SCHEMATIC REPRESENTATION OF POWER SYSTEM RELAYING

A report to the Relaying Practices Subcommittee I
Power System Relaying Committee
IEEE Power Engineering Society

Prepared by Working Group I5

Working Group Assignment

Report on common practices in the representation of protection and control relaying. The report will identify methodology behind these practices, present issues raised by the integration of microprocessor relays and the internal logic and external communication configurations, and present approaches to deal with these issues.

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1. Scope

This paper addresses the schematic representation of the protection and control systems used on power systems. This includes AC schematics, DC schematics, logic diagrams, data tables and single line diagrams that prominently feature relaying. There are other types of drawings that will be discussed but are not the subject of this paper including wiring diagrams, data communication schematics and those single line diagrams that do not significantly address relaying.

2. The Graphic Representation of Power System Relaying

Even though evolving technologies have affected all areas of system relaying there are some things that remain. There is still a common expectation that there be a hard-copy graphical representation of the protection and control system. This representation is used in the installation, testing, and maintenance of the system and is more commonly referred to as the schematics.

Schematics graphically arrange the components of a system to emphasize the functional arrangement as opposed to the physical arrangement. Emphasizing function facilitates an understanding of how the system is supposed to operate and makes functional testing of systems much easier because it highlights relationships between elements. Schematics show what is affected by the closure of any contact in a system or what inputs are needed by a component to enable an action. However it is fundamental that the schematic include some physical information so the expected actions can be matched to reality.

Yet, even though schematics remain, the adoption of those aforementioned emerging technologies is driving a redefinition of schematics. This has been evidenced by the discussions arising during efforts to revise IEEE C37.2 Standard Electrical Power System Device Function Numbers, Acronyms and Contact Designations and especially illustrated by the revision to add device number 16 – data communications device.

When C37.2 was first adopted, devices were single function and therefore the relationship between the function a device performed and the device itself was very close. Now, with the continuing implementation of multifunction devices, the requirement of C37.2 is not as much to standardize the reference to devices as to the reference to functions. This is motivated by a fundamental shift in schemes; as the number of physical components of a protection system has reduced, the functional complexity of that same system has increased.

There was a time when many power system operators had settled on schematics that struck a balance between the physical and the functional. Multifunction devices, data network devices and how relays input to each other are all now affecting that balance. With so many different people addressing the same issues in so many different ways, it seems like a good time to record the issues that have been addressed and the solutions that have been proposed.

2.1. Issues Behind the Need for this Report

A convergence of forces leads to the specific necessity of this report. One is the ongoing demographic shift in the industry work force that results in an annual net loss of expertise. Another is the unique opportunity at present to enable a considerable investment in the technical updating of the electrical power system in total. This rapid evolution of the grid includes transformative technologies that will redefine long standing practices. Some of these practices have never been fully documented in the first place and the window to the expertise that best understands these practices is limited. This report is intended to capture some of these best practices and their application to the new technologies. It also collects some of the new approaches to meeting the challenges raised by new technologies.

2.2. The Role of Schematics

A schematic is a diagram that represents the elements of a system using abstract, graphic symbols rather than realistic pictures. The reason for not emphasizing reality is to communicate function, instead. A schematic usually omits all details that are not relevant to the information the schematic is intended to convey, and may add unrealistic elements that aid comprehension. The information that the schematic is intended to convey is determined by its role. Three types of schematics are the single line diagram, AC schematic diagram and DC schematic diagram. Any depiction of reality by the single line diagram is on a large scale, it might show where major pieces of equipment are in relation to each other. On the other hand, though the AC and DC schematics still don't show reality in every detail, they will contain information that will provide the link between the real depiction of the equipment seen in wiring diagrams and the almost purely functional depiction shown in the single line diagram.

Specifically, an AC schematic diagram shows, by means of graphic symbols, the electrical connections and functions of a particular circuit arrangement. A DC schematic diagram is frequently used to represent the logic of electrical control systems (switching or relaying) including a number of switches or contacts, time delay and latching type relays, push buttons, limit switches, lights, and controlled devices like motor starters and solenoid operated valves. Consequently, the role of the schematic is to facilitate tracing the measuring and control circuits and the understanding of control functions without regard to the actual physical size, shape, or location of the component device or parts. In the schematic diagram, the symbolic elements are arranged to be easily interpreted by the viewer.

Power system relaying has unique requirements for long term accuracy to serve maintenance and troubleshooting needs. The facilitation mentioned above for tracing circuits and understanding functions is especially important to the requirements for maintenance and trouble shooting. For these reasons, these drawings will get special emphasis.

2.3. Drawing Types

There are several types of drawings used to document and communicate details of the protection system to those who need to understand it for the purposes of construction, installation, testing, maintenance, and event analysis.

