

OPTIMIZED DISTRIBUTION PROTECTION & CONTROL

ADVENTURES IN DIGITAL SUBSTATION CENTRALIZATION

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Optimized Distribution Protection & Control

Adventures in Digital Substation Centralization

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1] Abstract

Over the past 30 years, the evolution of protection and control relays has migrated from single-function electromechanical devices to multi-function microprocessor-based relays that include both protection and control (P&C) functionalities, thus optimizing by reducing the overall device count, system complexity and cost. The next step is to provide P&C functions into multiple multifunctional and multizonal devices with the overall substation protection scheme employing redundancy or backup. This is termed "Centralization."

This paper will discuss several distribution P&C architectures that implement feeder, transformer and bus protection across two or three multiple multifunctional and multizonal devices in a distribution substation with redundant or backup protective functions, providing partial centralized designs. The redundancy/backup capabilities and relative costs of each variant will be compared and contrasted. The proposed architectures will use IEC 61850 9-2LE merging units (MU) as analog and digital I/O interface to the distribution substation apparatus, process bus from the MUs to the P&C devices, and station bus for inter-device P&C GOOSE messaging.

2] Introduction

Five Tenants of Protective Relaying

In Lewis Blackburn's seminal text on system protection, *Protective Relaying, Principles and Applications*, in the first chapter, "Introduction and General Philosophies," he defines five facets of the art and science of system protection. The final of the five is Economics.

Economics: Maximum Protection at Minimal Cost

When designing P&C applications, we always strive to design for best economic effect with a holistic lens. This means the economic considerations should account for:

- CAPEX of equipment
- Protection system performance, including redundancy and resiliency considerations
- OPEX for future maintenance and upgrade
- Maintainability

It is with the above in mind that we explore the concepts of partial centralization to realize an optimal blend of these factors.

3] Quick Review of Digital Substation (DS)

A DS involves the use of merging units (MUs) to connect to yard elements (CT, VT, 52, 89, other), digitizing the data, then communicating with relays in the control house over fiberoptic networks. 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 information used for interlocking, breaker failure, protection modification and other uses are performed over "station bus" network. Figure 1 shows a simplistic view of the arrangement described above that employs a parallel redundancy protocol (PRP) architecture.

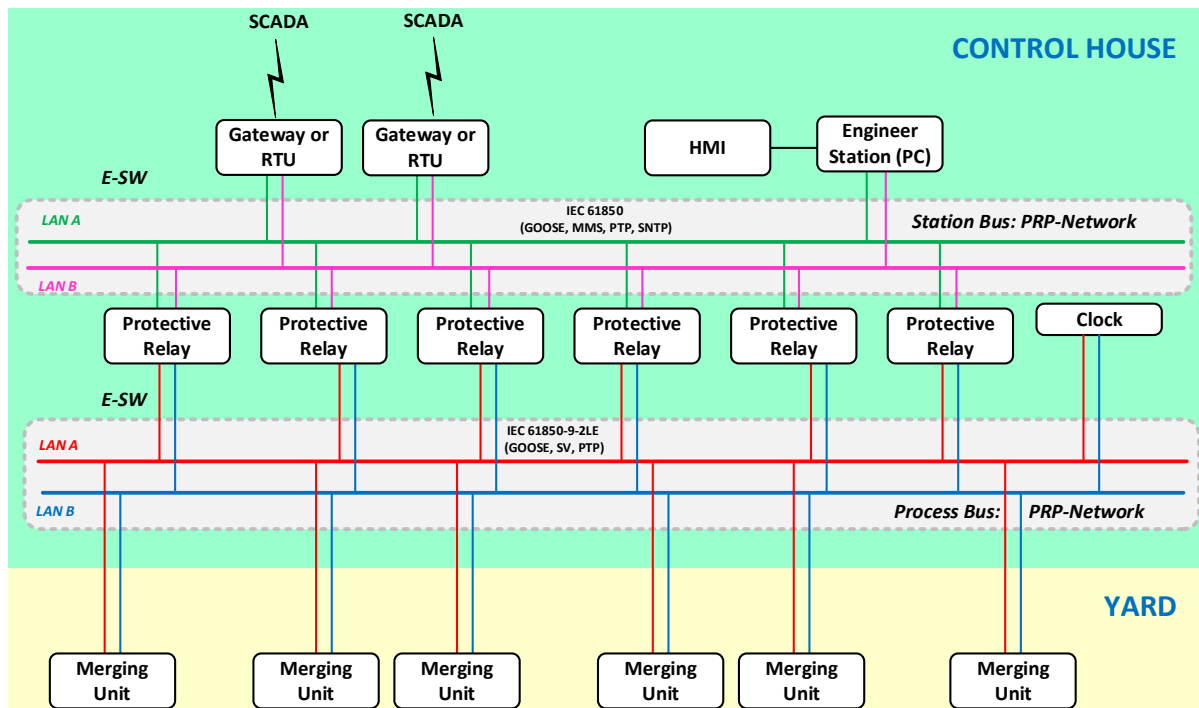


Fig. 1, Simple Block Diagram of a Digital Substation using Networked Process Bus and Station Bus

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. The reasoning 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 network connected yard elements.

4] Partially Centralization Systems

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.
- A combination bus/feeder, main, tie CB protection system that can cover ≤ 6 nodes of primary bus differential protection with breaker failure, ≤ 6 nodes of feeder/main/tie breaker protection, and another < 6 nodes of secondary bus differential protection

Single line drawings (SLD) of two systems follow in Figures 2, 3, 4 and 5:

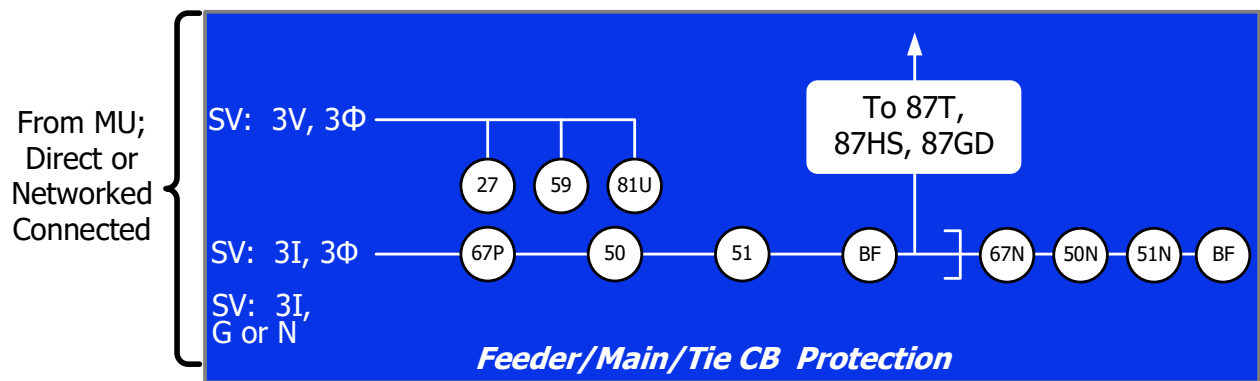


Fig. 2, Feeder, Main, Tie CB Protection For Transformer Protection System

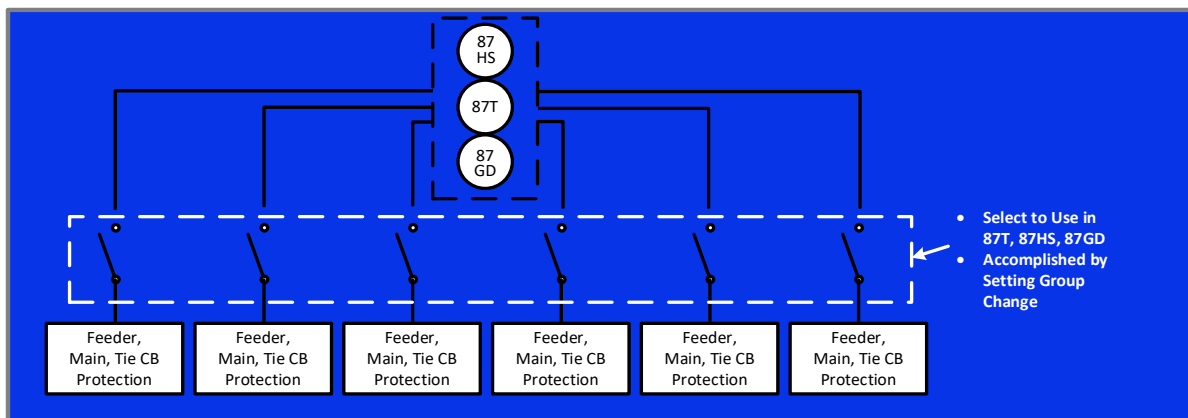


Fig. 3, Selectivity for 87T/87HS/87GD Sourcing for Transformer Protection System

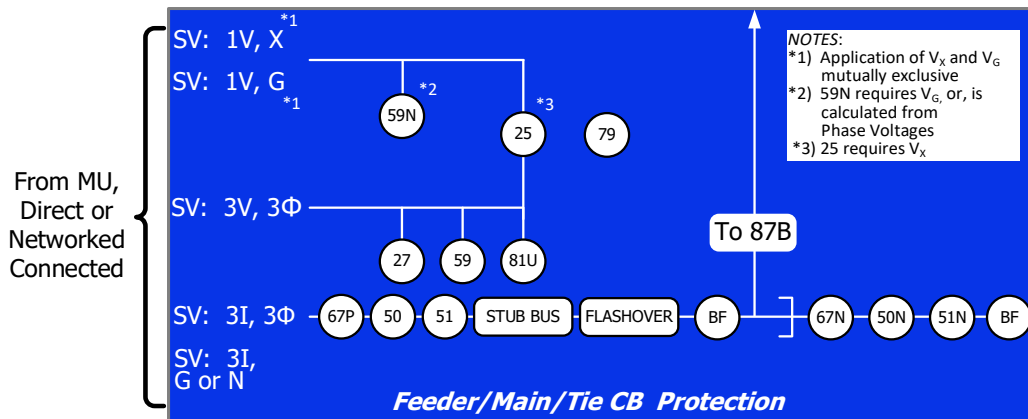


Fig. 4, Feeder, Main, Tie CB Protection of Combination Bus/ Feeder, Main, Tie CB Protection System

