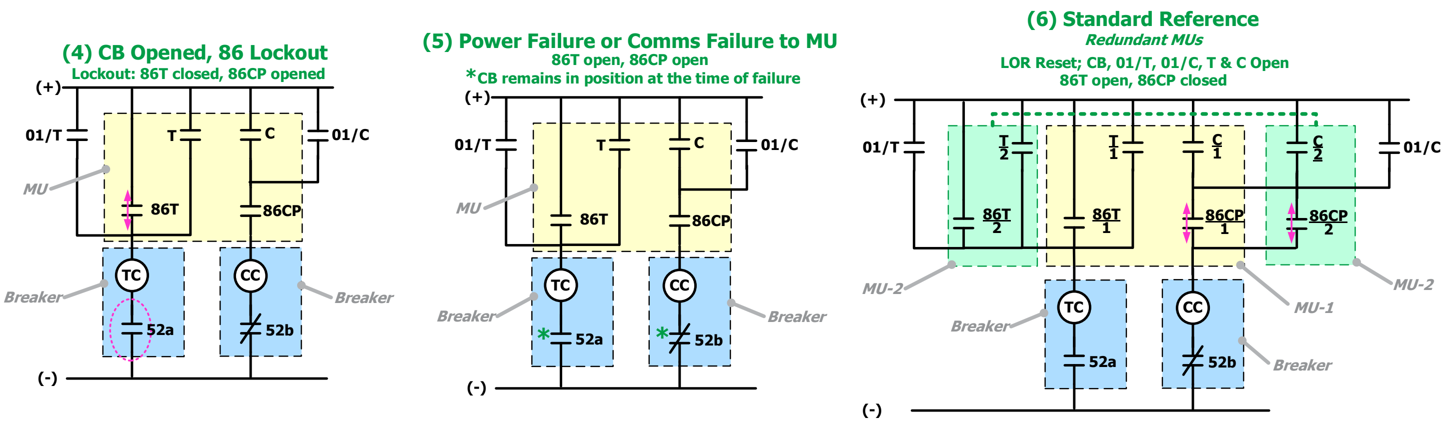


Fig. 22: MU-based LOF in CB Opened/86 Lockout, Power or Communications Failure to MU, and the Use of Dual MUs for LOF in Standard Reference

