Digital Substation Application Concepts for IBR Renewable Energy Plants

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Wayne Hartmann
Advanced Applications Advisor
GE VERNOVA
wayne.hartmann@ge.com

Mike Ramlachan
Lead Technical Application Engineer
GE VERNOVA
ravindranauth.ramlachan@ge.com

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1] Abstract

With the fast-tracked planned installations of Utility-Scale Inverter-Based Resource (IBR) Power Plants to the bulk power system, utilities, consultants, EPCs and developers are all seeking methods to standardize P&C designs and hasten execution. Many of these power plant designs incorporate a high voltage (HV) section or sections, pooling bus (PLB) section or sections and collector bus (CLB) sections. This paper will explore a typical power plant incorporating all these sections and suggest architectures for standardized yard-to-merging unit connectivity. As most of these power plants follow standardized approaches for the power infrastructure, the P&C also can provide a high degree of standardization.

2] Introduction: Collector Buses and Pooling Buses

CLBs and PLBs are used in renewable power plants such as wind or photovoltaic (PV) power stations to manage the power flow from the generation source to the transmission grid.
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In these distributed generation projects, power is produced by many individual sources, like wind turbines or solar panels. Each of these sources generates a relatively small amount of power at low voltage or lower medium voltage level (480V-4,160V). The collector substation aggregates this power and combines into a major block of power at a higher medium voltage (13.8kV-69kV). These major blocks of power are then combined into an output that can be fed into the transmission grid at HV level (115kV-230kV+).

This process is crucial because it allows the power generated by the individual sources to be efficiently transmitted and distributed to load centers. Without CLBs and PLBs, it would be difficult to manage and utilize the power generated by these distributed sources. CLBs and PLBs serve as critical links between the renewable power sources and the main power grid.

Factors to consider in CLB and PLB designs are:

- The design seeks to minimize losses and voltage drops within budgetary constraints.
- Factors considered in interconnecting cable design cost, real power losses, and voltage drop. A typical design goal is to keep average real power losses below 1%. At full output, real power losses can be as much as 2 to 4%. Interconnecting cabling from IBR sources to the collector buses and to step up transformers between the collector and pooling buses is typically underground.
- Metal-clad switchgear in weatherproof enclosures is often used for CLBs at 15kV and below.
- PLBs, at higher medium voltage levels, are typically outdoor air insulated design using vacuum breakers

In Figure 1, we compare and contrast a traditional Utility-scale powerplant with a single power source and an IBR renewable plant with the 100s of smaller energy sources.

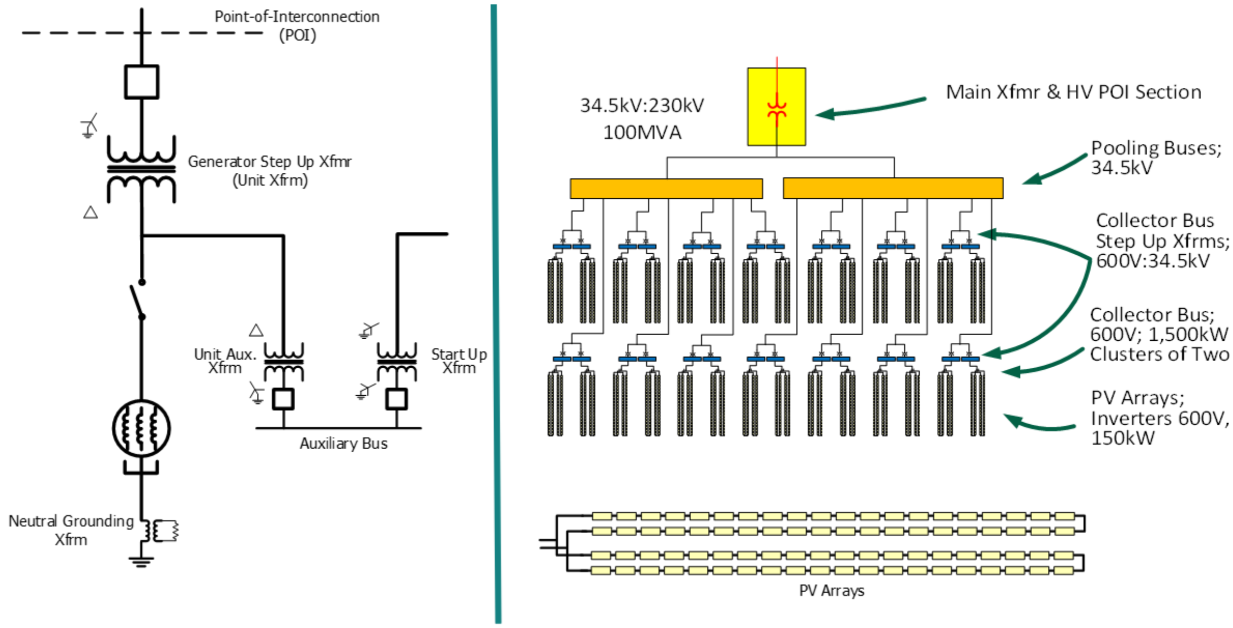


Fig. 1, Comparison of Traditional and IBR Renewable Powerplants

3] Quick Review of Digital Substation (DS)

A DS involves the use the merging units (MUs) to connect to yard elements (CT, VT, 52, 89, other), digitizing the data, then communicate with relays in the control house over fiberoptic cable. For this exploration, we are using a redundant networked 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 or zone information used for interlocking, breaker failure, protection modification and other uses are performed over "station bus" network.

Figure 2 shows a simplistic view of the arrangement described above.

We will make use of the standard infrastructure topology to develop a standard approach to the protection schemes using Digital Substation techniques, in particular, centralization.

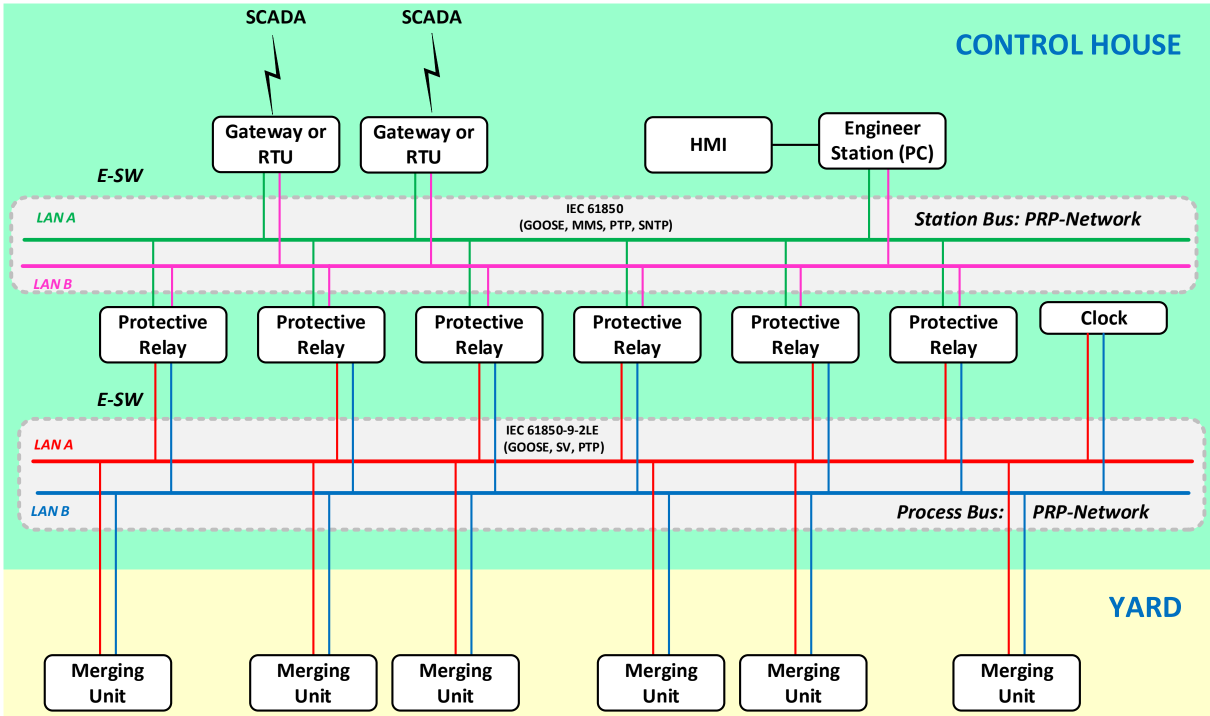


Fig. 2, Typical Block Diagram of a Digital Substation

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. Reason for this may be incompatibility of the yard element with the process bus, or philosophic choice to have some hardwire instead of or to supplement the process bus connected yard elements.

Why a Digital Substation?

- Opportunity for improved indices due to improved redundancy tactics
- Extends testing intervals (NERC PRC-005), provides greater protection system visibility
- Improves safety
- Can improve commissioning practices and reduce cost (OPEX)
- Can improve maintenance practices and reduce cost (OPEX)
- Eliminates wiring runs from the yard elements to the control house sited relay panels (CAPEX, signal integrity)
- With centralized designs, decrease the quantity of protection systems applied by 50%-75% or more.
- Decrease in wire, terminations, trenching and conduit (CAPEX)
- Decrease in engineering and labor associated with above and relay panels (CAPEX)
- Large opportunity for standardization in design reducing engineering hours (CAPEX)

4] Example Utility-Scale IBR Renewable Plant

An example Utility-Scale Solar Plant is shown in Figure 3. The plants various buses and voltage levels are listed below:

- Two [2] PLBs are used, each with seven [7] sources. AIS, Outdoor CBs.
- The PBLs are identical
- Seven [7] identical sources each PLB input
- The 28 CLBs are identical. LV Switchboards in weather-proof enclosures
- CLB connections are [10] 150kW, 600V inverters, a feeder to supply auxiliary power, and one output to CLB Step Up Xfmr.
- Two CLBs are grouped per PLB input
- Two PLBs input into the Main Xfmr

We will make use of the standard infrastructure topology to develop a standard approach to the protection schemes using Digital Substation techniques.