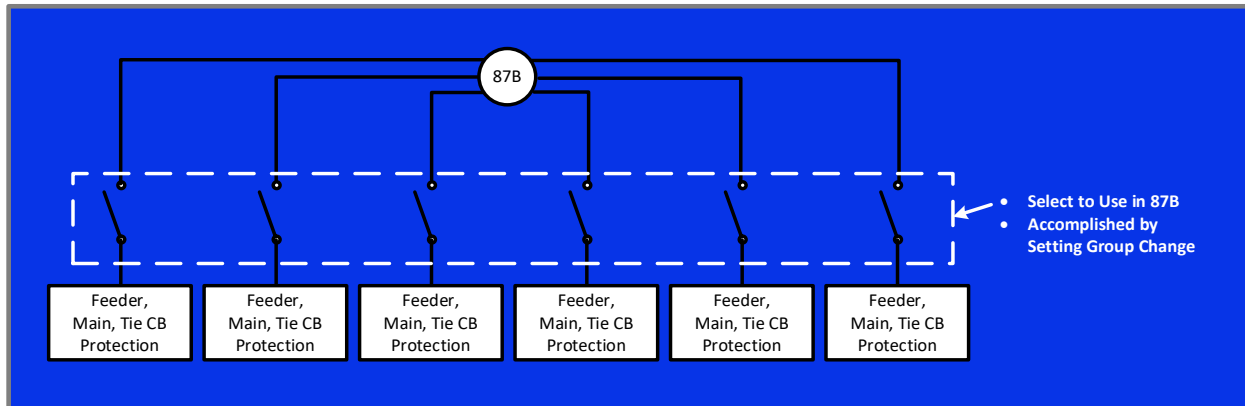


Fig. 5, Selectivity for 87B Sourcing for Combination Bus/ Feeder, Main, Tie CB Protection System

These two P&C systems, when used in combination to achieve distribution substation protection, will be compared and contrasted for equipment CAPEX using the following designs:

- Hardwired (single and redundant schemes)
- Direct connection process bus (single and redundant schemes)
- Network connected process bus (single and redundant schemes)

Why the partially centralized approach?

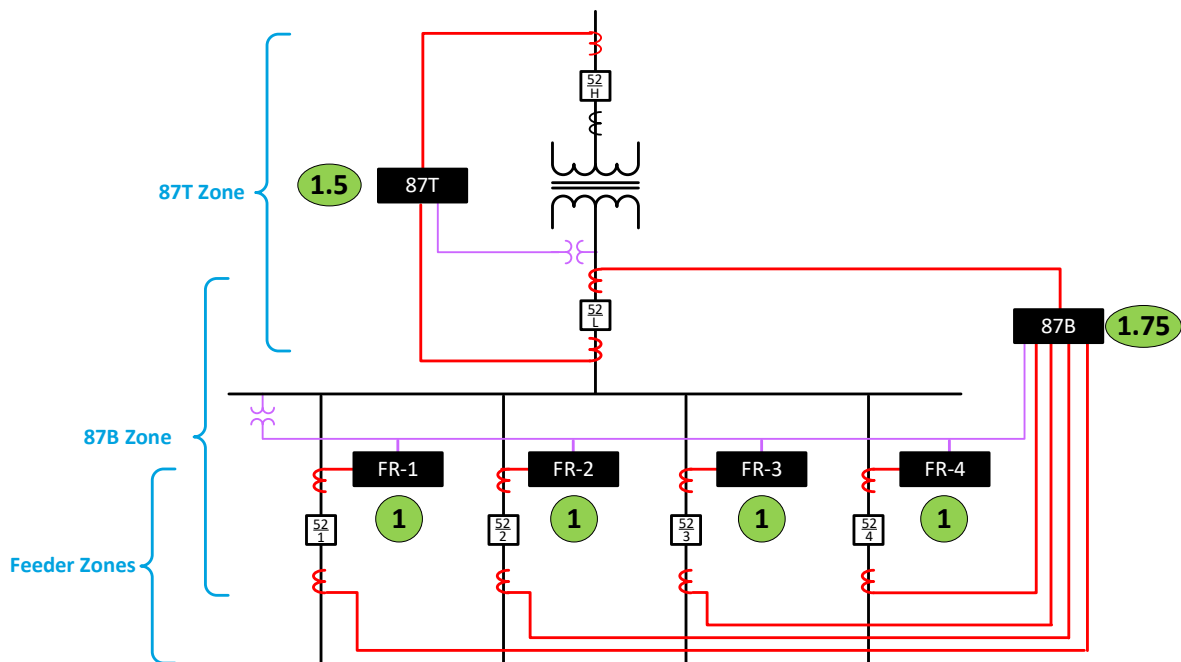
The partially centralized approach shown in this paper uses protective relay platforms. This offers engineers and technicians a familiar platform to design with as well as commission, test and maintain. It allows a move toward centralization without implementing a fully centralized design that engineers and technicians may be less familiar with. Partial centralization using protective relay platforms offers an incremental, familiar and rapidly deployable protection solution and provide redundant P&C functions.

5] CAPEX Exploration for Hardwired Systems, Direct Connected MU-to-Relay Systems and Network Connected MU-to-Relay Systems

To estimate CAPEX for the protection equipment used in various approaches, below is a per unit (pu) cost of the equipment, setting a hardwired feeder protection relay at 1pu cost. These pu assignments were based on present day Industry cost level observation. These levels could be adjusted with different or future relative cost levels.

- Hardwire Feeder Relay = 1pu
- Hardwire Transformer Relay = 1.5pu
- Hardwire Bus Relay = 1-1.75pu (Hi-Z=1, Low-Z=1.75)
- 61850-9-2LE Combination Bus/ Feeder, Main, Tie CB Protection System = 2pu
- 61850-9-2LE Transformer Protection System = 2pu
- MU = 1pu
- E-Net Switch = 1.25pu
- 1588 Clock = 1pu

Following we show various developments of protection designs to compare and contrast protection CAPEX equipment relative costs. The first study will be for a straight-bus substation with one transformer, transformer high side and bus side CBs, and four feeders with a single (non-redundant) protection system.



**Fig. 6, SLD of a Hardwired Straight Bus Substation, Single (non-redundant) Protection System
CAPEX Protection Equipment Cost = 7.25pu**

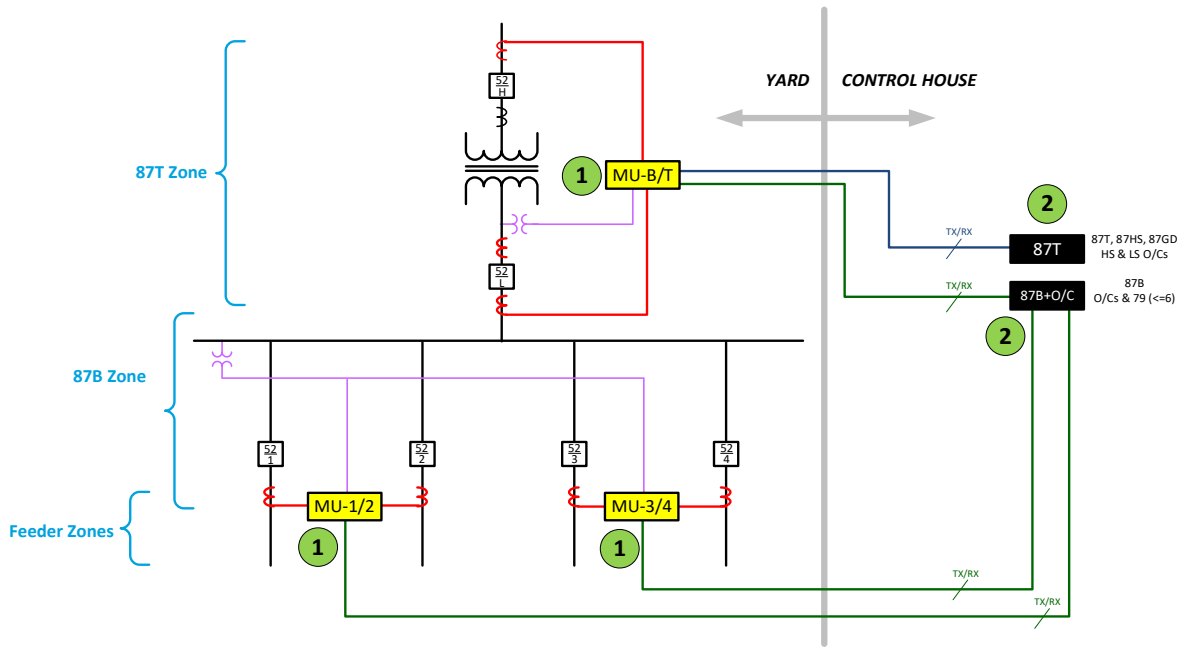


Fig. 7, SLD of a MU-Relay Direct Connected Straight Bus Substation, Single (non-redundant) Protection System CAPEX Protection Equipment Cost = 7pu