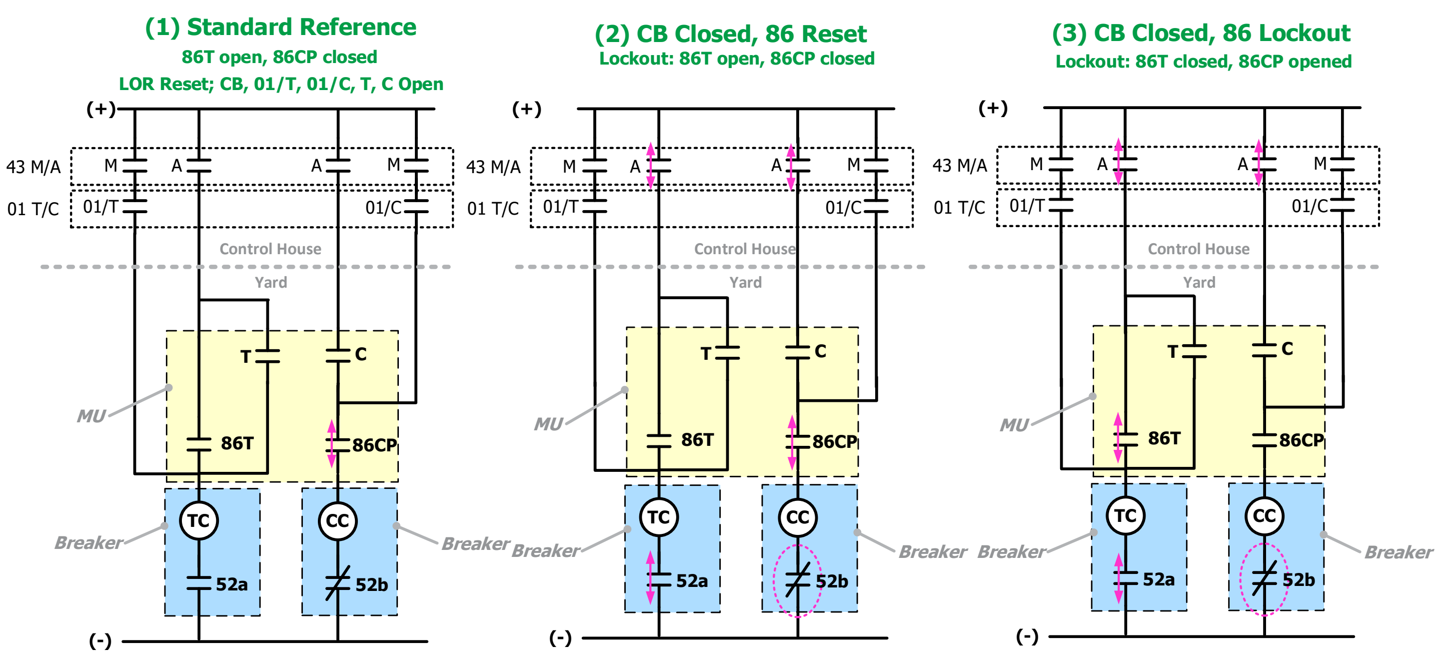


Fig. 23: MU-based LOF in Standard Reference, CB Closed/86 Reset, CB Closed/86 Lockout, and the Use of Dual MUs for LOF in Standard Reference, All With 43M/A and 01/T-C Switches

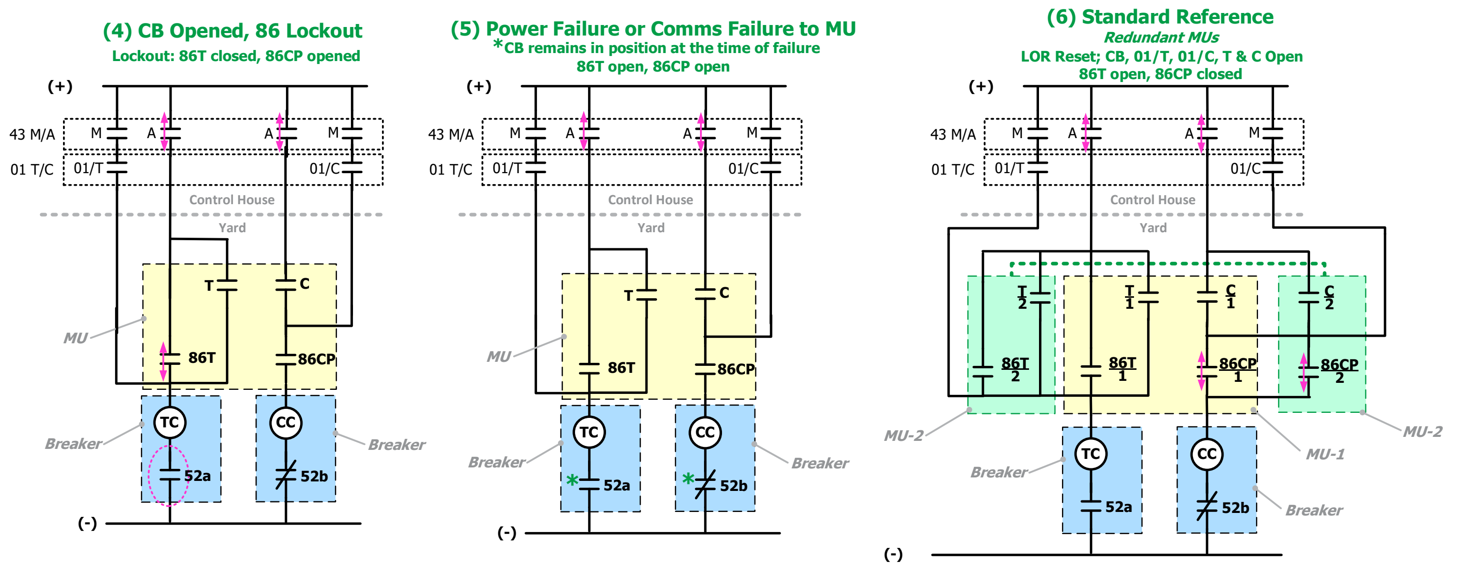


Fig. 24: MU-based LOF with CB Opened/86 Lockout, Power or Communications Failure, and the Use of Dual MUs for LOF, All With 43M/A and 01/T-C Switches

Aside from the addition of the hardwired switches, the operation of the LOF is the same as the sequences without the hardwired switches.

Figure 25 shows the use of a low contact density lockout relay working with a protective relay to integrate with the distributed LOF. Certain operational environments may mandate the use of a traditional lockout relay for observation of targeting and manual reset.