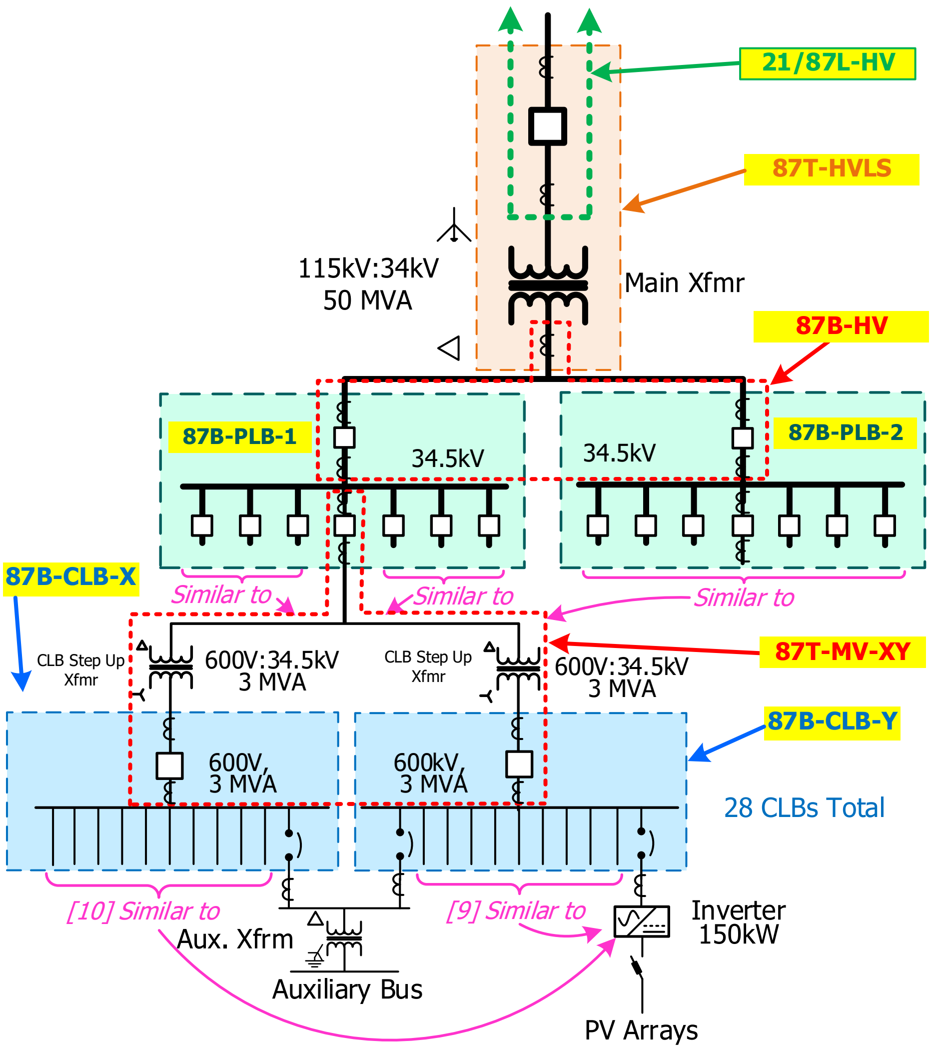


Fig. 3, Example Utility-Scale Solar Plant

5] Protection Philosophy and Design

An economical protection method to employ with the Collector and Pooling Buses is the use of partially centralized systems. Partially centralized systems combine an element suite for a given zone or zones of protection, plus multizonality, that is, protecting different zones with the same protection system.

For our study, we will assume use of two protection systems for application in partially centralized distribution protection schemes:

- A transformer protection system that can cover <=6 nodes, employing a definable and selectable transformer differential zone, with all nodes employing overcurrent, voltage and frequency elements. This is referred to as System #1.
- A combination bus/feeder, main, tie CB protection system that can cover <=28 nodes of primary bus differential protection with phase and neutral/ground overcurrent, overvoltage, neutral overvoltage and breaker failure protections for each node. The differential protection may be divided into <=3 zones. This is referred to as System #2.

Single line drawings (SLD) of two systems follow in Figures 4, 5, 6 and 7:

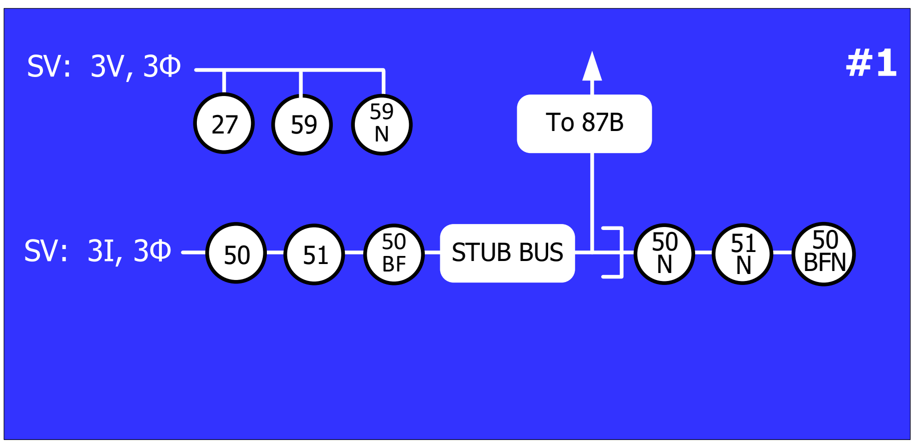


Fig. 4, System #1, Multifunction, Multizonal (Centralized) Transformer Differential and Feeder/Main/Tie Protection System SLD

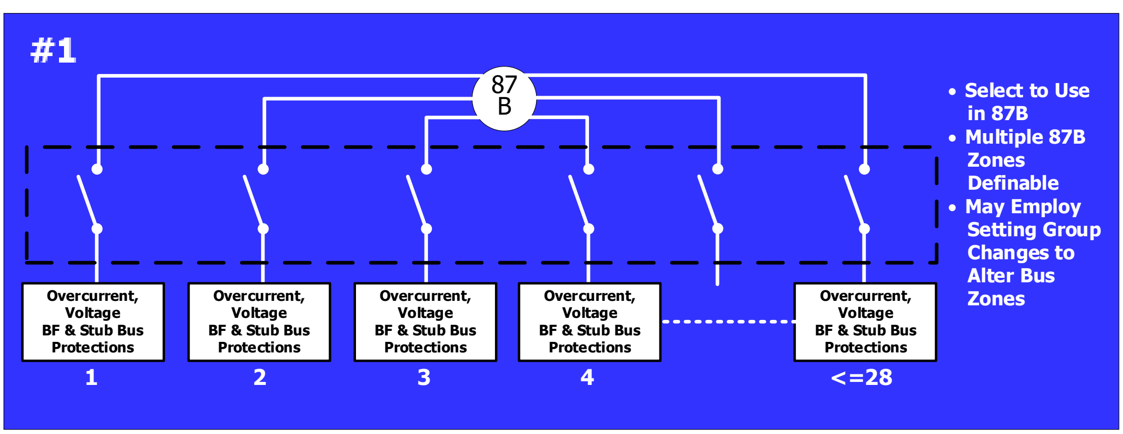


Fig. 5, System #1, 87T Selectivity for Multifunction, Multizonal (Centralized) Bus Differential and Feeder/Main/Tie Protection System

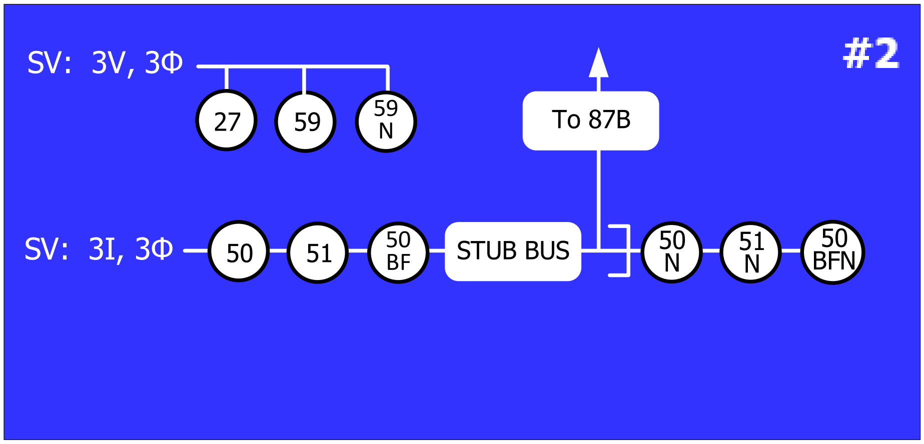


Fig. 6, System #2, Multifunction, Multizonal (Centralized) Bus Differential and Feeder/Main/Tie Protection System SLD

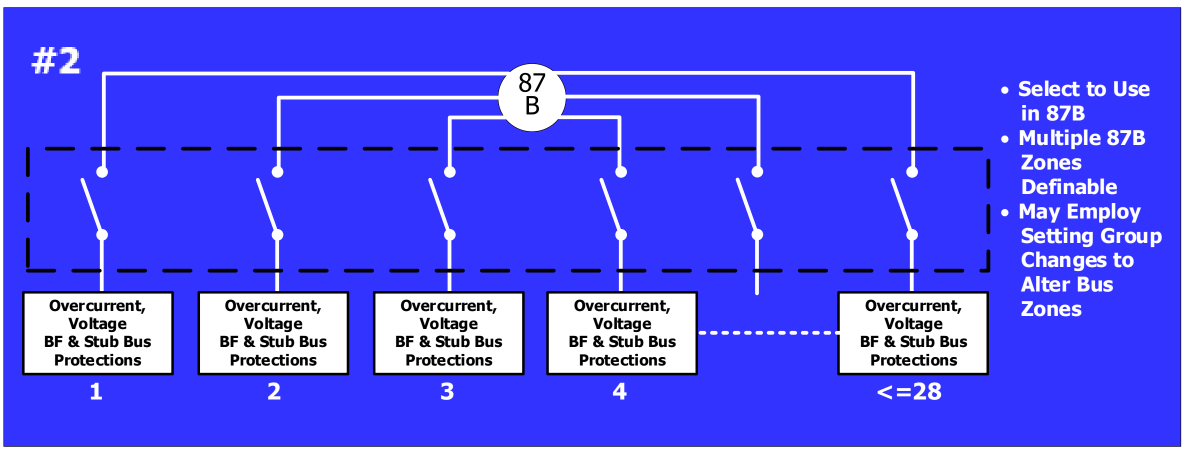


Fig. 7, System #2, 87B Selectivity for Multifunction, Multizonal (Centralized) Bus Differential and Feeder/Main/Tie Protection System

CLB and CLB Step Up Xfrm MU Application

Figure 8 shows an overall SLD for a set of two CLBs and a partial of the PLB it is connected to.