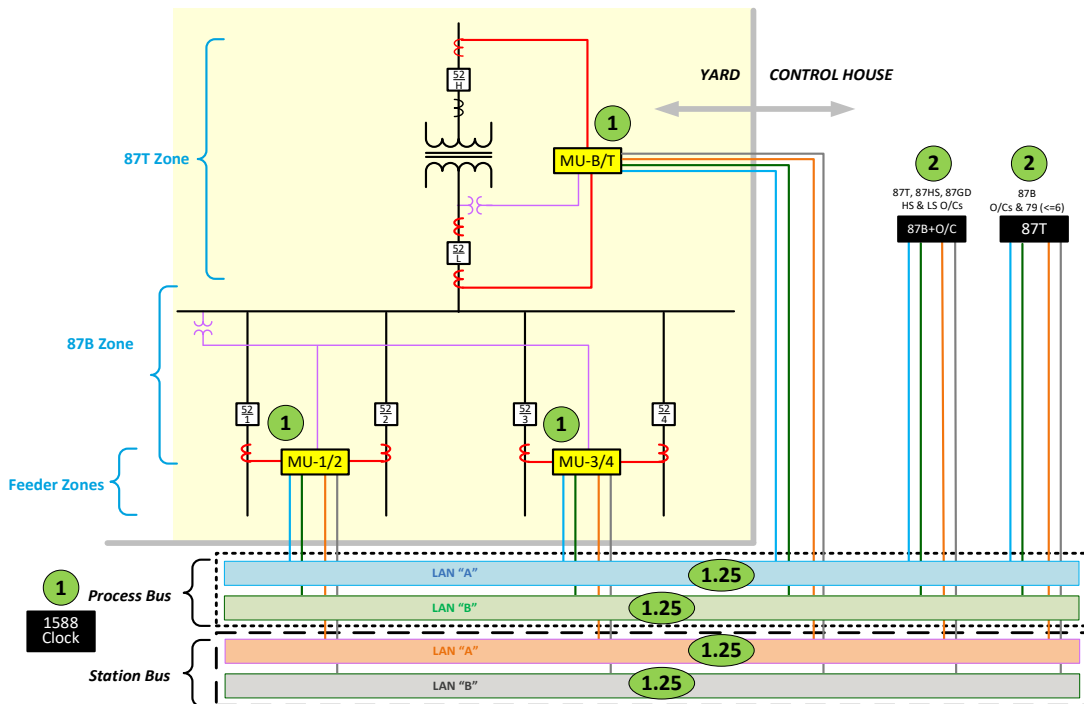


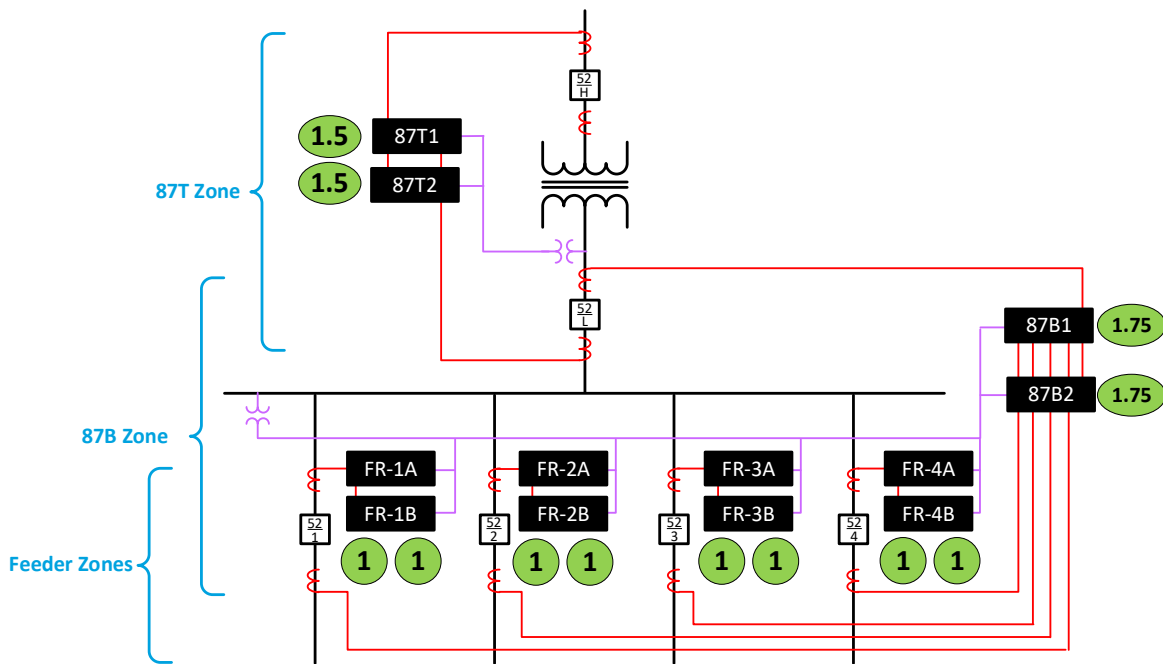
Fig. 8, SLD of a MU-Network-Relay Connected Straight Bus Substation, Single (non-redundant) Protection System CAPEX Protection Equipment Cost = 13pu

Pu cost comparison summary for the straight bus substation, single (non-redundant) protection system:

- Hardwired: 7.25pu
- MU-Relay Direct Connected: 7pu
- MU-Network-Relay Connected: 13pu

Employing a partially centralized direct connected solution to this straight bus, single protection scheme (non-redundant) substation is approximately the same CAPEX as a hardwired solution for protection equipment. The partially centralized network connected solution is approximately double the CAPEX for protection equipment, however it offers self-monitoring and backup protection in the event of either the 87T or 87B+O/C systems (this is covered in more detail later in this paper).

The second study will be for a straight-bus substation with one transformer, transformer high side and bus side CBs, and four feeders with a redundant protection system.



**Fig. 9, SLD of a Hardwired Straight Bus Substation,
Redundant Protection System
CAPEX Protection Equipment Cost = 14.5pu**

Before we move to the partially centralized approach for this and other substations we develop, following we define a way to provide redundancy for merging unit (MU) failure for feeder positions without doubling the amount of MUs. See Annex A for additional information on sampled value source switching and MU and instrument transformer failure considerations.

Figure 10 below shows how two MUs can apply for two CBs, with one MU connected to the load side currents, supplying the bus protection and the other MU connected to the bus side CTs, supplying the feeder protection. Using FA and FB as example feeders:

- MU FA1/FB1 is connected to bus side CTs FA-F and FB-F and would be used to supply the feeder protection.
- MU FA2/FB2 is connected to bus side CTs FA-B and FB-B and would be used to supply the bus protection.

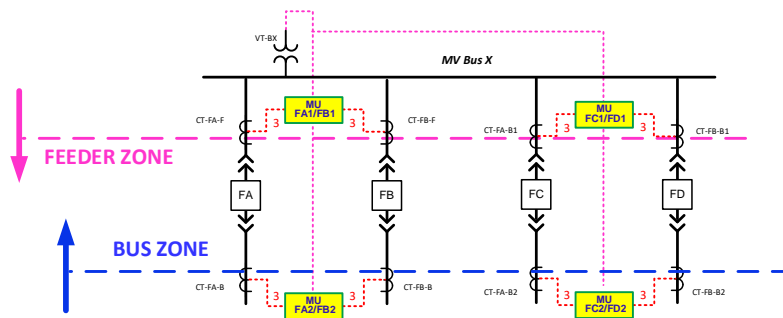


Fig. 10, Obtaining Redundancy for Feeder MUs without Doubling MU Quantity

Concentrating on FA and FB, if MU FA2/FB2 fails, the bus relay would now use sampled value streams provided by MU FA1/FA2. The two feeders would no longer be in the bus zone, but they would still be protected by the feeder relaying. To obtain the limited redundancy without doubling the quantity for MUs, in distribution applications this may be acceptable condition for the possibility of MU failure.

Concentrating on FC and FD, if MU FC1/FD1 fails, the feeder protection relay would now use sampled value streams provided by MU FC2/FD2. The feeder zone would start on the load side of the CBs. The feeders would still be in the bus zone in the event of a fault in the breaker. This would be an acceptable long term operation condition as there is no gap in coverage and proper protection is maintained.

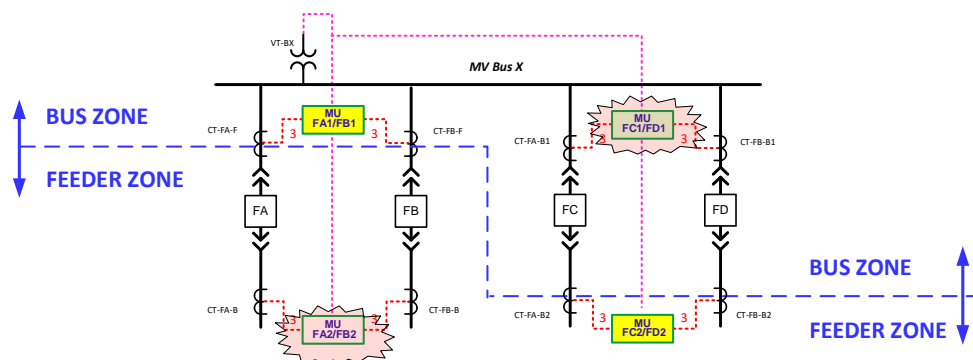
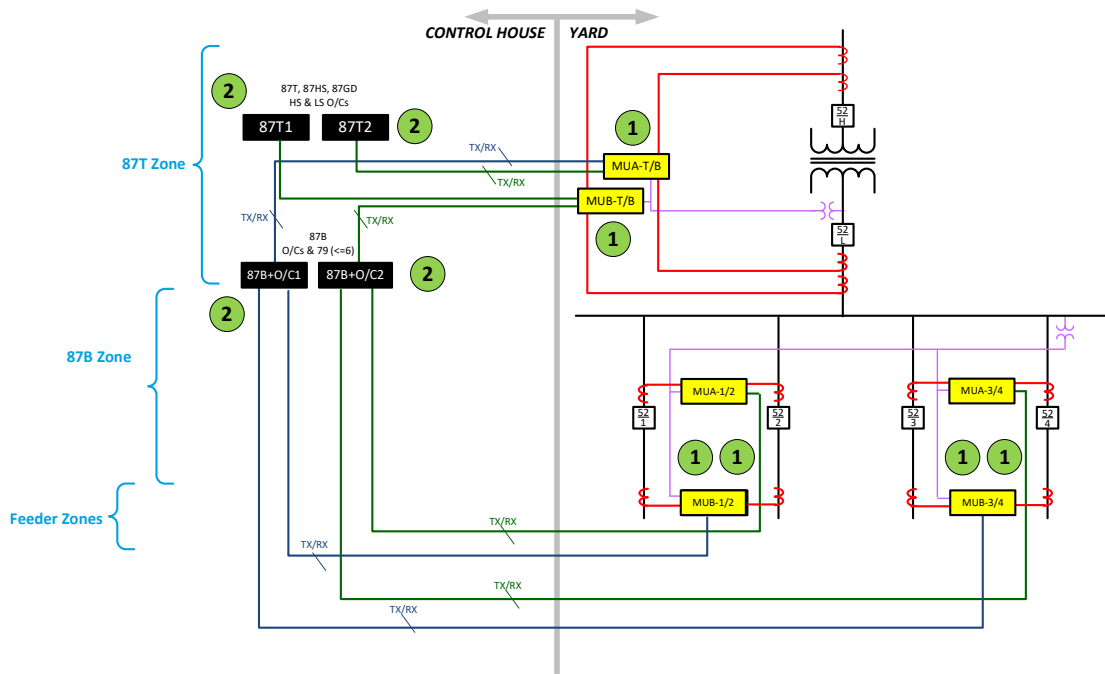
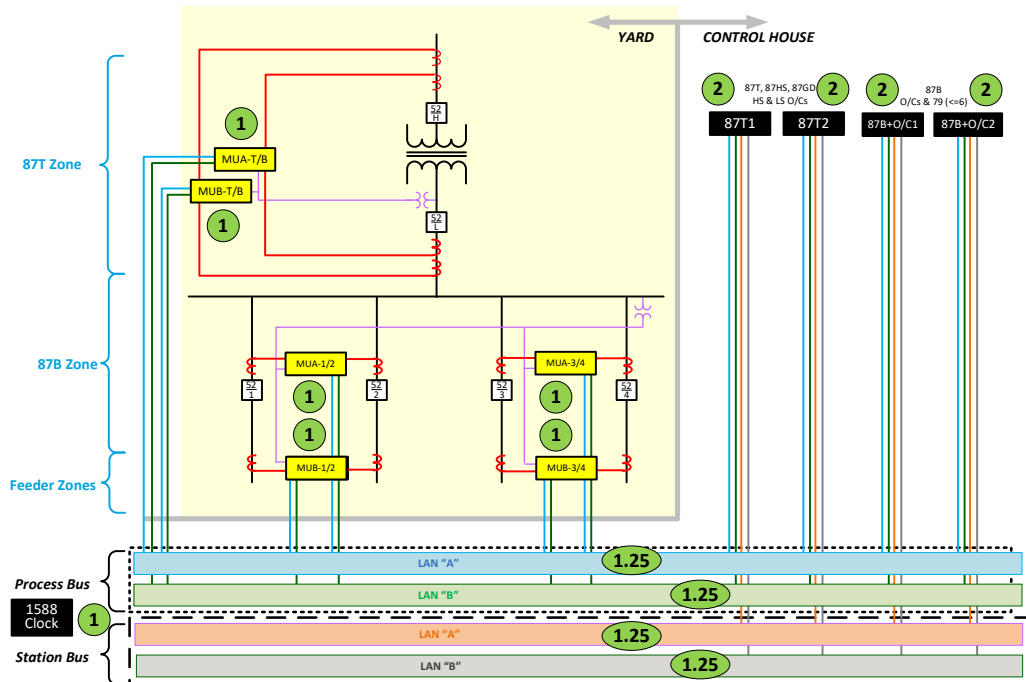