The typical drawing set will include the drawing types listed here and described in the following sections.

- Single-line diagram (meter and relay single line or one line diagram)
  - Shows the overall scheme and connections and interactions between equipment and relay system components but in a simplified manner. For example, it uses a single line to represent three phases (hence the name "single line"). The information is shown schematically, but the high-voltage portion is usually shown in a pseudo-physical layout that matches or mimics the actual bus layout in the substation. All relays and other major components are assigned a unique identification. The identification is carried through the entire drawing set. There may be other drawings in the single line format. There may also be a one line diagram that emphasizes the power system equipment and does not detail the relay system components but only those elements connected directly at the primary voltage. This may be referred to as the "station", "station one line", or "power one line" diagram. There may also be a simplified one line diagram showing all the protection schemes and their intended zones of protection. This is referred to as the "protection zone" or "meter and relay single line" diagram.
- AC schematics (AC three-line diagram, three-line connection diagram, current and potential diagrams, elementary wiring diagrams)
  - Shows detail about the connections between the instrument transformers (CTs and VTs) and the relay system components. These are schematic diagrams that allow users to quickly trace a signal through the circuit and understand the function without regard to the actual physical wiring locations. Detail will include specific terminal numbers of devices and test switches to which connections are made. Intervening connections to terminal blocks may or may not be shown depending upon the level of completeness desired. (Complete wiring detail is shown in the wiring and connection diagrams. Adding the detail shown in the wiring diagrams to the schematics may make them too confusing and detract from overall understanding.)
- DC schematics (relay systems almost universally use DC for the controls; control ladder diagram or sometimes these are also referred to as elementary wiring diagrams)
  - Schematic diagrams that show interconnection of components and how they function in the control circuit without regard to the physical locations of the components. These allow users to quickly trace control signals through the circuit and understand the function of the various components. Detail will include specific terminal numbers of devices and test switches to which connections are made. Control flow is generally shown so that the diagram is read from upper left to lower right.
- Communication diagram [telecommunications, block diagram, local area network (LAN) architecture diagram]

  - Telecommunications related diagrams detail operating requirements for the mode of telecommunication in use, i.e. power line carrier, fiber optic, telephone, microwave, etc.
  - Inter-device communication diagrams show the interconnection of components and how they communicate to each other without regard to physical locations of the components. Detail will include specific port numbers of devices to which connections are made.

- Logic diagrams (to represent the control logic programmed in devices)
  - Show the function of the control logic in the control scheme. Logic gate symbols are used to show the Boolean logic functions performed. These diagrams show graphically how the inputs are processed with delay timers and level comparisons to generate outputs. Logical Outputs may be combined with the status of other logic for further processing, get communicated to other devices over communication circuits, or assert physical output contacts that cause some action in the control circuit.
- Panel layout diagrams (panel arrangement diagrams, front views, electrical arrangement diagrams)
  - Show the physical locations of components on the panel. These are usually scale drawings for the purpose of fabrication. All items are uniquely identified so that the specific device can be found in the schematics.
- Wiring diagrams (panel wiring diagrams, control wiring diagrams)
  - Show the point-to-point connections between components. Wiring diagrams are pseudo-physical to match the layout of the components on the panel as if looking at the panel from the side where the wiring takes place (back view if wired from the back). This gives a road map of the connections between devices to facilitate assembly, debugging, and testing. Connections may be shown either by a line representing the wire between the two points or with a label next to each terminal indicating the destination device and terminal. Modern practice most often uses the labeling method which is easier to read when there are a lot of connections on the panel. The wire destination labels may be listed in tabular form next to each device instead of individually next to each device terminal.
- Interconnection wiring diagrams
  - Show the connections between control panels and other panels or equipment. Interconnection cables are shown using “off-page connectors” that indicate the drawing number where the other end of the cable can be found. Off-page connectors will be unambiguously identified as to their destination. Panel interconnections may be shown on the same drawings as the panel internal wiring instead of having a separate interconnection diagram.
- Miscellaneous schematics and wiring diagrams
  - These complete the drawing set to show the various miscellaneous connections that must be made to equipment for proper function of the equipment but do not directly impact the control scheme. An example of

these drawings would include the AC power connections to cabinet heaters, circuit breaker tank heaters, substation yard lighting, and power to pumps, fans, and motors. Note also that this report emphasizes those drawings specific to a single site however there are many other graphical representations that support the design of protection and controls systems by detailing connections between substations. Drawings that show proposed interconnections and relative arrangements of transmission lines, power transformer banks, power circuit breakers, and other network elements are sometimes called planning diagrams or project diagrams. These drawings might also provide telecommunication circuit path information for different functions such as remote control, protection, and or wide area schemes. These drawings have minimum design detail and are intended to show functional interconnections and basic equipment requirements.