When the protective relay declares a lockout condition, the lockout signal is sent to the MU(s) that should act on it. In addition, when using an output on the protective relay, the lockout is tripped into the lockout state. The lockout close permissive contact is brought to a protective relay input where it will block the lockout function resetting until the electromechanical lockout relay is reset. This gives operations personnel the same functionality that they are accustomed to and helps to ease the change management aspect of the distributed lockout function.

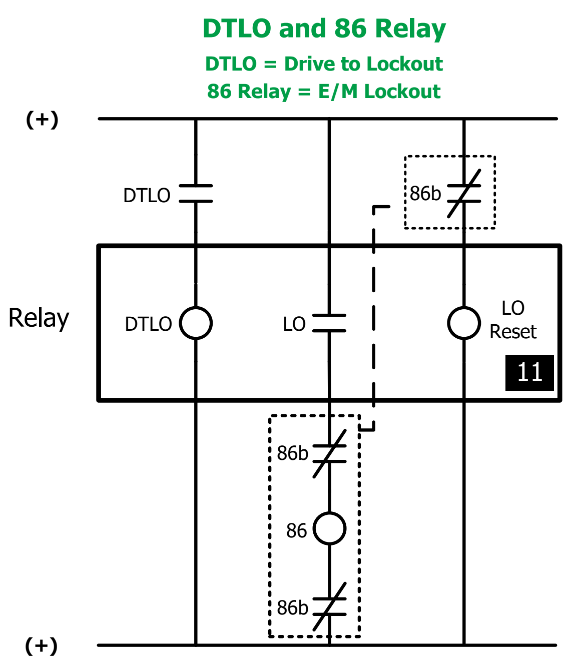


Fig. 25: Use of Low-Contact Density Panel Mounted Lockout Switch for Switched-Based Targeting and Reset

Redundancy Improvements

In hardwired designs, when one requires redundant protection, a System A and System B may be installed. The two systems may use identical protection, or they may use different principles, such as a line distance and line differential protection. The redundancy concept is typically employed from instrument transformer to relay to trip/close circuits in hardwire designs.

In digital substation designs, the concept extends to instrument transformer, MUs, relays, and trip/close circuits.

In hardwire designs, if an instrument transformer or associated wiring is compromised, the relay dependent on it will typically block affected protections, rendering the relay non-functional until the issue with instrument transformer is resolved. In digital substation designs, countermeasures can be implemented to keep the associated relay in-service by switching sampled value input to another MU. This is where the use of redundant MUs provides redundancy improvements. Figure 26 shows such a development of redundant MUs and CTs at the same electrical nodes.

Protection System A is connected to MU T-A, which is connected to CT-T-1A and CT-T-2A. Protection System B is connected to MU T-B, which is connected to CT-T-1B and CT-T-2B. There is redundant coverage for the nodes about CB-T.

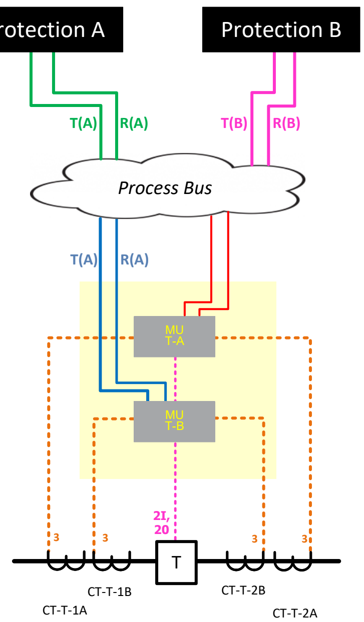


Fig. 26: Redundant Systems A & B Using CTs, MUs, and Relays

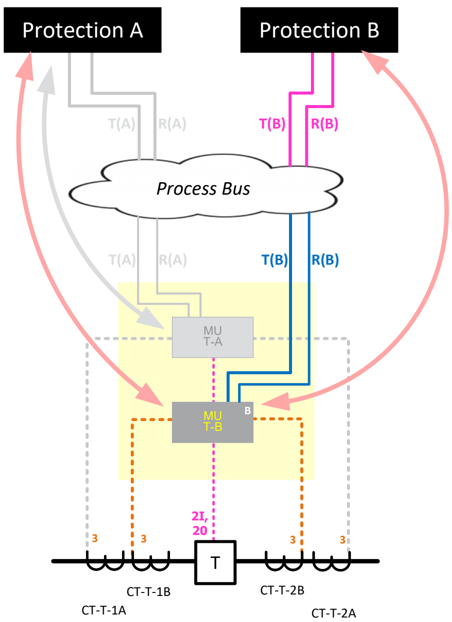


Fig. 27: MU T-A Failure with Relay A Employing Crosscheck with MU Switchover to MU T-B