Fig. 11, MU Failures and Redundancy Considerations



**Fig. 12, SLD of a MU-Relay Direct Connected Straight Bus Substation, Redundant Protection System
CAPEX Protection Equipment Cost = 14pu**



**Fig. 13, SLD of a MU-Network-Relay Connected Straight Bus Substation, Redundant Protection System
CAPEX Protection Equipment Cost = 20pu**

Pu cost comparison summary for the straight bus substation, redundant protection system:

- Hardwired: 14.5pu
- MU-Relay Direct Connected: 14pu
- MU-Network-Relay Connected: 20pu

Employing a partially centralized direct connected solution to this straight bus, redundant protection scheme substation is approximately the same CAPEX as a hardwired solution for protection equipment. The partially centralized network connected solution is approximately 35% more CAPEX for protection equipment, however it offers self-monitoring and the ability to remain fully functional with failed CTs.

The third study will be for a M-T-M substation with two transformers, transformer high side and bus side CBs, two buses with four feeders, one main, and a shared tie with a single (non-redundant) protection system.

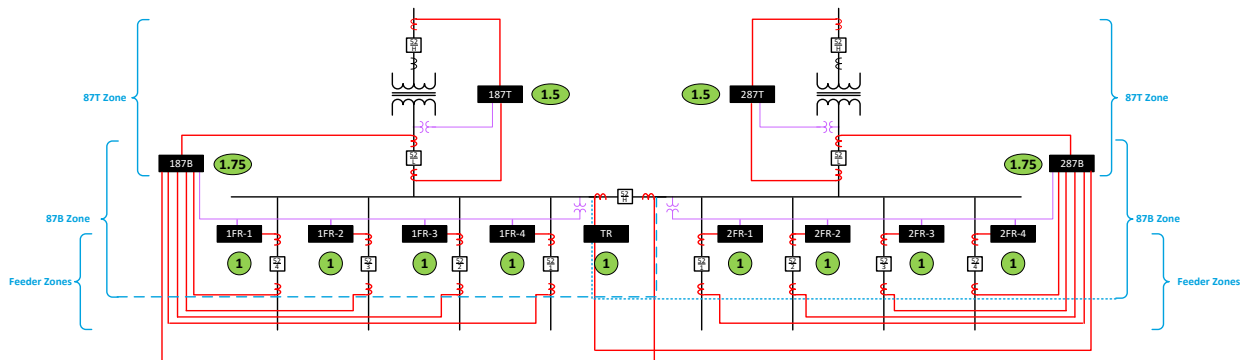


Fig. 14, SLD of a Hardwired M-T-M Substation, Single (non-redundant) Protection System CAPEX Protection Equipment Cost = 15.5pu

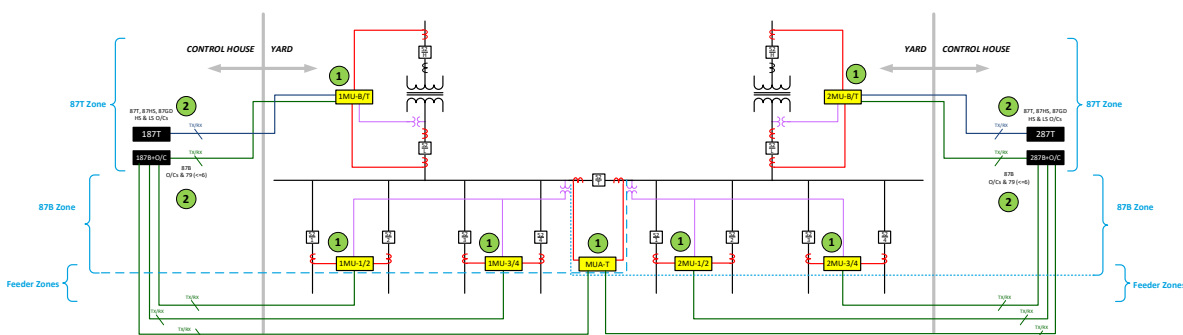
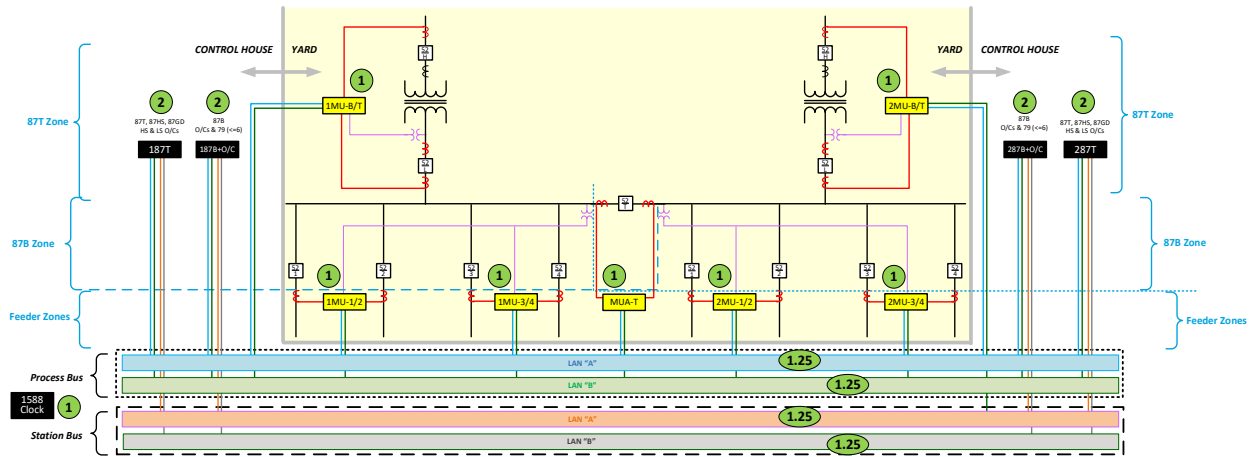


Fig. 15, SLD of a MU-Relay Direct Connected M-T-M Substation, Single (non-redundant) Protection System CAPEX Protection Equipment Cost = 15pu



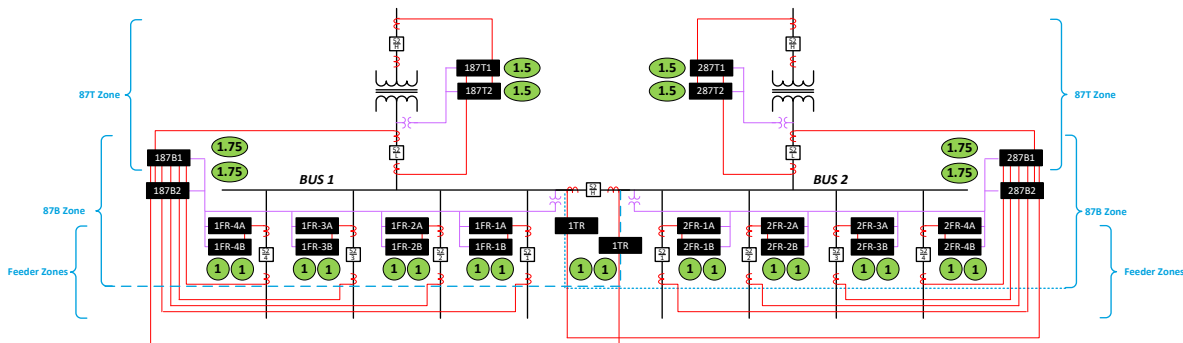
**Fig. 16, SLD of a MU-Network-Relay Connected M-T-M Substation, Single (non-redundant) Protection System
CAPEX Protection Equipment Cost = 21pu**

Pu cost comparison summary for the M-T-M substation, single (non-redundant) protection system:

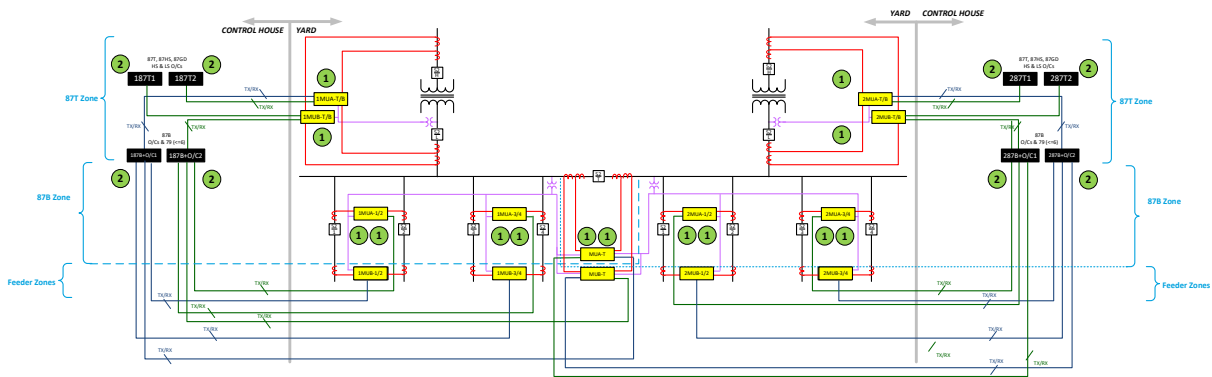
- Hardwired: 15.5pu
- MU-Relay Direct Connected: 15pu
- MU-Network-Relay Connected: 21pu

Employing a partially centralized direct connected solution to this M-T-M, single protection scheme (non-redundant) substation is approximately the same CAPEX as a hardwired solution for protection equipment. The partially centralized network connected solution is approximately 35% more CAPEX for protection equipment, however it offers self-monitoring and backup protection in the event of either the 87T or 87B+O/C systems (this is covered in more detail later in this paper).