2.4. Drawing Hierarchy

There is a hierarchy of detail that exists between these drawings. The single line is the most simplified schematic and least detailed. It relies on basic symbols to represent different types of equipment.

The AC and DC schematics contain the next level of detail as they now indicate specifically how a device is connected to other devices. The symbols are still fairly simple but now must be large enough to contain the necessary connection details and, for multifunction devices, function details. Devices are usually arranged in a fashion that emphasizes function over location.

The remaining drawings contain the greatest detail. For most of these drawings, not only do they maintain the connection details carried from the schematics but also the physical details that allow for the specific location of the device and the connection of numerous wires. In these drawings, devices must be shown precisely as physically oriented to insure the quality of the installation. In these drawings, the representations are much closer to how the devices actually look and may be a view of the device provided by the manufacturer.

Logic diagrams contain the same level of detail as wiring diagrams. As the functions that were formerly interconnected through wiring are now performed internally in intelligent electronic devices (IEDs) or logically between IEDs, logic diagrams detail specific programming in the IEDs that is either native in the IED or customized by the user. These drawings may include tables that spell out specific messages sent by IEDs to other IEDs.

Therefore, with this hierarchy in place, quality control can be obtained by comparing single line to schematic and then schematic to wiring diagram. This ensures that the functional requirements portrayed in the single line are carried through the last wiring diagram.

2.5. Uses of Drawings by Different Parties

The amount of detail provided by each type of schematic drawing depends upon the intended use. Drawings often have multiple uses each with relative importance and each with special requirements. Day to day activities associated with power system work include planning, designing, managing, estimating, commissioning, testing, operating, maintaining, consulting, and providing legal records. The activities are performed by personnel from different organizational groups such as attorneys, project managers, electricians, relay technicians, design engineers, substation operators, system dispatchers, and system planners. How each function is situated within the organizational structure of a power system operator might impact how the different types of drawings are combined and used. Certain functions such as real time power system operation have very high priority when compared to activities such as accounting that can be done at any time after the fact. This is then reflected into the level of detail contained by each type of drawing depending upon its purposes and priorities.

Documentation of the functionality, locations, and interconnections of power system equipment should be complete, concise, clear, and easy to follow. This enhances the ability of technicians to quickly troubleshoot, locate, and solve power system problems. Information that is of high importance to a system planner may not be so important to a system dispatcher or to a maintenance electrician or switchman, and vice-versa.

Reliable power system operation requires certain types of drawings to present information in a way that provides priority to this operation function. A hierarchy or level of detail is recommended for each type of drawing so that when a problem occurs, a highest level survey may first be accomplished. Once relationships between, and relative locations of, malfunctioning equipment can be identified by high-level, wide-view drawings, then lower-level, more narrow-view drawings with greater detail can be consulted.

For example, the Station One Line Diagram is often the highest level drawing which shows the relative arrangement of switchyard equipment. The primary purpose is to aide in day to day operation and switching of the power facility. As a second purpose, Station One Line Diagrams are also needed and used to plan and design additions and changes to the power system. These, as well as all the other types of drawings, may also become a legal record of information. Because of the importance of this drawing to power system operation, a wide view of how controls and protective relays interface with the controlled switchyard equipment is typically provided on the One Line Diagram. Only a minimum amount of information, such as switch position, identification, basic ratings, instrument transformer locations and relay and control system interconnections are shown to avoid unnecessary clutter or ambiguity. Equipment interconnections shown by other design drawings might depend upon these identifications, for example the drawing that shows the control cable layout.

An illustration of how different purposes are addressed in a drawing involves an example of how drawings serve the operating function and the maintenance efforts. Substation operators often designate equipment based on its relationship to the rest of the power system. For instance, a high voltage line may go between Station Alpha and Station Beta so it might be known by operators as the Alpha Beta Line and the circuit breaker that feeds this line would be the Alpha Beta CB. However, functions such as installation and maintenance need to treat the station as a closed system. Equipment will be given unique designations within this closed system. This allows two things to happen. Designs can be standardized across substations. And designs are more stable because they don’t have to be changed if the power system changes. So the Alpha-Beta CB may also be known as

CB100. This way, if Station Gamma gets built between Alpha and Beta and operators now know the breaker as the Alpha-Gamma CB, maintenance can still know it as CB100.

More detailed, narrow views are necessary for troubleshooting and are provided by drawings such as the AC schematics, DC schematics, logic diagrams, and communication diagrams. All of these drawings are typically used by relay technicians or craftsmen for troubleshooting or for routine equipment maintenance. They are also used by designers to help determine requirements for future additions and modifications.