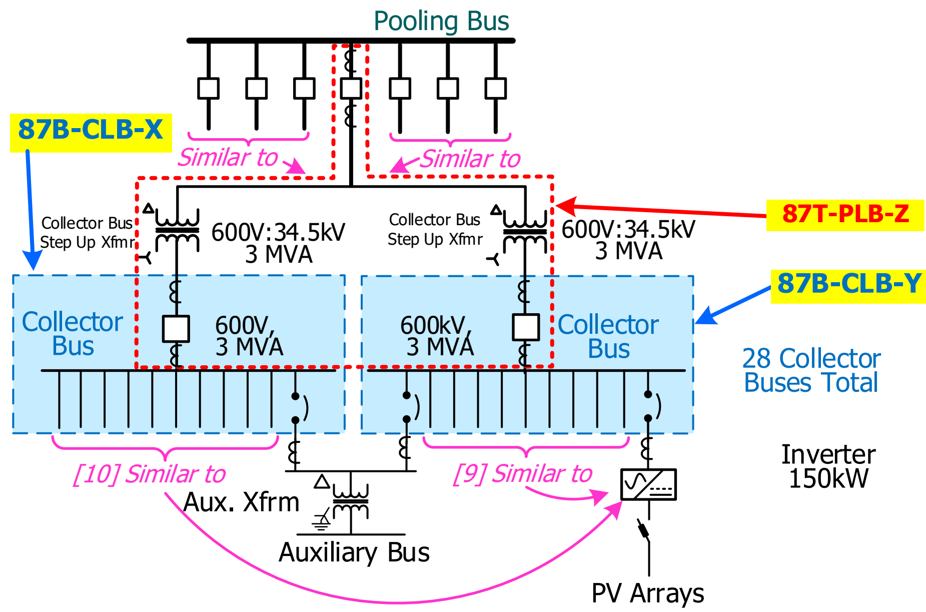


Fig. 8, SLD of CLBs to PLB

Figure 9 shows the CLB yard-to-MU connectivity.

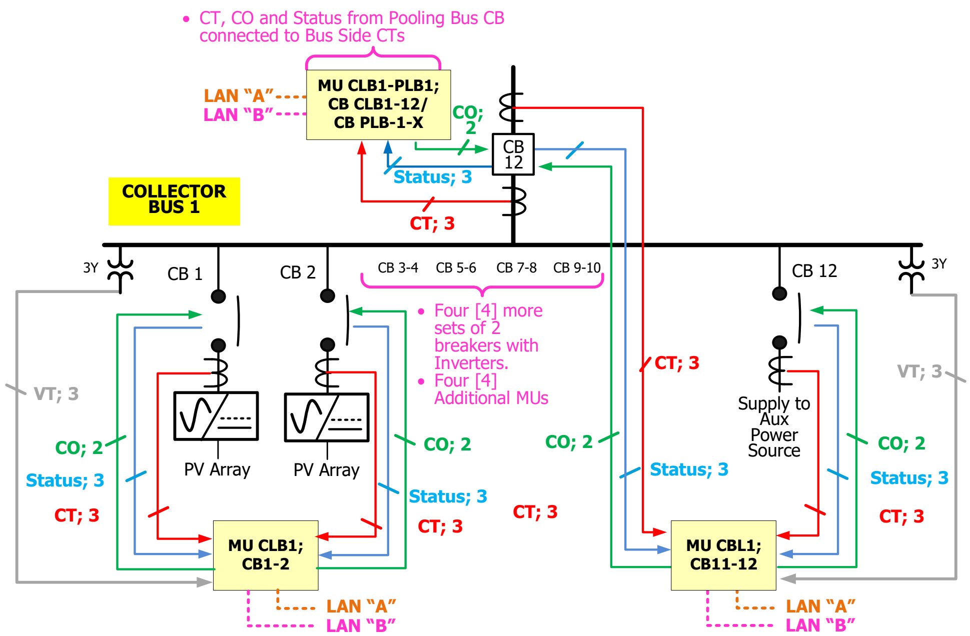


Fig. 9, Yard to MU Connectivity, CLB MUs

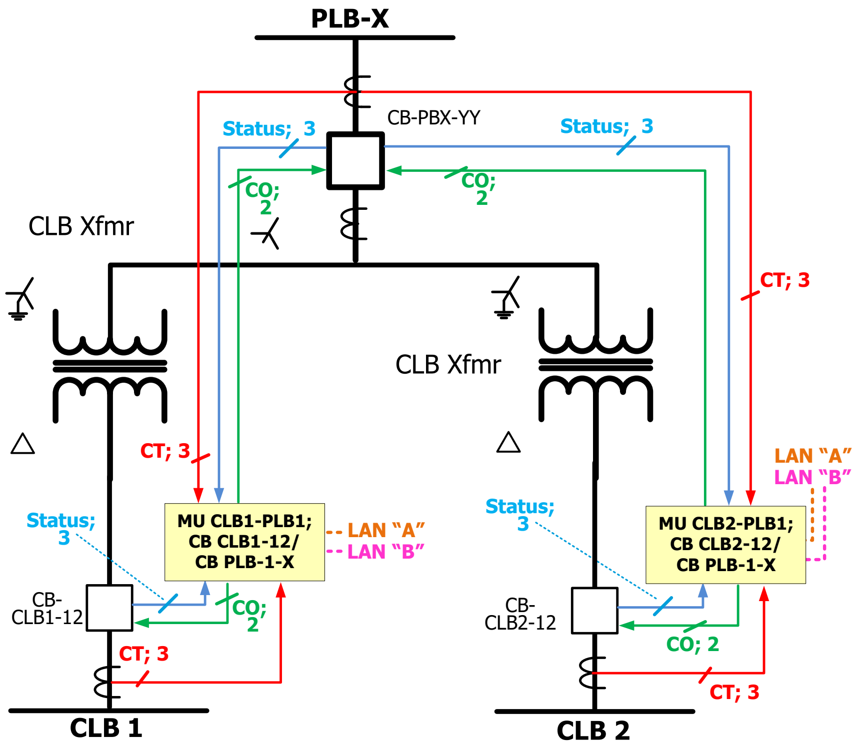


Fig. 10, Yard to MU Connectivity, CLB MUs

Referencing Figures,8, 9 and 10, for CLBs, System #2, will cover two [2] CLBs and cabling to the CLB Step Up Transformer low side winding. Description of infrastructure and protection application:

- Seven [7] groups of two [2] CLBs per PLB input, 7 2-CLBs connected to each PLB
- Each CLB has 10 Inverters, One [1] Auxiliary Source and one [1] Main as nodes (12 nodes)
- Overcurrent, voltage and breaker failure protection provided for all nodes
- Each CLB is a 12 node 87B zone, 87CLB-X and 87CLB-Y
- Total nodes used by CP#2 = 12+12+1 = 25 (<=28)
- Non-redundant protection for the set of two CLBs will require one [1] Protection System #2
- Non-redundant protection for the set of two Collector Buses application will require 14 MUs.
- Non-redundant protection for the set of two CLB Xfmrs will require one [1] Protection System #1

PLB MU Application

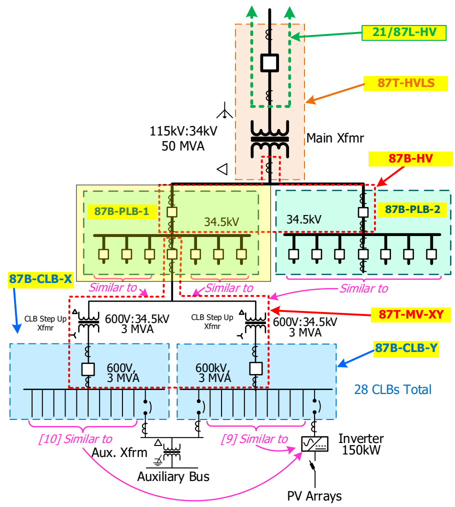


Fig. 11, SLD Highlighting PLB

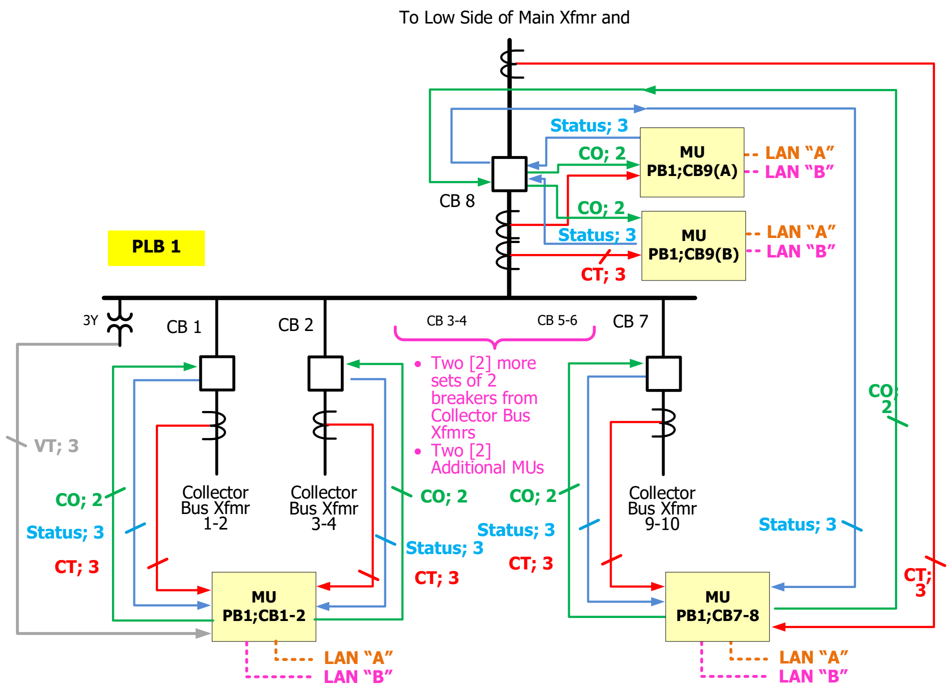


Fig. 12, Yard to MU Connectivity, PLB MUs

Referencing Figures 11 and 12, for PLBs, System #2, will cover two [2] CLBs Description of infrastructure and protection application:

- Yard to MU Connectivity for PLB 1; PLB 2 similar
- Non-redundant protection for the set of two CLBs will require one [1] Protection System #2
- Total nodes used by CP#2 = 8+8 = 16 (<=28)
- Non-redundant protection for the set of two Collector Buses application will require 8 MUs.
- Redundant MUs on PLB Main CB bus side as they are part of the Main Xfmr 87T (HV, NERC)

Main Xfmr and HV Interconnection MU Application

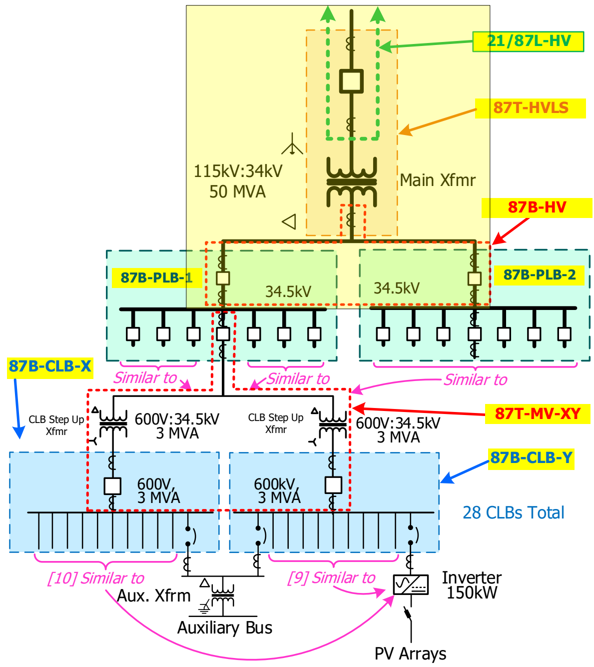


Fig. 13, SLD Highlighting PLB

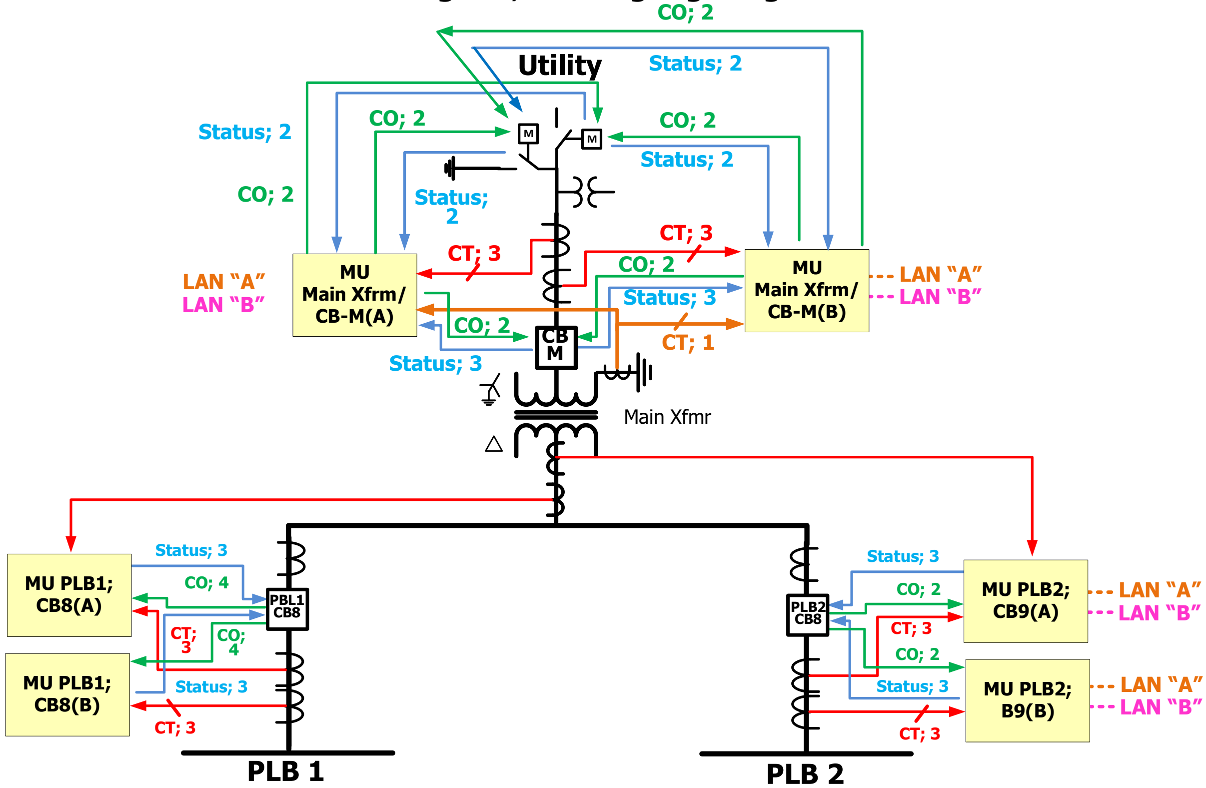


Fig. 14, Yard to MU Connectivity, PLB to HV Utility

Referencing Figures 13 and 14, description of infrastructure and protection application:

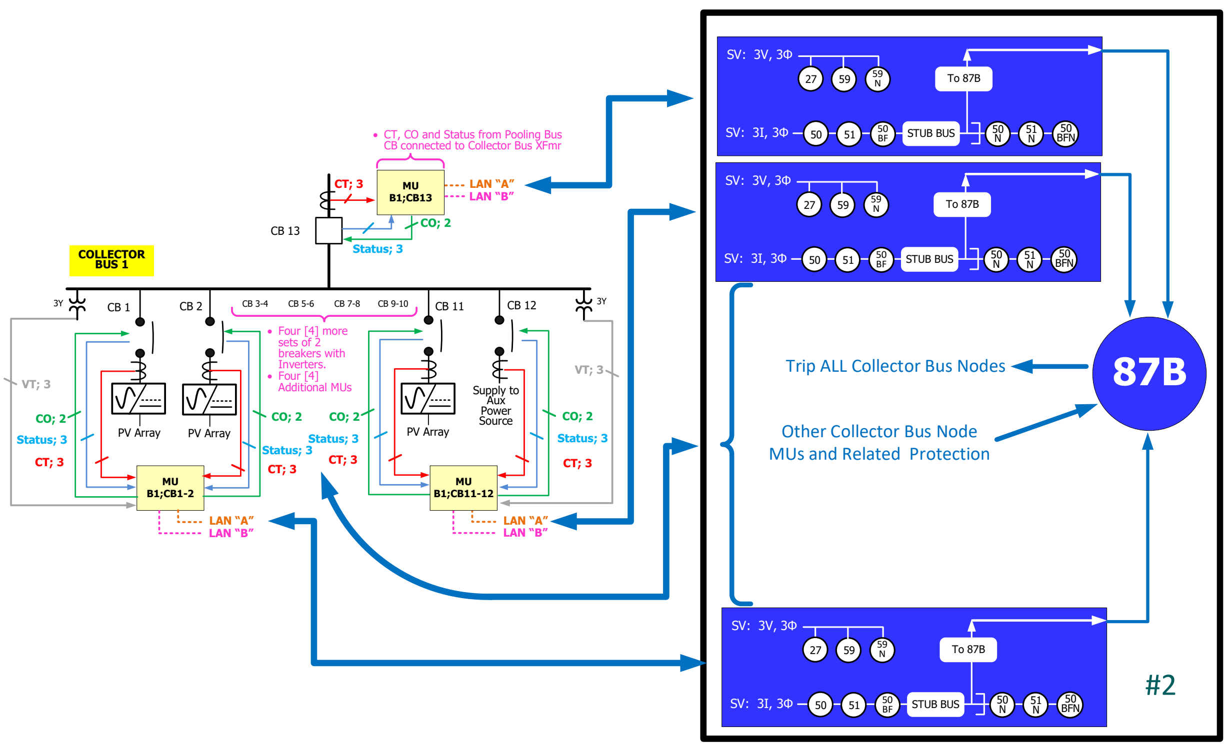
- For CLB Main CBs, and the cabling to the Main Xfmr low side CTs, one [1] System #2 will cover two [2] CLBs Main BBs, cabling to the Main Step Up Transformer low side winding.
- For the Main Xfmr, two [2] System #1 will provide redundant coverage
- For the HV Utility POI, two [2] line protection systems will provide coverage.
- Six [6] MUs will be used to provide redundant HV POI Line Protection, redundant Main Xfmr Protection and non-redundant PLB to Main Xfmr low side bus protection.

Protective Relay – MU Relationships: CLB

Referencing Figure 15, for each inverter connection CBs, auxiliary supply CB and main CB, System #2 provides overcurrent, voltage and BF protections. The respective CB is tripped for any protection trip. In the case of BF, all CBs connecting the CLB are tripped.

For nodes on the CLB, System #2 provides bus differential protection. For a bus differential trip, all CBs connecting the CLB are tripped.

A BF of the Main CB will be cleared by an upline PLB input CB.



Note: All MU-Relay signals through networked connection.
Connections shown here are to show relationships only.