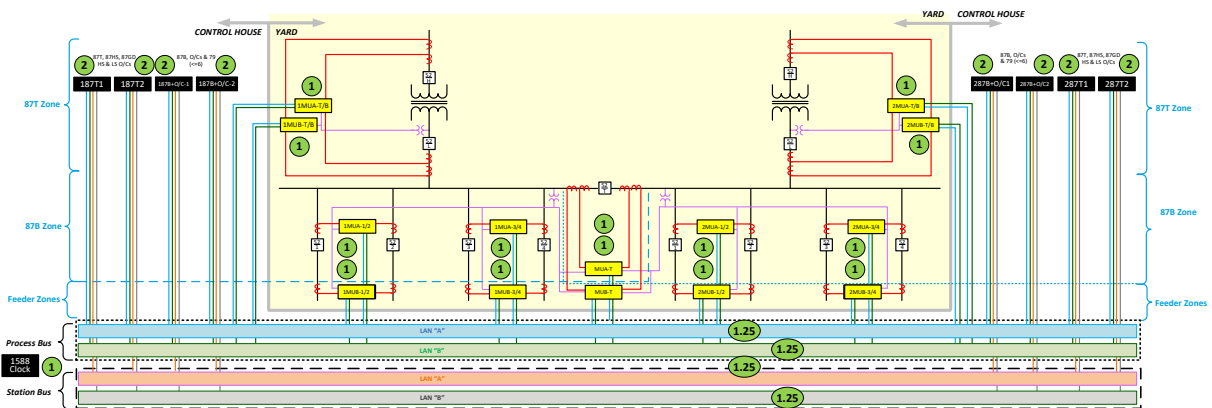
The fourth study will be for a M-T-M substation with two transformers, transformer high side and bus side CBs, two buses with four feeders, one main, and a shared tie with a redundant protection system.



**Fig. 17, SLD of a Hardwired M-T-M Substation, Redundant Protection System
CAPEX Protection Equipment Cost = 31pu**



**Fig. 18, SLD of a MU-Relay Direct Connected M-T-M Substation,
Redundant Protection System
CAPEX Protection Equipment Cost = 30pu**



**Fig. 19, SLD of a MU-Network-Relay Connected M-T-M Substation,
Redundant Protection System
CAPEX Protection Equipment Cost = 36pu**

Pu cost comparison summary for the M-T-M substation, redundant protection system:

- Hardwired: 31pu
- MU-Relay Direct Connected: 30pu
- MU-Network-Relay Connected: 36pu

Employing a partially centralized direct connected solution to this M-T-M, redundant protection scheme substation is approximately the same CAPEX as a hardwired solution for protection equipment. The partially centralized network connected solution is approximately 16% more CAPEX for protection equipment, however it offers self-monitoring and the ability to remain fully functional with failed CTs.

6] Backup versus Redundancy Application

Using the MU-Relay Network Connected Straight Bus Substation, Single (non-redundant) Protection System, we will develop backup protection schemes in the event of a partially centralized protection system failure.

In Figure 20 below, the 87T relay is protecting the transformer using CTs on the system and bus side of the transformer that are connected of MU-B/T. The 87T subscribes to the two sampled value (SV) streams from MU-B/T. The bus is protected by the 87B+O/C relay, subscribing to SV streams from MU-B/T (low side of transformer), MU-1/2 and MU-3/4. The feeders are protected by the 87B+O/C relay subscribing to SV streams from MU-1/2 and MU-3/4.

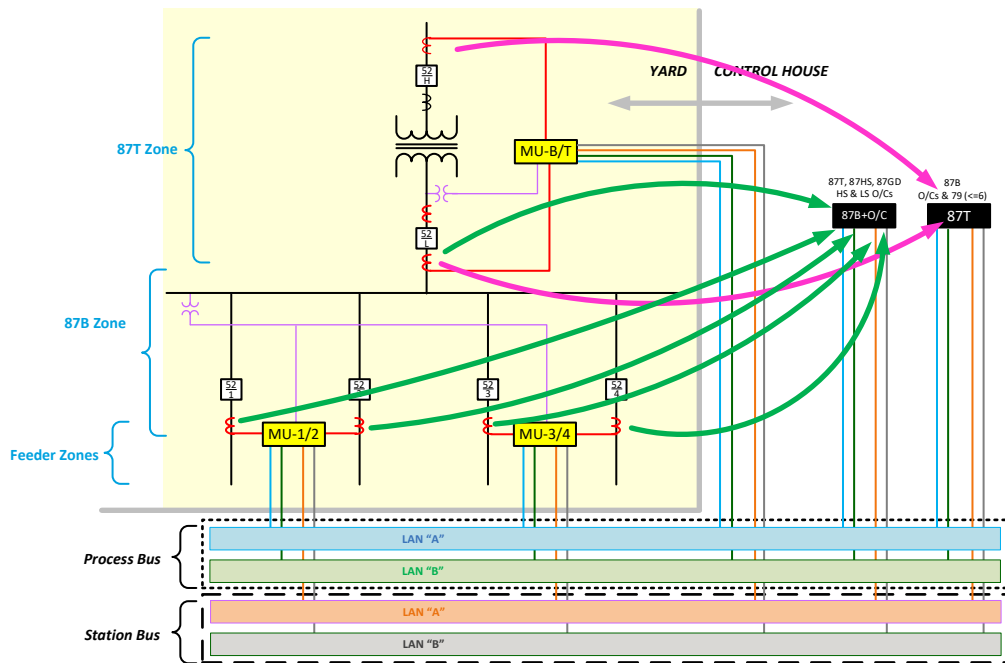


Fig. 20, SLD of a MU-Network-Relay Connected Straight Bus Substation, Single (non-redundant) Protection System, Sourcing of Currents for Functions

In the event of a 87T relay failure as seen in Figure 21 below, the failure is detected by the 87B+O/C relay. The 87B+O/C relay changes setting groups, and the 87B+O/C relay now subscribes to MU-T/B and uses the high side CT's associated SV stream, plus the feeder currents from MU-1/2 and MU-3/4 and employs zone sequence interlocking for the combination of bus and transformer primary protection. For inrush restraint, 2nd control is used on the reverse interlock scheme. The entire reverse interlock scheme is programmed and performed in the 87B+O/C relay.

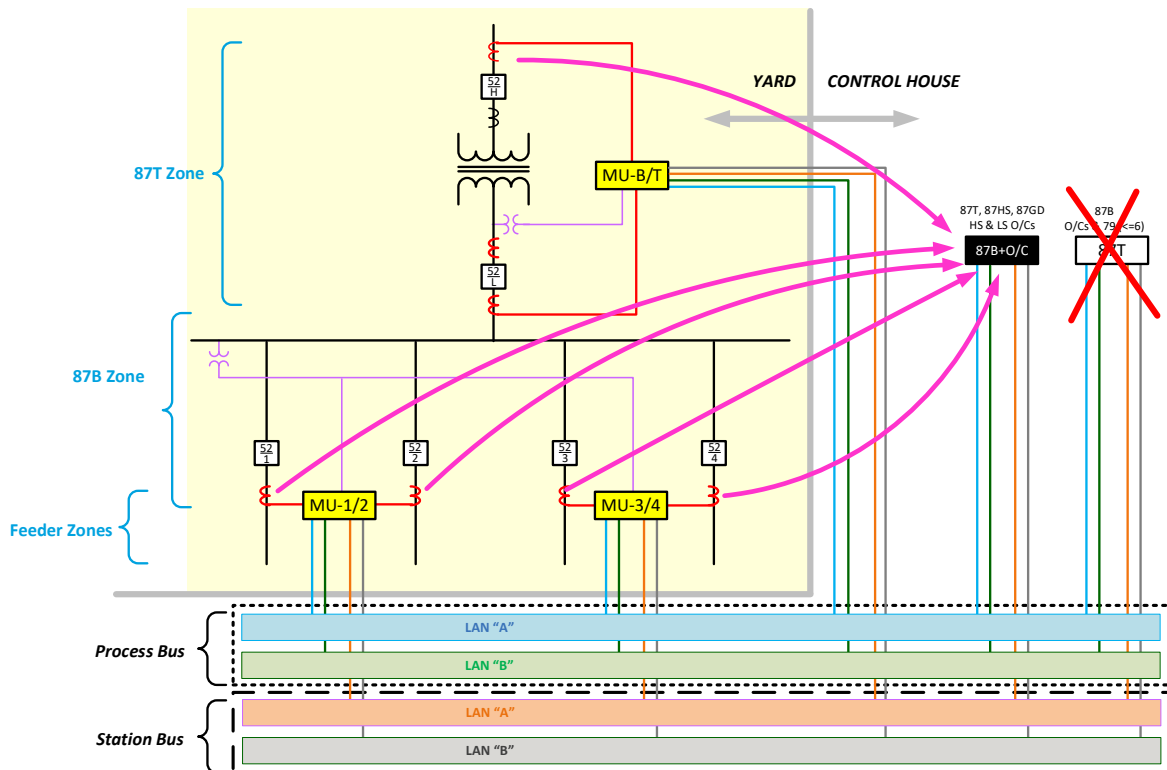


Fig. 21, SLD of a MU-Network-Relay Connected Straight Bus Substation, Single (non-redundant) Protection System, Failure of 87T Relay and Use of the 87B+O/C Relay for Backup

In the event of an 87B+O/C relay failure as seen in Figure 22 below, the failure is detected by the 87T relay. The 87T relay changes setting groups, and the 87T relay now subscribes to MU-T/B using the high side CT's associated SV stream, plus the feeder currents from MU-1/2 and MU-3/4. The feeder currents are now used by the 87T and 87HS elements, along with the high side transformer current, to perform the combination of bus and transformer primary protection. For feeder protection, overcurrent protection is applied for each feeder position by the 87T relay. For feeder protection, overcurrent protection is applied for each feeder position by the 87T relay.