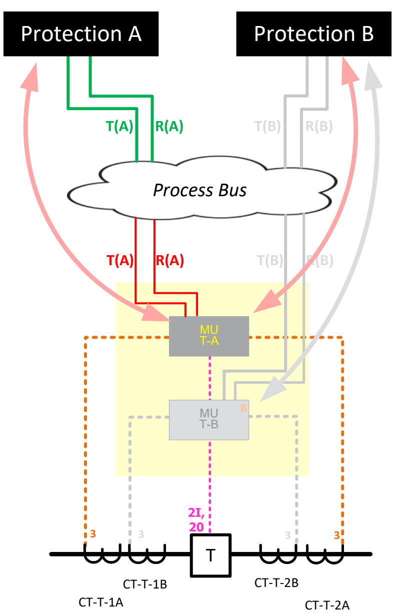


Fig. 28: MU T-B Failure with Relay B Employing Crosscheck with MU Switchover to MU T-A

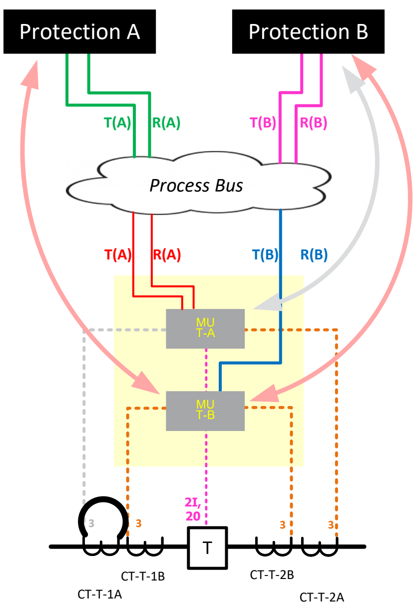


Fig. 29: CT-T-1A Failure with Relay A Employing MU Switchover to MU T-A

In Figure 27, MU T-A fails. The failure is sensed by Relay A and Relay A switches to MU T-B.

In Figure 28, MU T-B fails. The failure is sensed by Relay B and Relay B switches to MU T-A.

In Figure 29, CT-T-1A shorts. Relay A detects the anomaly using cross-checking, blocks operation, and raises an alarm.

Centralization and Hybrid Redundancy

Centralization is the use a of multizonal, multifunction protection platform, versus a single multifunction function relay per zone.

- One can have full centralization, where two computing platforms virtualize the protection for the entire substation.
- One can employ partial centralization, where certain zones of a substation protection scheme are consolidated into one platform.

A method to use partial centralization to save on application costs is to employ a hybrid redundancy scheme. This can be used to save on costs in non-critical applications, such as low-impact distribution feeders.

Figure 30 shows an example of hybrid redundancy using partial centralization. Our example is a M-T-M, with Bus A and Bus B, each bus with four feeders, a source breaker, and a common tie breaker.

- Bus A, primary overcurrent:
  - A multifunction feeder relay is employed at each individual feeder position, main and tie.
- Backup overcurrent and primary/backup 87B:
  - A multifunction, multizonal relay is applied at the six nodes for each bus, providing:
    - Backup feeder protection for the main, feeders, and common tie
    - Primary 87B for one bus section
    - Backup 87B for the other bus section

The two multifunction, multizonal systems providing the backup overcurrent and bus protections are shown with dashed boxes around them. The primary individual multifunction feeder relays at each feeder, main, and tie position are omitted for clarity.

Redundancy analysis:

- If any given primary multifunction feeder relay fails, the multifunction multizonal backup overcurrent elements provide protection.
- If any given primary bus protection and backup overcurrent multifunction, multizonal relay fails, the other multifunction, multizonal bus protection system can provide bus protection. The primary multifunction feeder relays remain, providing protection for their respective feeder positions.