Fig. 15, Protective Relay – MU Relationships: CLB

Protective Relay – MU Relationships: CLB to PLB, CLB 87B

Referencing Figure 16, for the two CLB Main CBs and the PLB input CB, System #2 provides overcurrent, voltage and BF protections. The respective CB is tripped for any protection trip. In the case of BF, all CBs connecting the CLB are tripped.

For nodes on the CLB, System #2 provides bus differential protection. For a bus differential trip, all CBs connecting the CLB and PLB tripped.

A BF of a PLB input CB will clear the respective PLB.

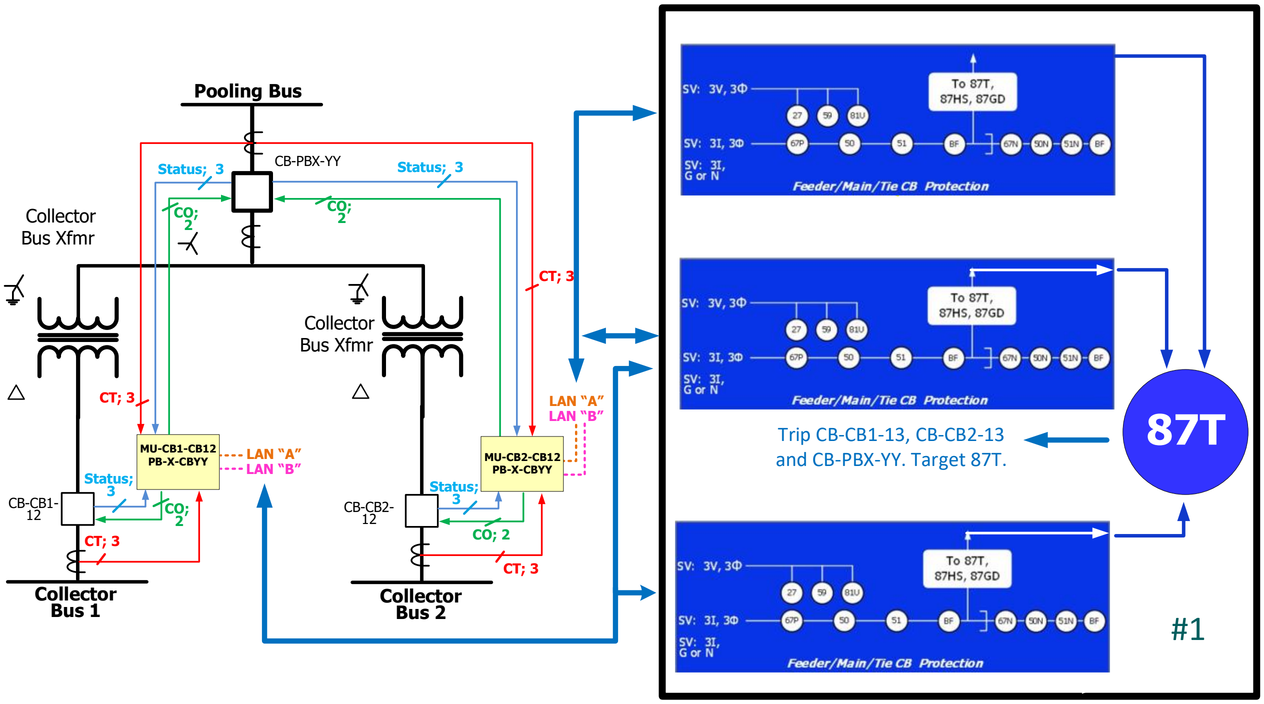


Fig. 16, Protective Relay – MU Relationships: CLB to PLB, CLB 87T

Protective Relay – MU Relationships: PLB

Referencing Figure 17, for the PLB Input and Main CBs, System #2 provides overcurrent, voltage and BF protections. The respective CB is tripped for any protection trip. In the case of BF, all CBs connecting the PLB are tripped.

For nodes on the CLB, System #2 provides bus differential protection. For a bus differential trip, all CBs connecting the CLB and PLB tripped.

A BF of a PLB Main CB will trip CB M.

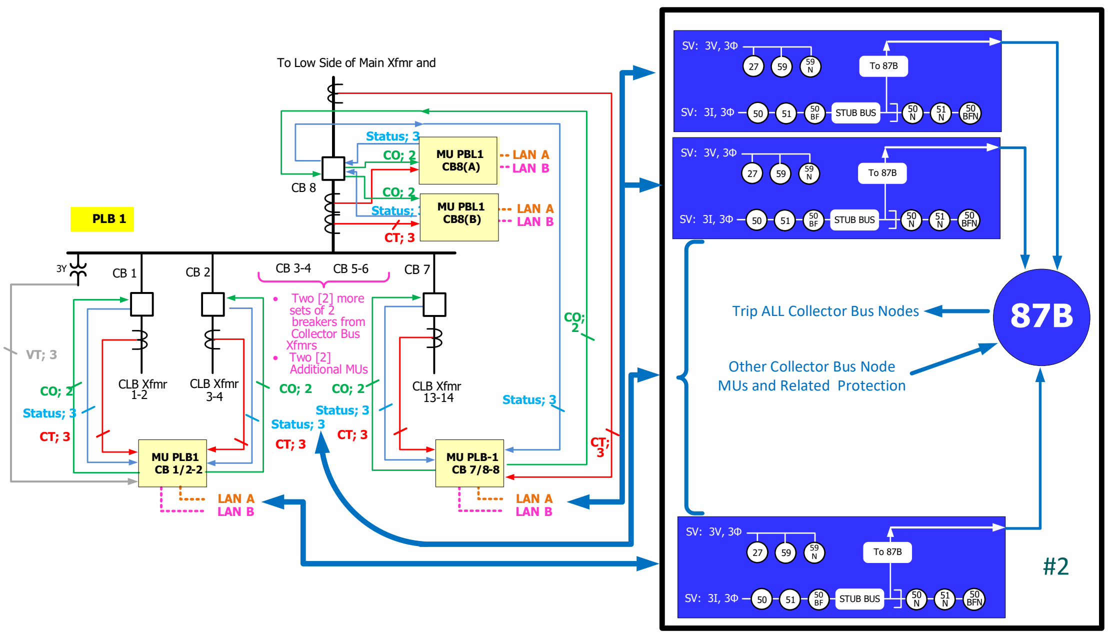


Fig. 17, Protective Relay – MU Relationships: PLB

Protective Relay – MU Relationships: Main Xfmr 87T

Referencing Figure 18, for the two PLB Main CBs, System #2 provides overcurrent, voltage and BF protections. The respective CB is tripped for any protection trip. In the case of BF, all CBs connecting the PLB are tripped.

For the two PLB Main CBs, cables between the PLB and Main Xfrm, the Main Xfmr, and CB M, System #2 provides bus differential protection. For a bus differential trip, all CBs connecting the PLB and the Utility POI (Main CB) are tripped.

A BF of a PLB output CB will clear the respective all PLB CBs.

A BF of CB-M will transfer trip to upline transmission system CBs.

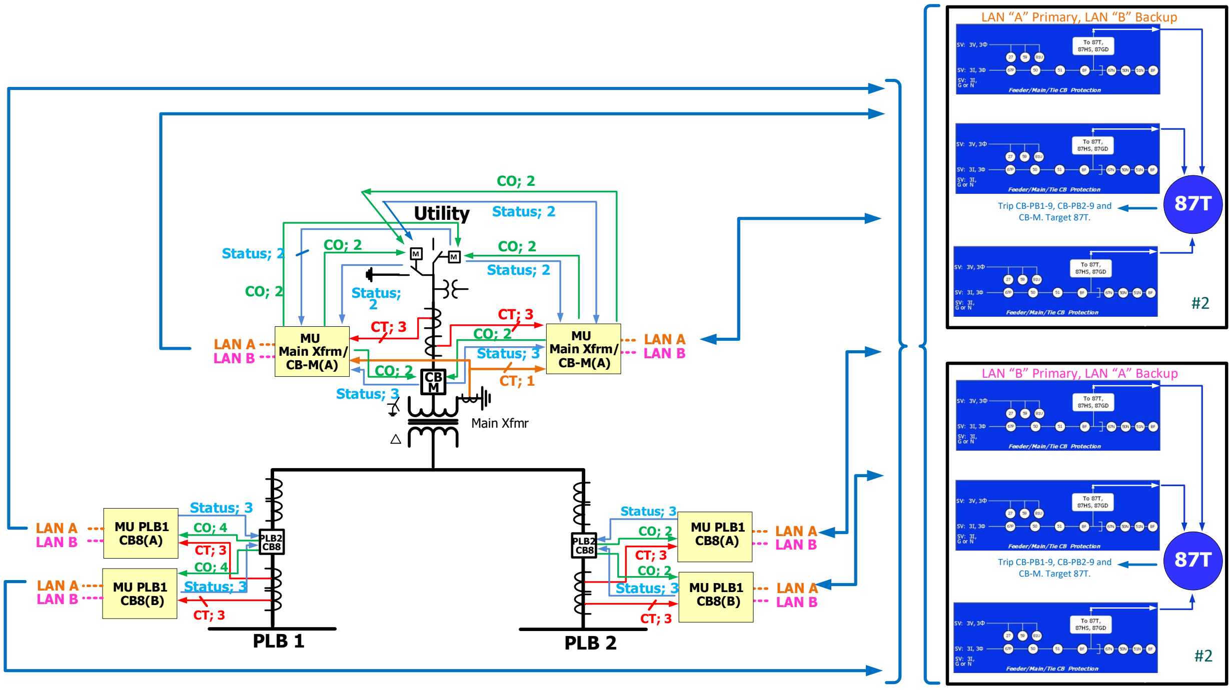


Fig. 18, Protective Relay – MU Relationships: Main Xfmr 87T

Protective Relay – MU Relationships: Utility POI

Referencing Figure 19, for the CB M, the Utility POI, dual line protection systems are employed. Exact element fleet and principle used are dependent on the Bulk System Owner. CB M is tripped for any line protections that trip in either redundant protection system.

A BF of CB-M will transfer trip to upline transmission system CBs.