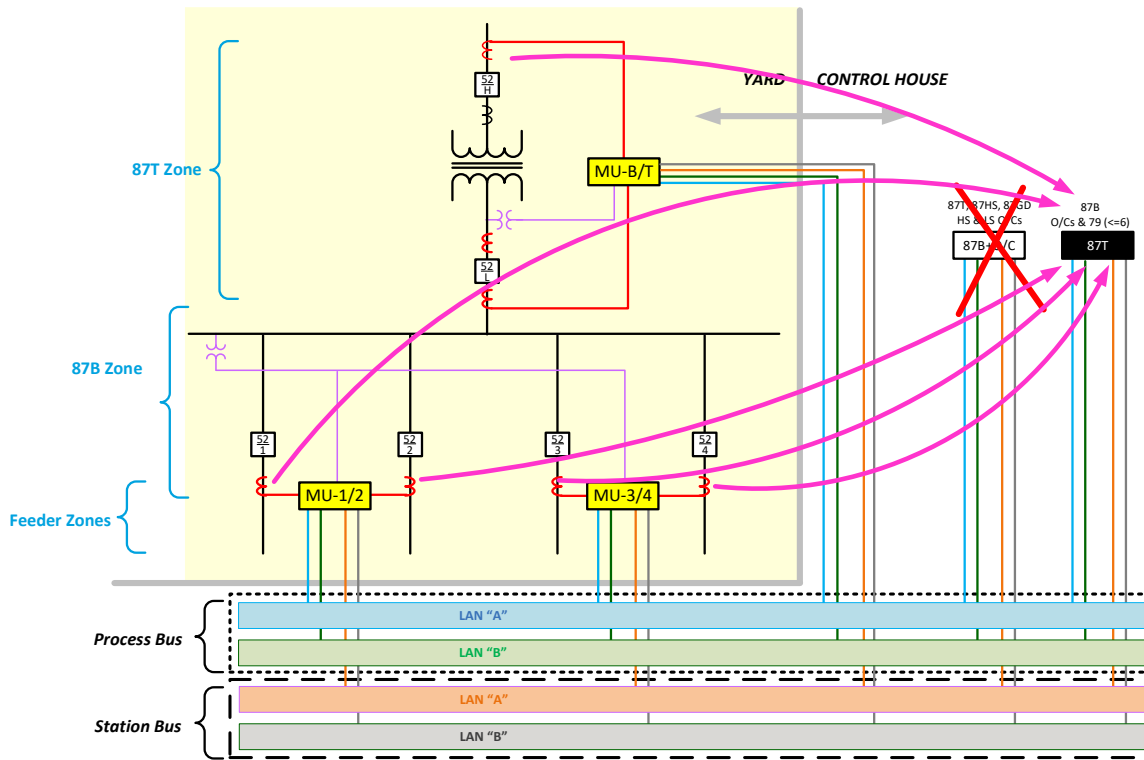


Fig. 22, SLD of a MU-Network-Relay Connected Straight Bus Substation, Single (non-redundant) Protection System, Failure of 87B+O/C Relay and Use of the 87B+O/C Relay for Backup

While a failure of one of the partially centralized systems impacts the quality of the protection, some backup protection is provided by the other functioning partially centralized system until the failed system can be replaced.

7] Hybrid Partially Centralized Application

Some applications and philosophies may lead to applying a full functionality feeder relay per feeder, and then use a partially centralized solution for bus primary/backup and feeder backup protection. This type of design would yield a *hybrid partially centralized* solution.

Figure 22 shows an example of hybrid redundancy using partial centralization. Our example is a main-tie-main station, (M-T-M), with Bus A and Bus B, each bus with 4 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 6 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 with dashed boxes around them.

In the event of an individual feeder relay failure, the combination bus/multiple feeder relay system provides the feeder protection.

In the event of the combination bus/multiple feeder relay system failure, the individual feeder relays provide the feeder protection, and the other bus combination bus/multiple feeder relay provides the bus protection and feeder protection.

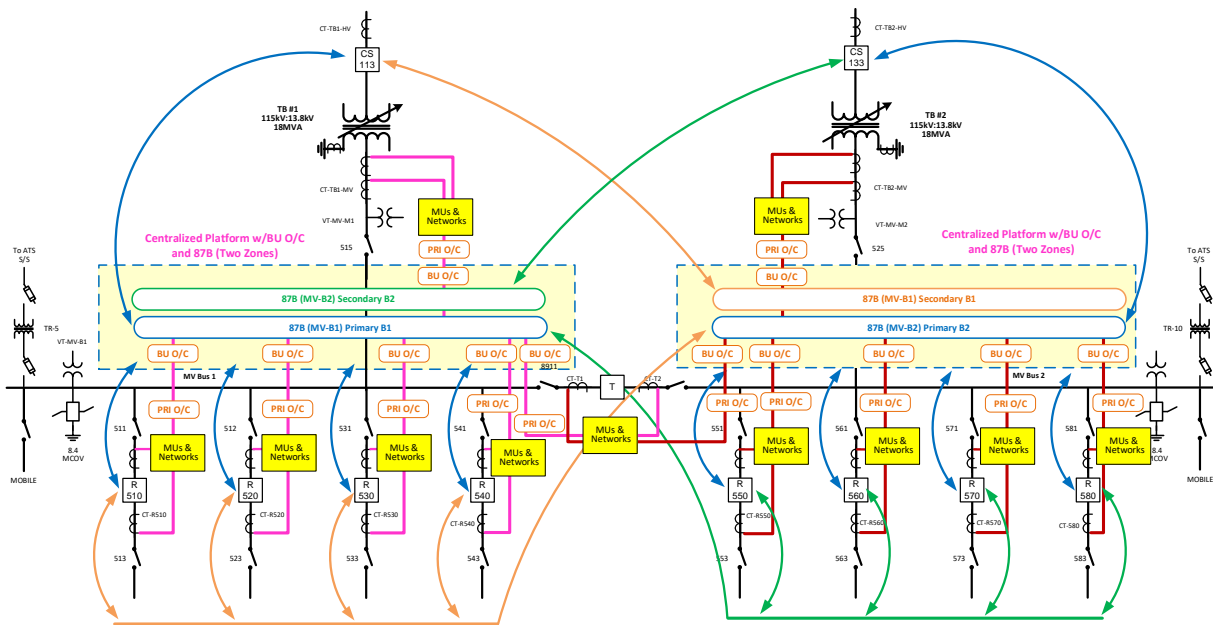


Fig. 23, SLD of a MU-Network-Relay Connected M-T-M Substation, Hybrid Redundancy Protection System,

Summary and Conclusions

- Economic considerations can be used to employ partially centralized protection systems.
- CAPEX cost for protection equipment for partially centralized direct connected protection systems are similar to an equivalent hardwired protection system.
- Although not discussed in this paper, one also realizes the reduction in design, engineering, installation (wiring and terminations), commissioning and maintenance for the partially centralized approach, direct connected or networked. This can offset the increased CAPEX for networked designs and produce overall project savings for both direct connected and networked designs. These reductions are discussed in a previous work that is listed in the references, "The Copper Diet – Recipes to Promote Standardization, Centralization and Redundancy in a Digital Substation World." Additionally, see Annex B.
- Excellent redundancy can be provided by partially centralized systems, exceeding hardwired designs.
- With non-redundant partially centralized designs, it is possible to apply acceptable backup protection

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7. "*The Copper Diet - Recipes to Promote Standardization, Centralization and Redundancy in a Digital Substation World*," Wayne Hartmann, Georgia Tech Protective Relay Conference, Atlanta, GA, May 2021

Author Biographies

Wayne Hartmann is Solutions Growth Leader (NAM) GE Grid Solutions. 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 Grid Solutions, 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."

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Annex A: Sampled Value Source Switching and MU and Instrument Transformer Failure Considerations

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.

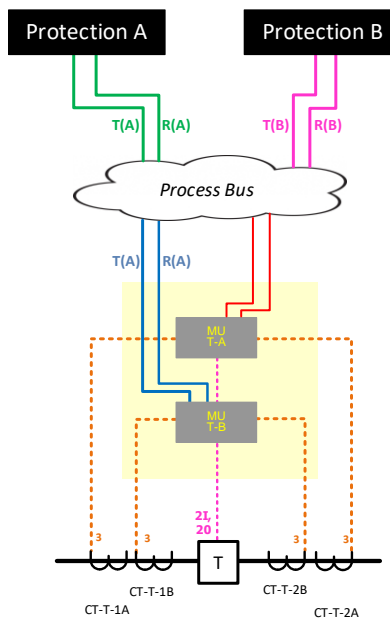


Fig. A1, Redundant System A & B using CTs, MUs and Relays

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.

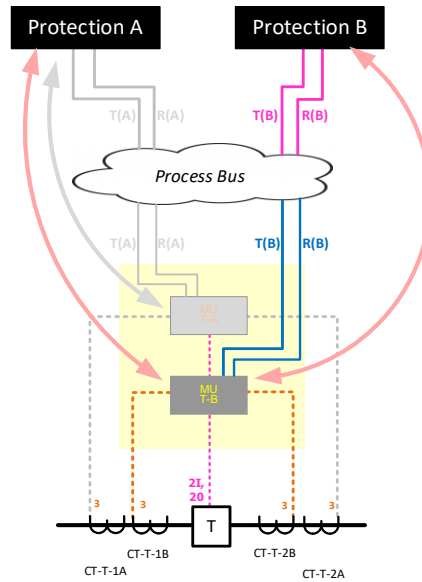


Fig. A2 MU T-A Failure with Relay A Employing Crosscheck with MU Switchover to MU T-B

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.

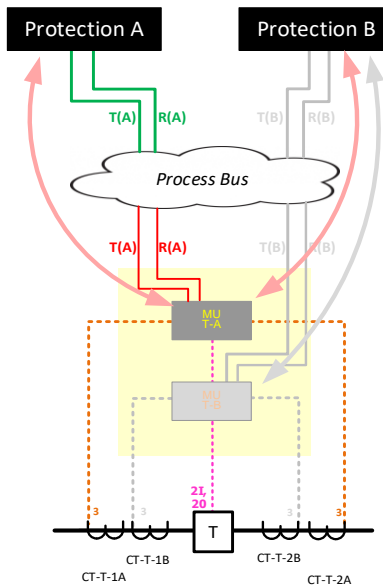


Fig. A3, MU T-B Failure with Relay B Employing Crosscheck with MU Switchover to MU T-A

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.