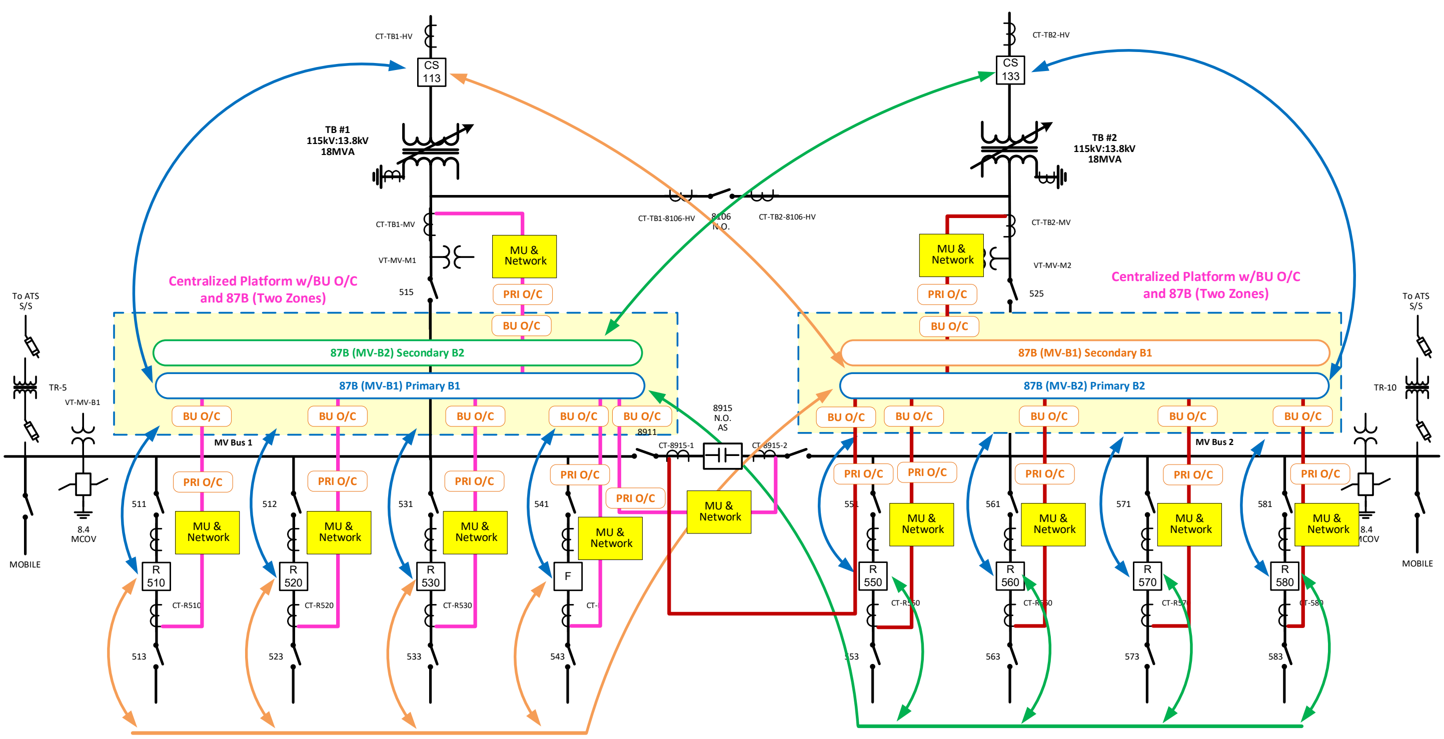


Fig. 30: Centralization and Hybrid Redundancy Example

Summary and Conclusions

- "Begin with the end in mind." The end state of your digital substation should be a consistent, standardized design.
- Build the SLD with yard-to-MU connectivity that promotes standardization
- AC 3-line and DC elementaries will also then enjoy standard designs
- A distributed lockout function can be employed with process bus design and MUs
- Hybrid designs combining hardwire and process bus are possible, especially in brownfield applications where hardwires may already exist
- Improved redundancy for MU and IT failures can be addressed with redundant MU systems, redundant electrical node connectivity, and relays capable of detecting anomalies in the ITs and MUs and switching MU sources
- As one of its attributes, centralization allows economical application of primary and backup functions.

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Wayne also contributed to McGraw-Hill's Standard Handbook of Power Plant Engineering.

Acknowledgments

The author thanks his wife, Lisa, for giving him the time on nights and weekends to produce this paper.

The author also thanks Peter Hoffman and the Operation and Automaton Standards Group at Duke Energy (Charlotte) for the time we worked together and the opportunity to learn what standard development is from inside a utility.

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