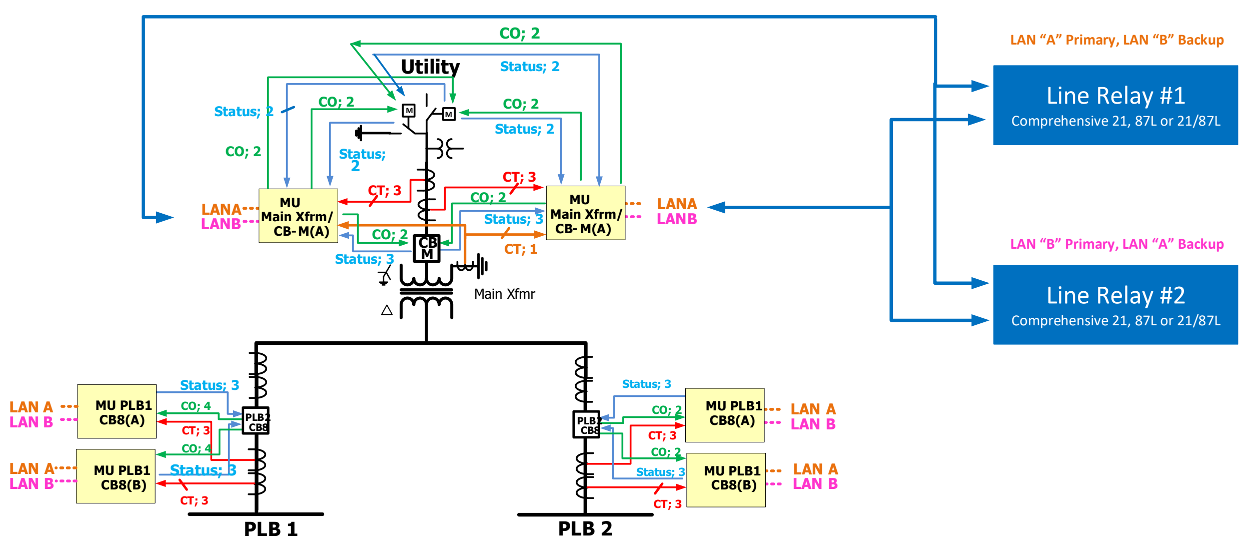


Fig. 19, Protective Relay – MU Relationships: Utility POI

MU and Relays: Enclosures or Use of Existing Compartments

In retrofit application, MUs typically are housed in kiosks or enclosures, strategically sited close to the process they are connecting to. Designing, fabricating and installing enclosures incurs cost. In Greenfield designs, for outdoor breakers, breaker panels may be used for enclosing the MUs provided there is adequate space. This space may be requested during the breaker quoting phase of the project. In Greenfield designs, for metal-clad switchgear, the LV compartments where relays would typically be mounted can be used for enclosing the MUs and centralized relays. In cases where breaker cabinets or switchgear LV compartments were not available, one could employ dedicated enclosures as needed.

Figure 20 shows tactics for enclosing MUs and relays in a Greenfield design.

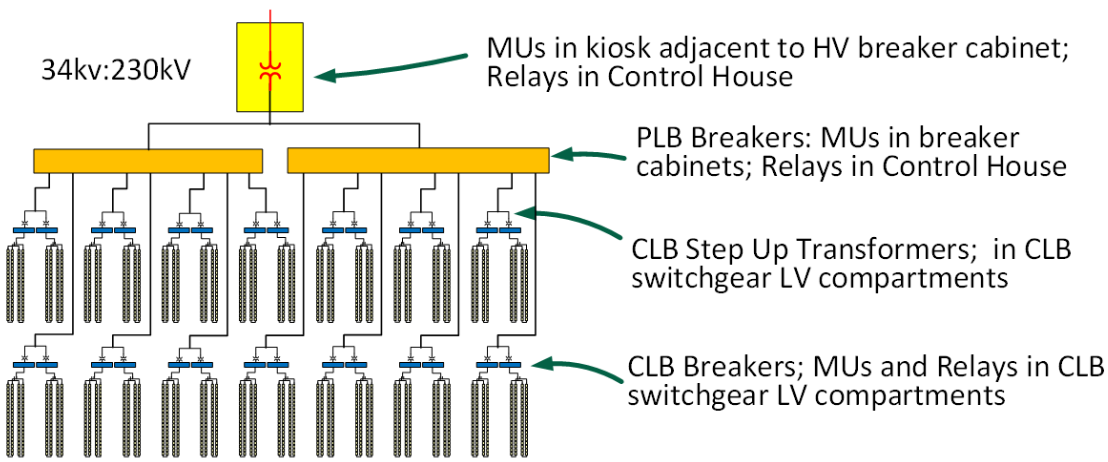


Fig. 20, MU & Relays: Placement in Greenfield Design

Summary and Conclusions

- In some Utility-Scale IBR Renewable Plants, there may be high quantity use of granulized and repeated power infrastructure.
- These designs lend themselves to the use of centralization for a high degree of standardization in the P&C design.
- Savings on the quantity of protective devices, quantity of panels and space inside the control house can be obtained.
- In Greenfield applications, MUs can often be housed in breaker cabinets and LV switchgear compartments, with attendant enclosure and civil savings. As one of its attributes, centralization allows economical application of primary and back functions.
- In Greenfield applications, MUs can often be housed in breaker cabinets and LV switchgear compartments, with attendant enclosure and civil savings.
- A large amount of standardization can occur from the standardized design and fabrication of MU enclosures (if applied)
- Wiring runs from MUs to the yard elements are short and standardized.
- If the MU information for all accessed points is brought into the control house, the Operators have full view of every element off the plant, from the high voltage POI to the individual inverter AC inputs, without having to travel to various areas of the plant.

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Author Biography

Wayne Hartmann is Advanced Applications Advisor (NAM) GE VERNOVA. In this role, he explores the application of new technologies in protection and control with Electric Utilities, Industrials and the Consultants the support them. Wayne also provides market research, input for new product development and is active working with the Sales and Application Teams.

- Before joining GE VERNOVA, he was in Standards Development at Duke Energy, and in Application, Sales and Marketing Management capacities at Beckwith Electric, PowerSecure, General Electric, Siemens Power T&D and Alstom T&D.
- Wayne is a Senior Member of IEEE and serves as a Main Committee Member of the Power System Relaying and Control Committee (PSRCC) for over 30 years.
    - Chair Emeritus of the IEEE PSRCC Rotating Machinery Subcommittee ('07-'10).
    - Contributed to numerous IEEE Standards, Guides, Reports, Tutorials and Transactions, delivered Tutorials at IEEE Conferences, and authored and presented numerous technical papers at key industry conferences.
- Contributed to McGraw-Hill's "Standard Handbook of Power Plant Engineering."

Acknowledgment

- The author thanks his Wife, Lisa, for giving him the time on nights and weekends to produce this paper. Lisa, you are always great support.

ANNEX A: Improved Redundancy

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

In digital substation designs, the concept extends from instrument transformer to MUs to relays to 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 A1 show 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.

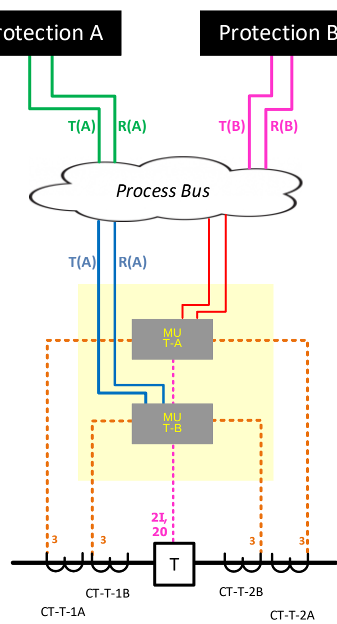

Fig. A1, Redundant System A & B using CTs, MUs and Relays

In Figure A2, MU T-A fails. The failure is sensed by Relay A using crosschecking of the SV signals, and Relay A switches to MU T-B.

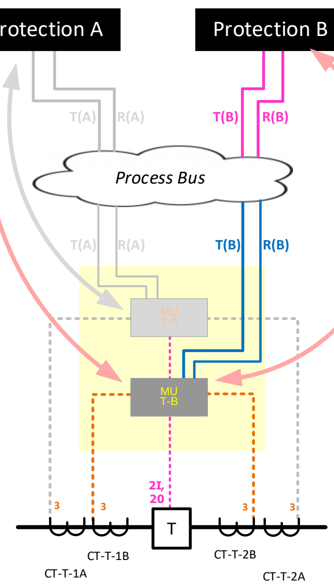

Fig. A2 MU T-A Failure with Relay A Employing Crosscheck with MU Switchover to MU T-B

In Figure A3, MU T-B fails. The failure is sensed by Relay B using crosschecking of the SV signals, and Relay B switches to MU T-A.

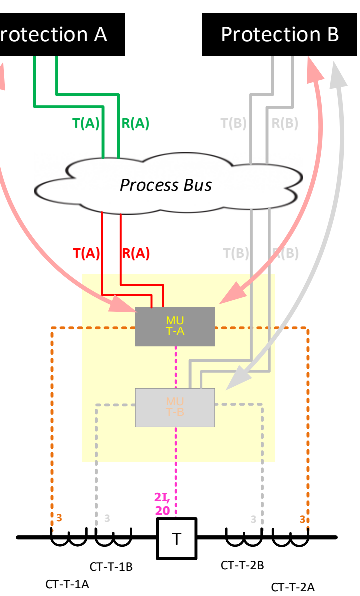

Fig. A3, MU T-B Failure with Relay B Employing Crosscheck with MU Switchover to MU T-A

In Figure A4, CT-T-1A shorts. Relay A detects the anomaly and blocks operation, and switches MUs to MU T-B, employing CT-T-2A.