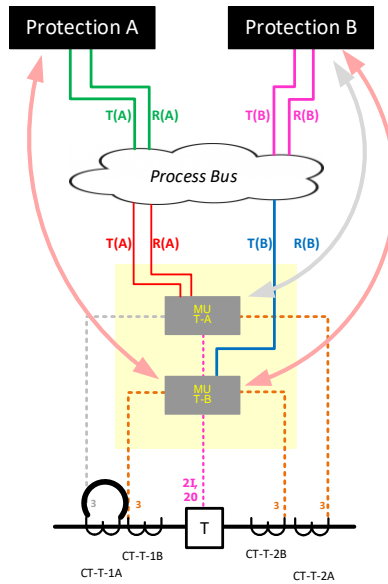


Fig. A4, CT-T-1A Failure with Relay A Employing MU Switchover to MU T-A

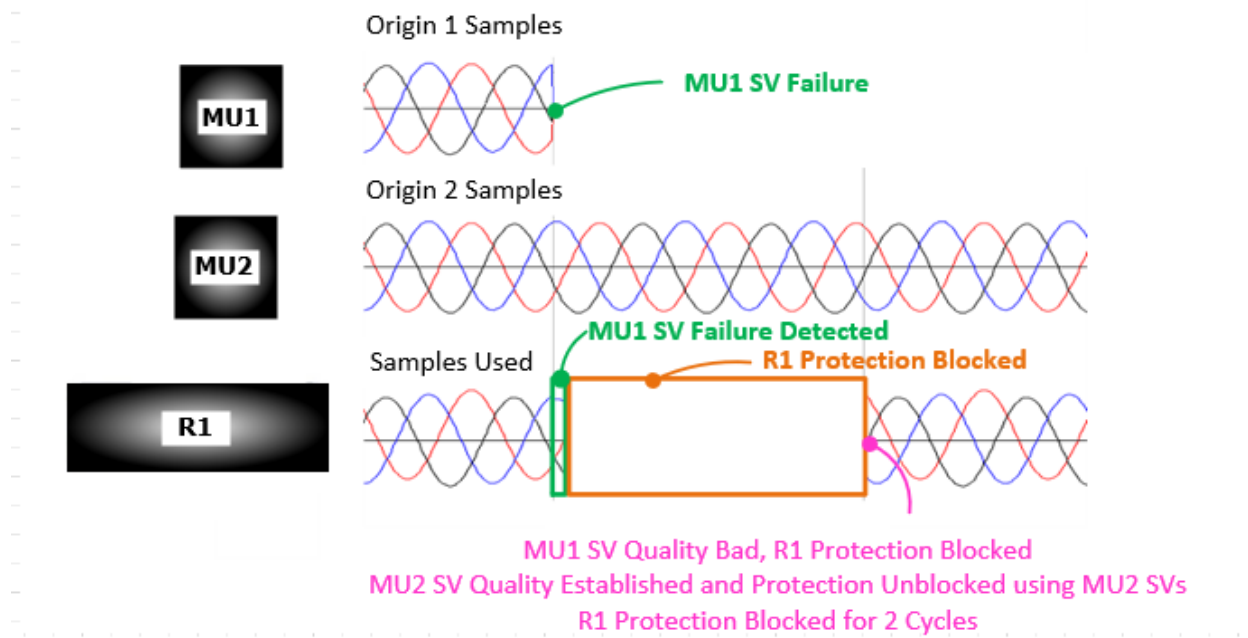


Fig. A5, Protection Blocking During MU SV Changeover

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.

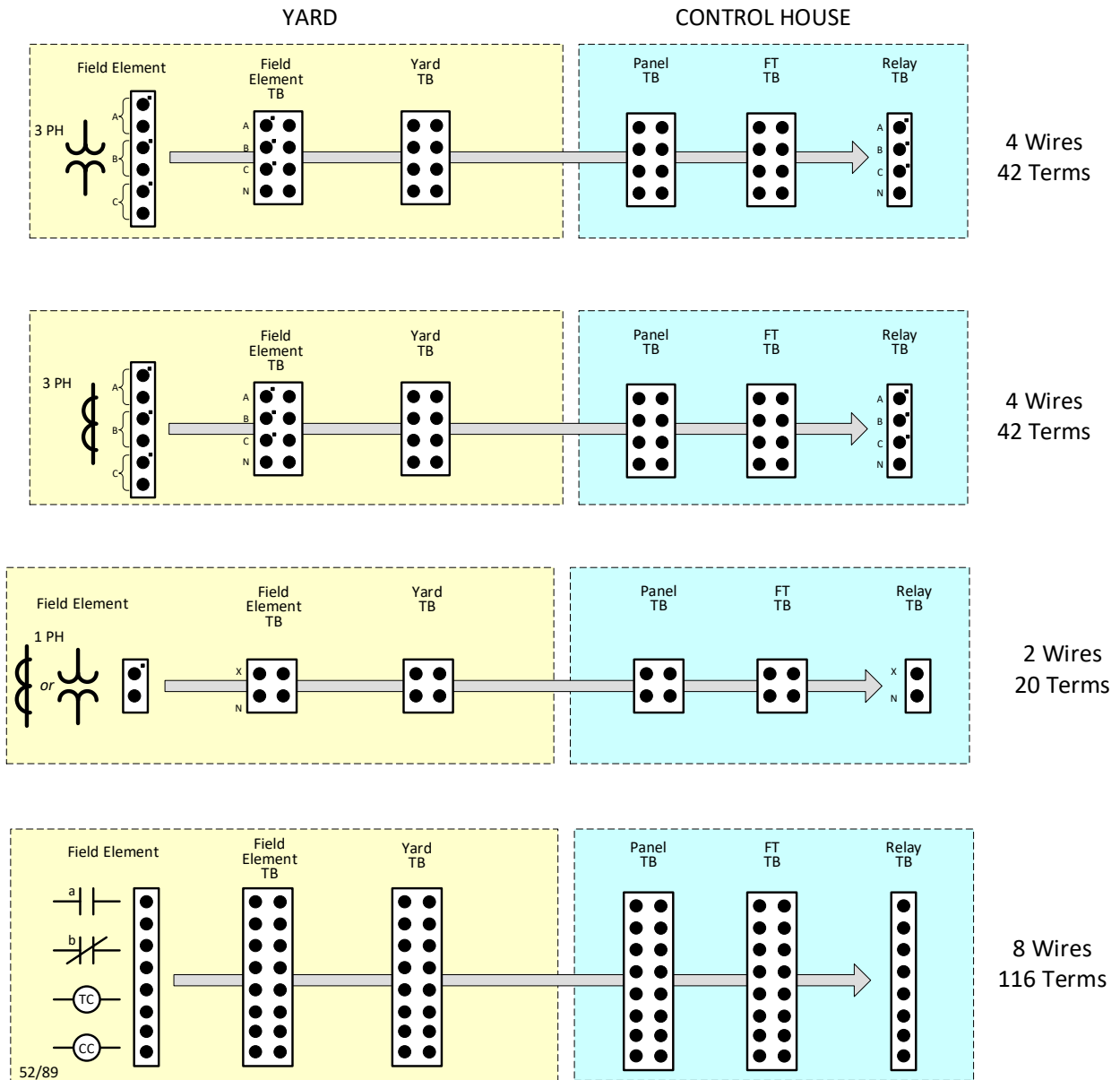


Fig. B1, Hardwired Terminations (Typical)

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

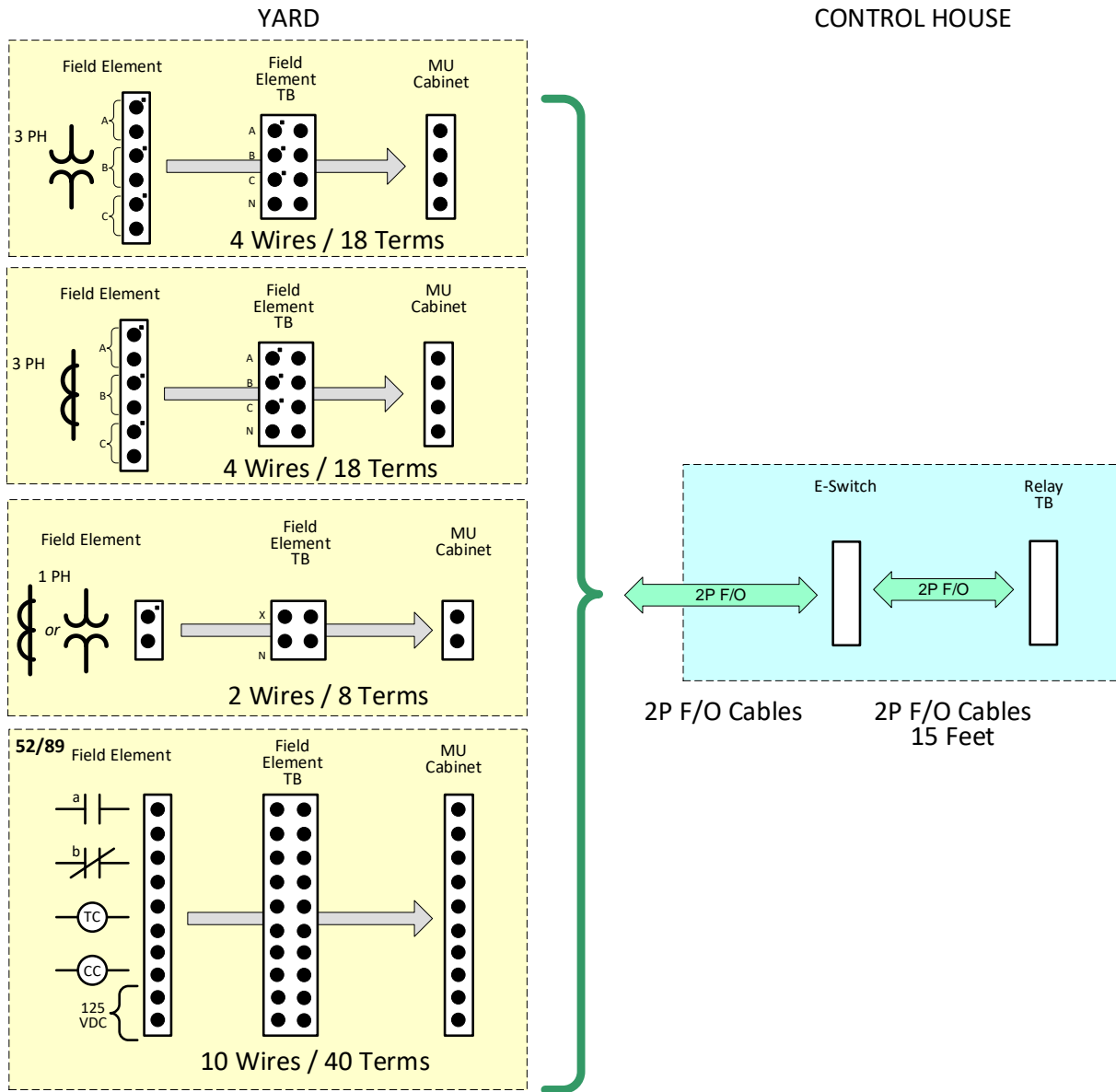


Fig. B2, Digital Substation Terminations (Typical)