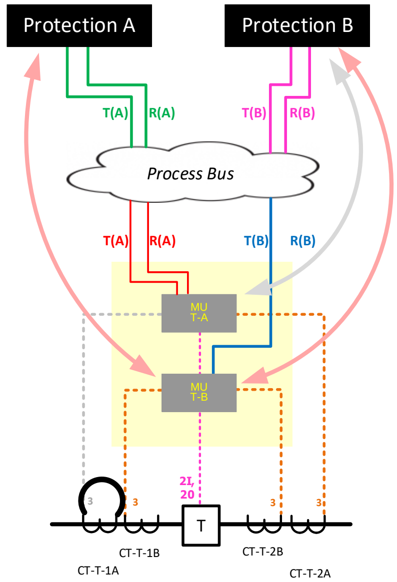

Fig. A4, CT-T-1A Failure with Relay A Employing MU Switchover to MU T-A

For redundancy of status and commands:

- Both MUs of the redundant set publish status. Both relays of the redundant set subscribe to the status messages.
- Both relays of the redundant set publish GOOSE commands. Both MUs of the redundant set subscribe to the GOOSE messages.

Annex B: Standardization of Yard-Merging Unit Connectivity and Panel Quantity/Complexity Reduction

The following AC and DC termination drawings illustrate the reduction of wiring and terminations using Centralized Digital Substation Design, decreasing terminations by 3:1, with attendant reduction in engineering and commissioning time.

The following termination diagrams illustrate typical hardwired connectivity from the yard to the relay panels.

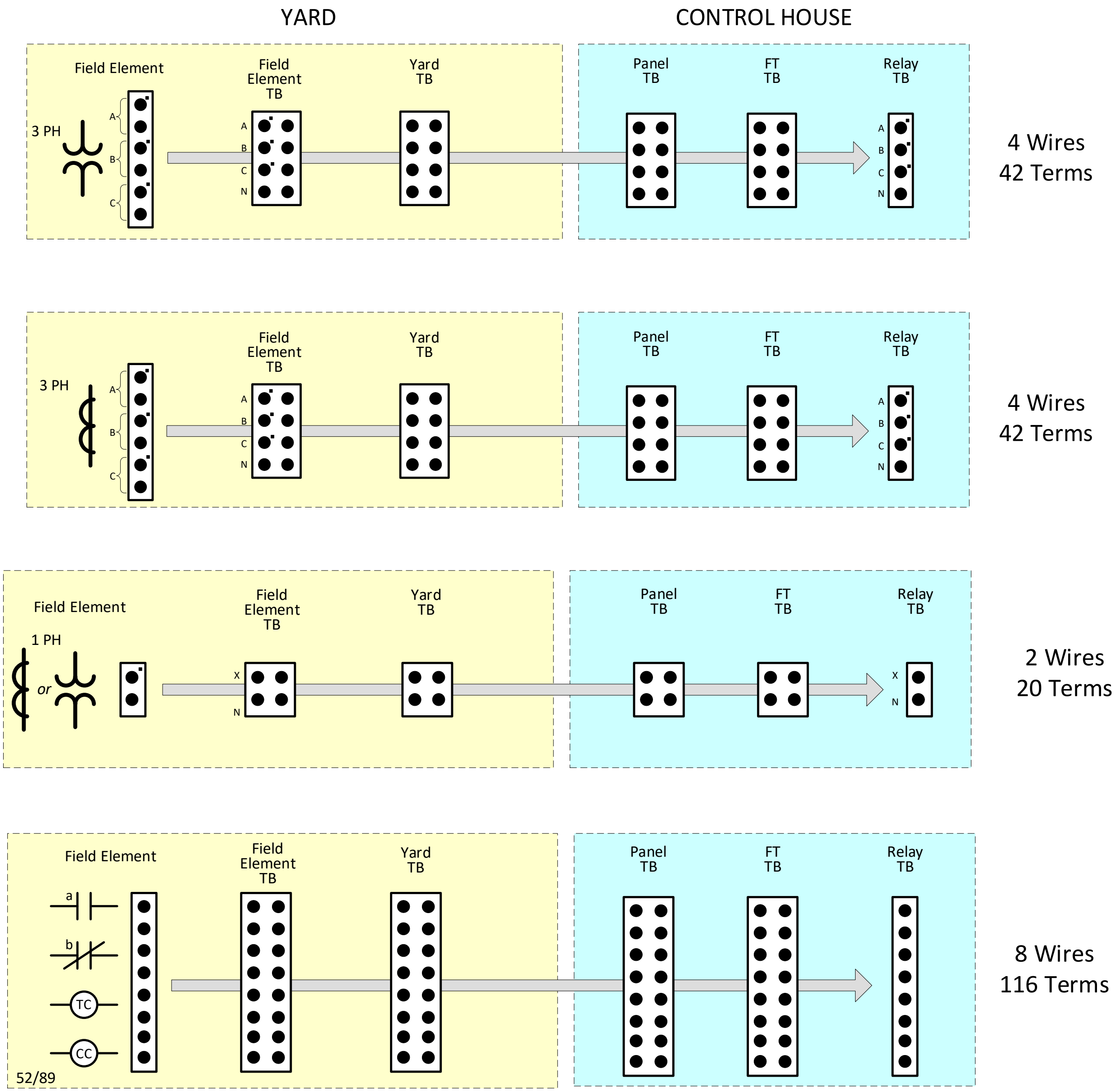

Fig. B1, Hardwired Terminations (Typical)

The following termination diagrams illustrate typical hardwired connectivity from the yard to the relay panels.

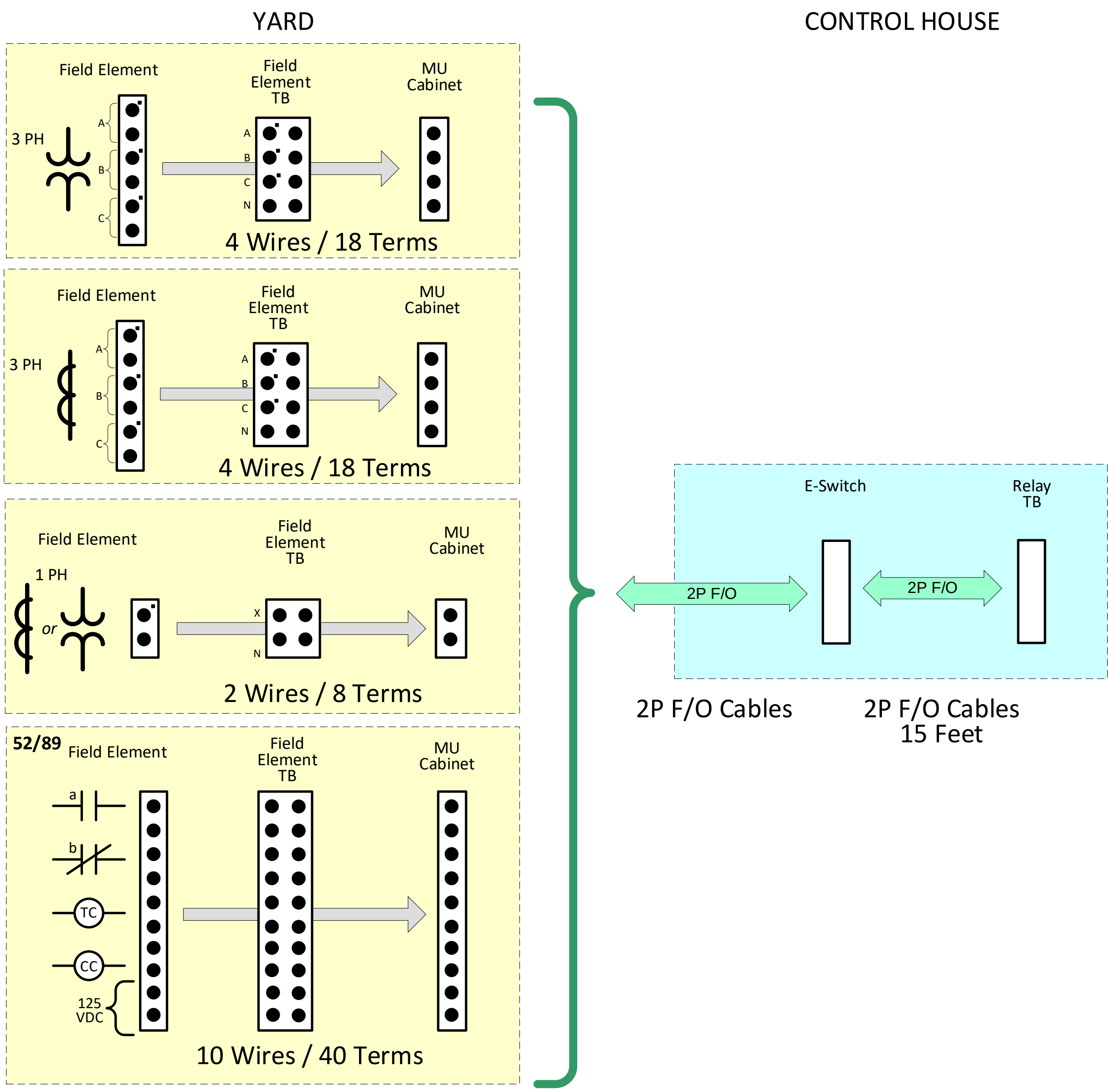

Fig. B2, Digital Substation Terminations (Typical)

The following AC 3-Line diagrams illustrate how yard-to-merging unit connectivity may be standardized, thereby decreasing engineering and design.

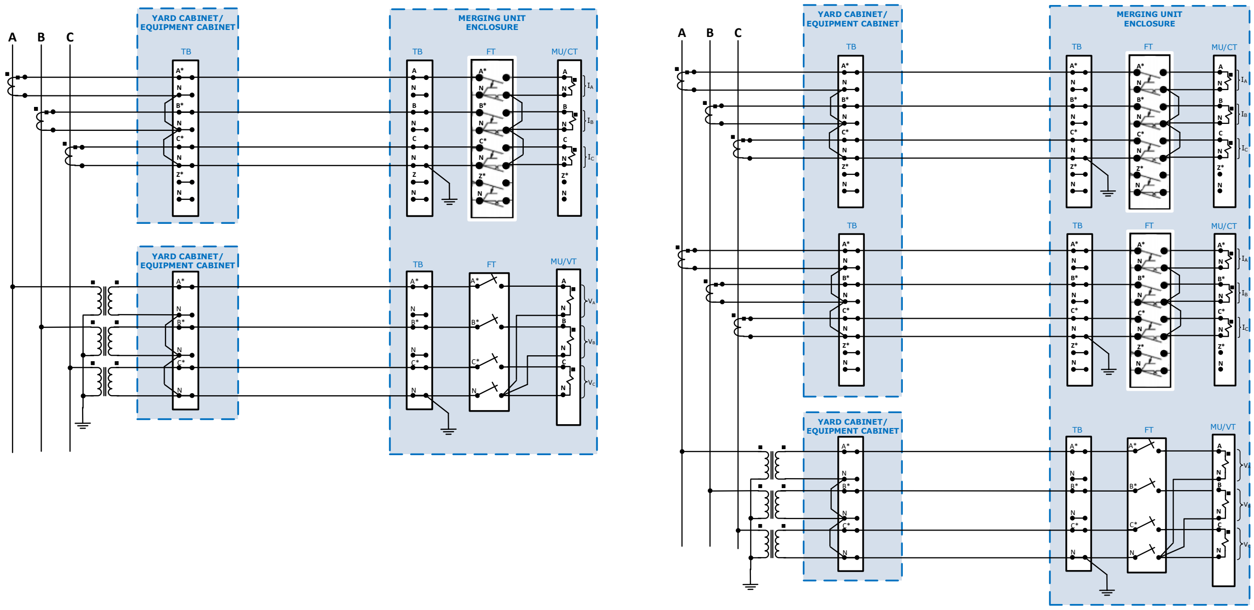

Fig. B3, AC 3-Line Typicals, Yard-to-Merging Unit Connectivity

The following DC Elementary diagrams illustrate how yard-to-merging unit connectivity may be standardized, thereby decreasing engineering and design.

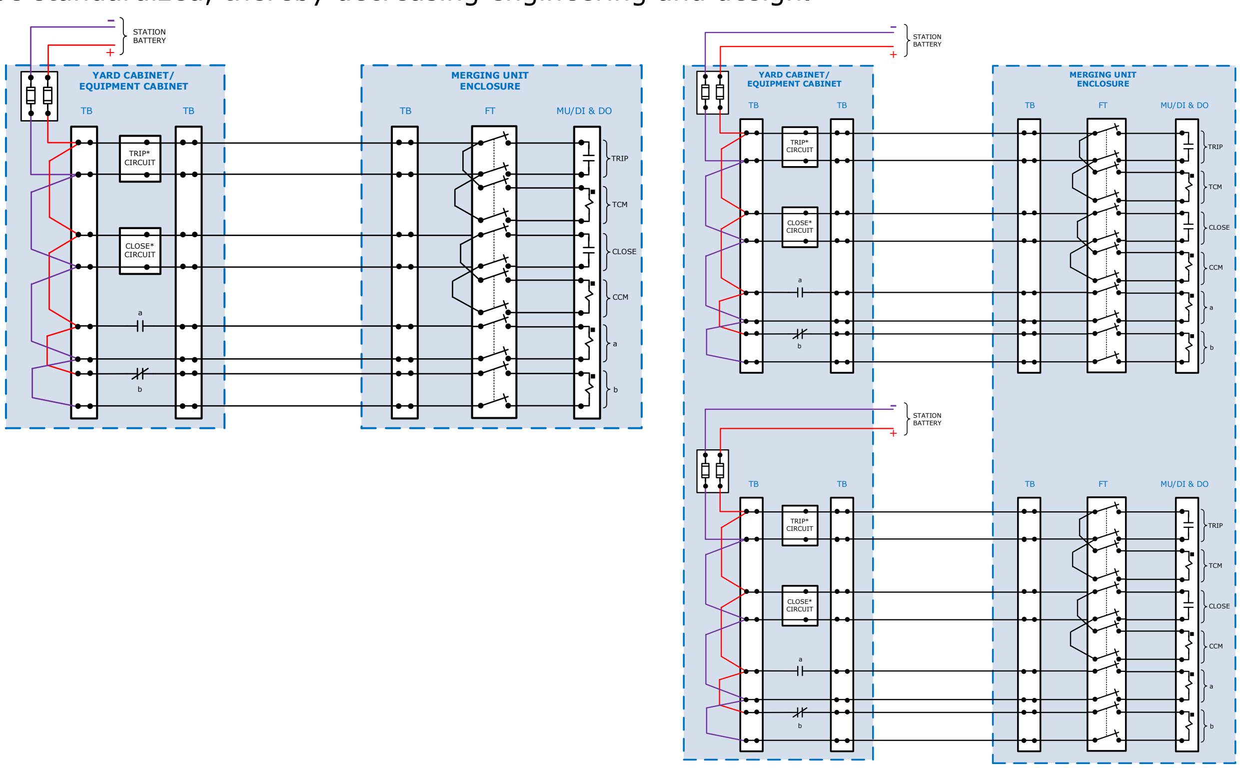

Fig. B4, DC Elementary Typicals, Yard-to-Merging Unit Connectivity

The following diagrams illustrate how [A] use of panel switches and merging units greatly decreases panel complexity [B]. merging units may be used to create a distributed lockout function.

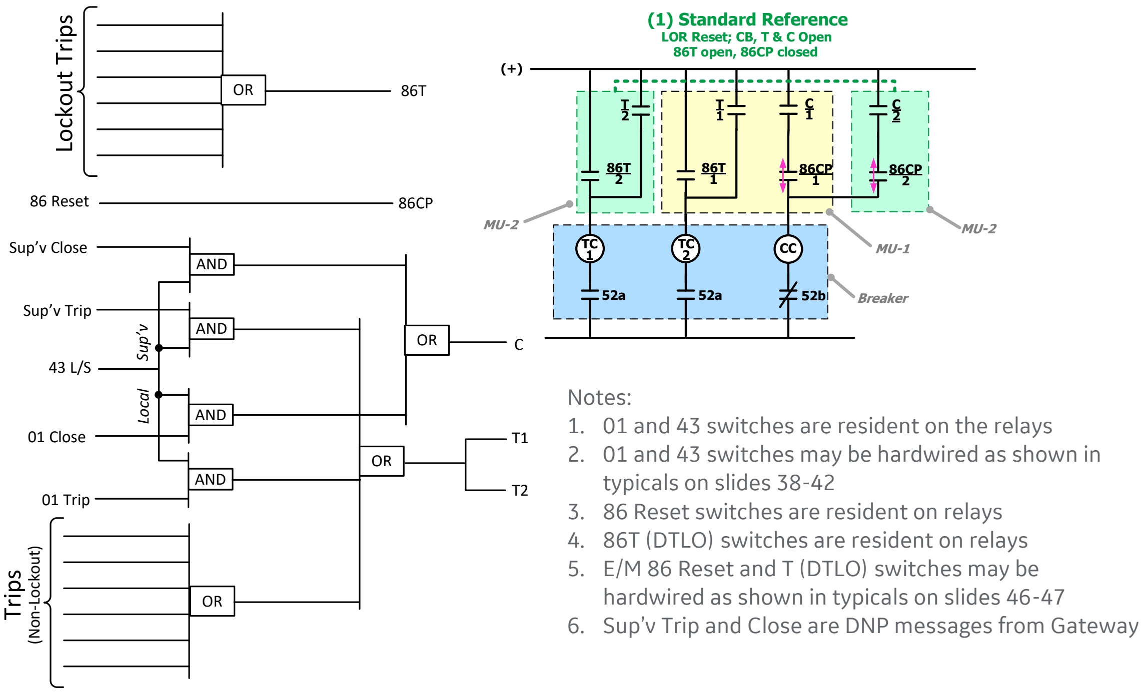

Fig. B5, Merging Unit Lockout/Trip/Close Functionality DC Elementary and Logic

The following diagrams illustrate the standardization, reduction in wiring and decrease in panel quantity and complexity.

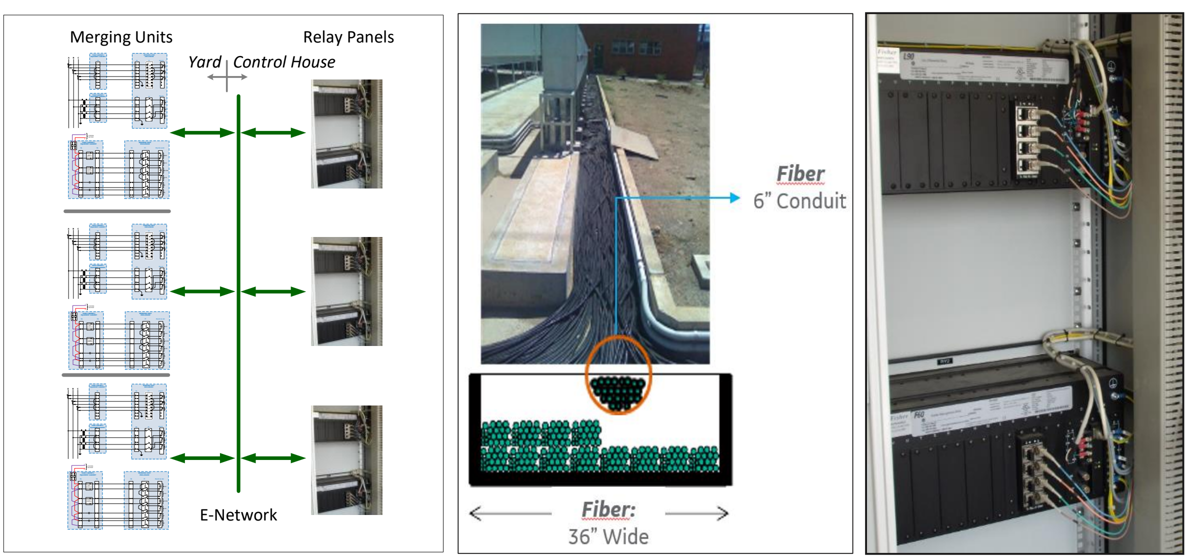

Fig. B5, Merging Unit Lockout/Trip/Close Functionality DC Elementary and Logic