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

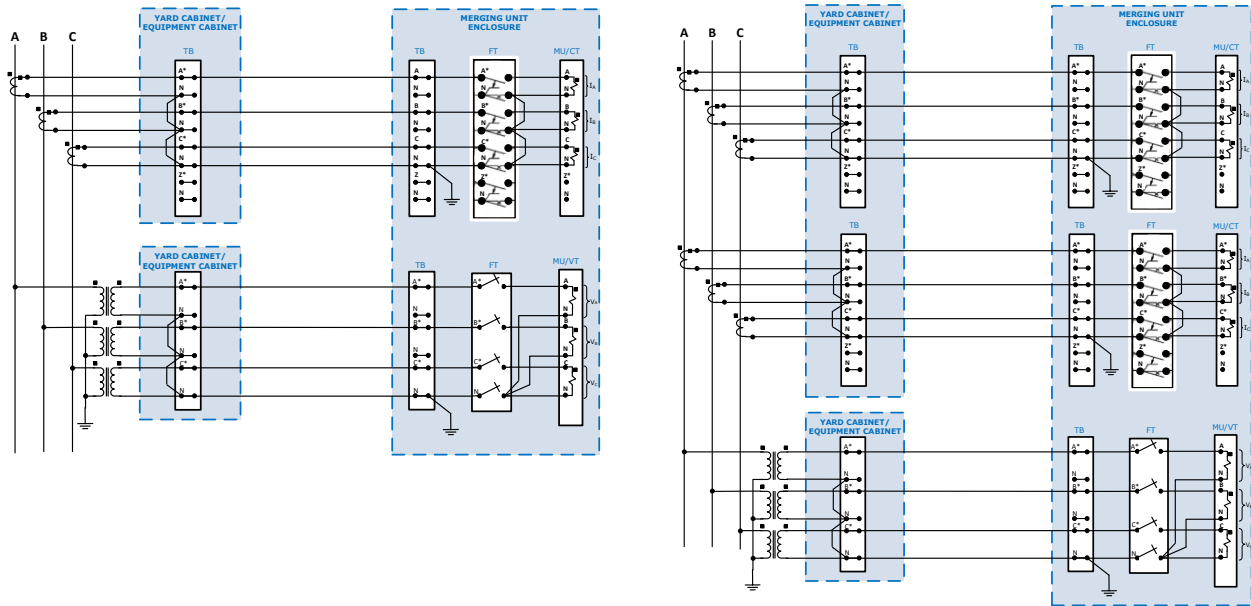


Fig. B3, AC 3-Line Typicals, Yard-to-Merging Unit Connectivity

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

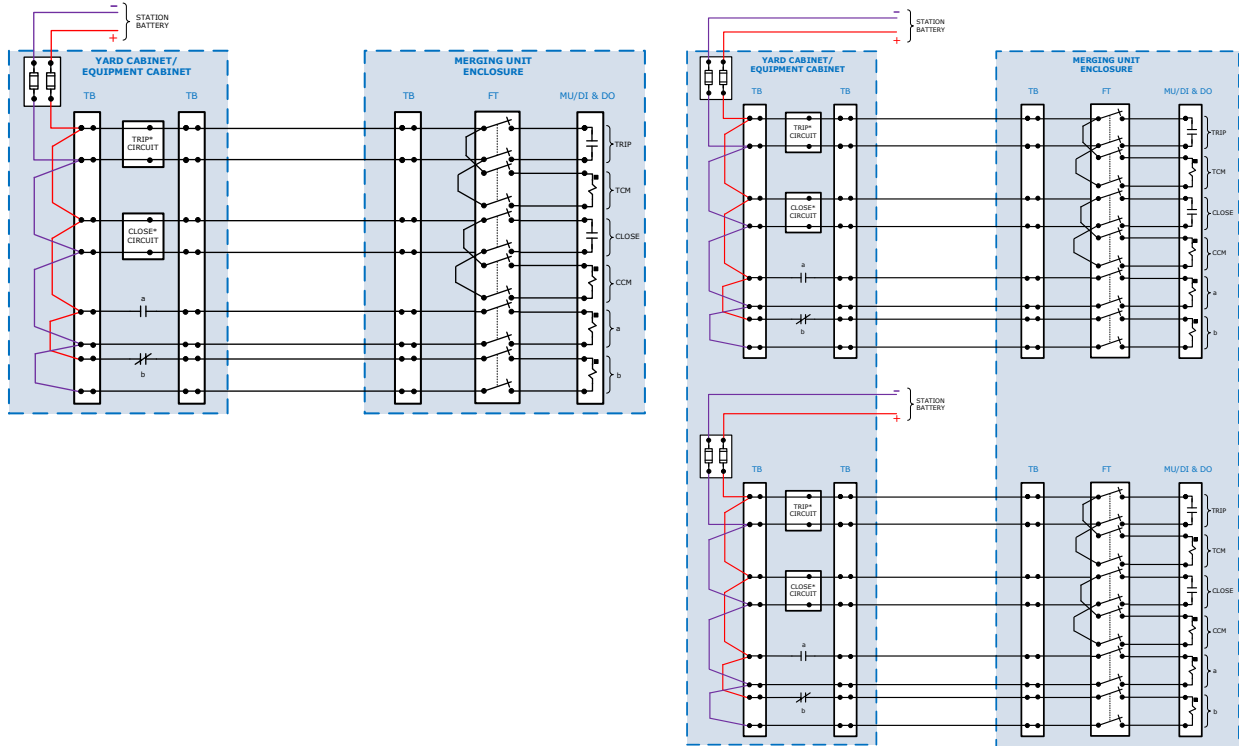


Fig. B4, DC Elementary Typicals, Yard-to-Merging Unit Connectivity

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.

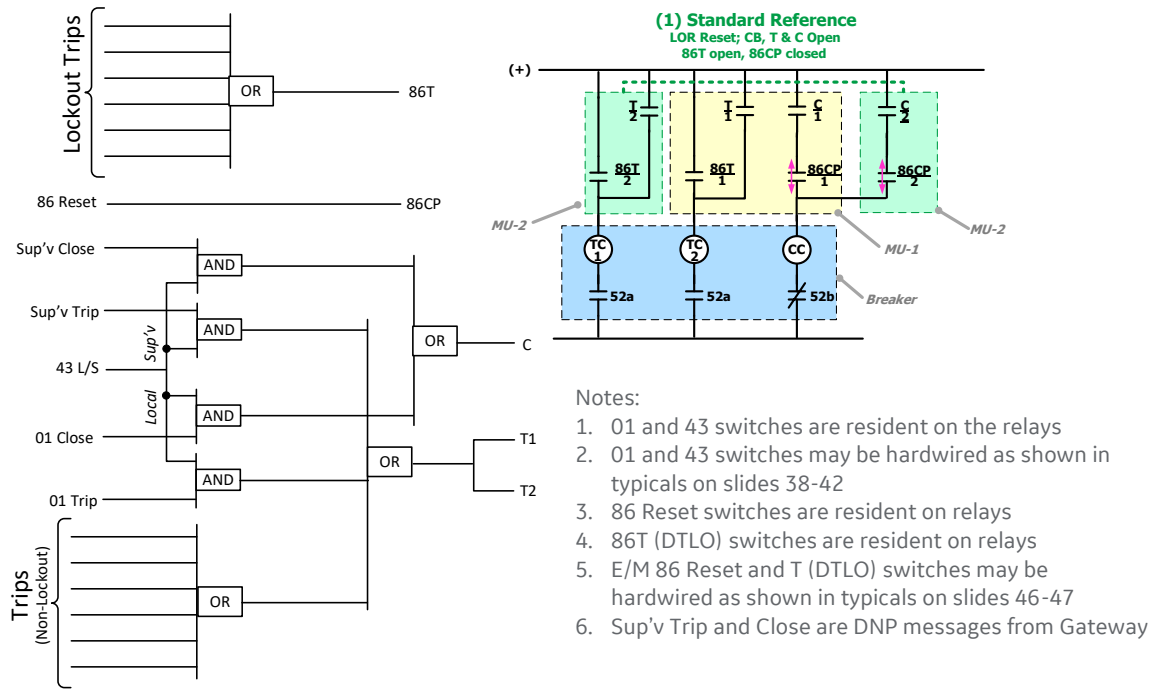


Fig. B5, Merging Unit Lockout/Trip/Close Functionality DC Elementary and Logic

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

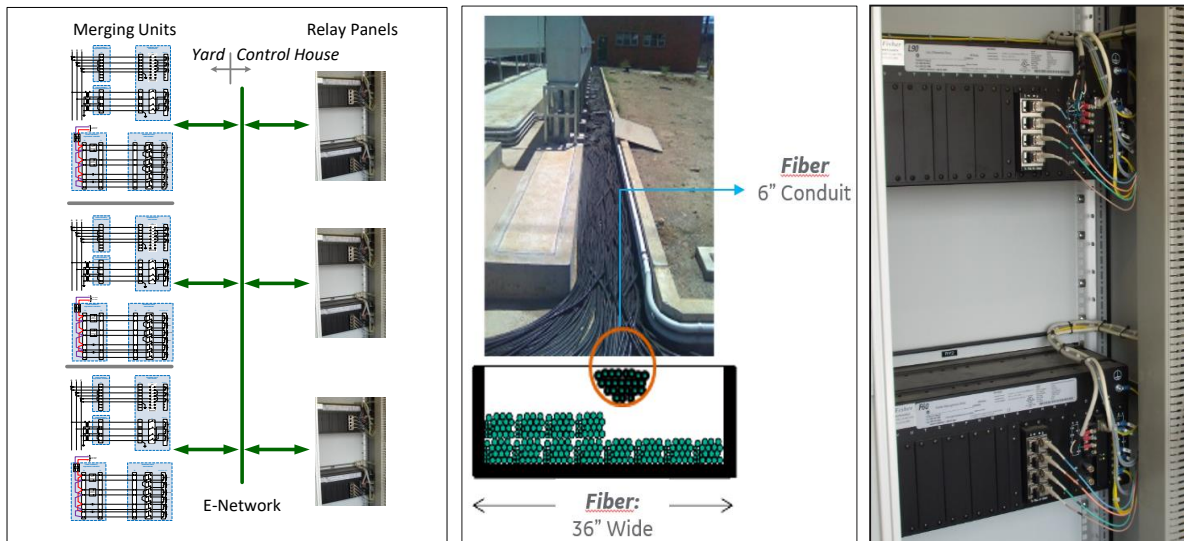


Fig. B5, Merging Unit Lockout/Trip/Close Functionality DC Elementary and Logic