Those tasked with constructing the system have a need for great detail. Panel wiring drawings are used to show electrical connections between devices within panels. Layout drawings are used to show exact dimensions and the panel arrangement for relays, test switches, terminal blocks, and other panel mounted equipment. Alpha numeric equipment identifiers are used to uniquely identify each device showing precisely where it is located on the panel. These locators might also be shown on relay and control schematic diagrams to help technicians quickly locate problematic equipment. Because of the level of detail on these drawings often material lists are included which describe and identify each device located on that panel by manufacturer type number. These lists might also be used for accounting purposes.

3. Protection Zone Diagram

The Protection Zone Diagram is a single line graphic representation of the substation showing the protective relay systems within the substation. Figure 1 is an example of this type of diagram. There is a legend box on the diagram that shows the definitions of the abbreviations used. These abbreviations are used inside a "bubble" to identify the type of protection used on each zone and are placed along the zone line. A short list of examples of the legend is: BD = bus differential, TD = transformer differential, BF = breaker failure and LP = line protection.

One benefit to using this diagram is the zones are over lapping each other to insure no holes of protection within the substation. An "X" placed anywhere within the substation on the Protection Zone Diagram to indicate a fault location will show which relay system(s) and breakers would operate. Once the protection zones have been identified this diagram helps determine placement of CTs.

This diagram shows all equipment numbers, i.e. breaker numbers, bus numbers and kV, transformer number and rating, and location and quantity of VT's.

An example of a bus differential zone from Figure 1in the lower right area: a line is drawn from the side of the breakers where the bus differential current transformers are located to the low side of the transformer, where its current transformer is. Notice how the low side of the TD zone wraps around the BD zone.

Also notice the LP symbol in the lower left of the diagram representing line protection. Because this line protection "looks" in the direction of the line, we can put arrows on the zone, but we cannot enclose the box because the zone actually extends beyond to the next substation.

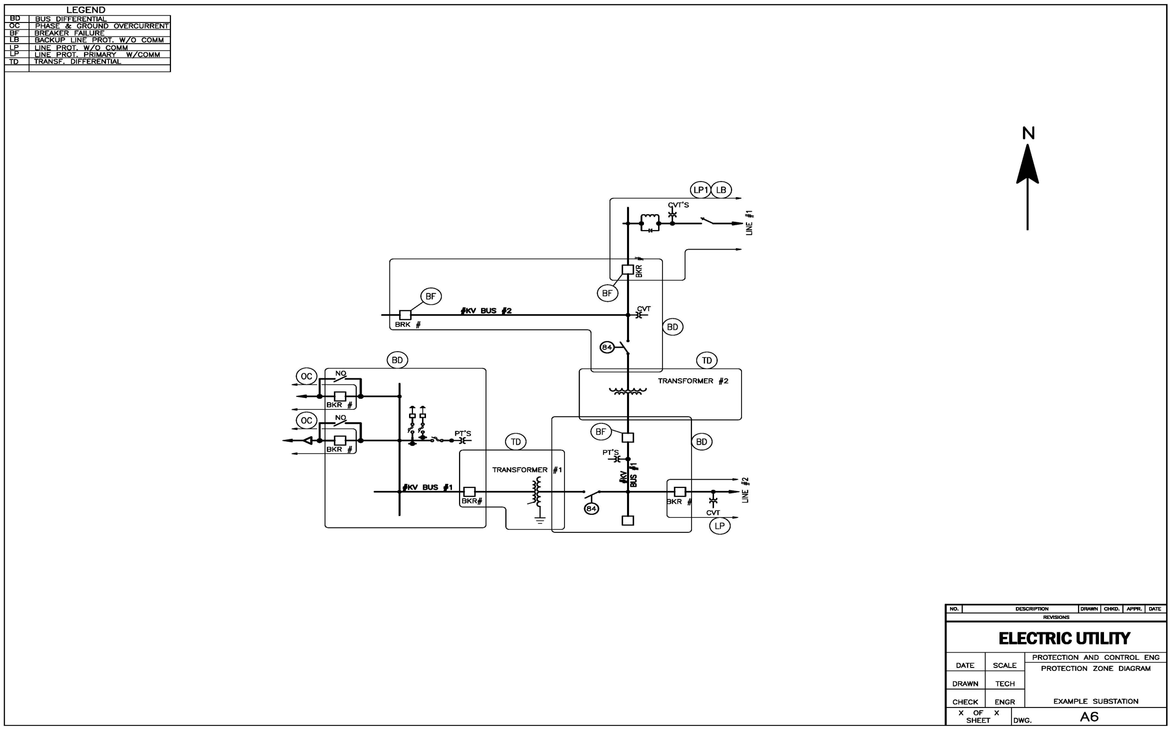


Figure 1: Protection Zone Diagram

4. Single Line Diagrams

The single line diagram (SLD) is the most basic of the set of diagrams that are used to document the electrical functionality of the substation. Its emphasis is on communicating the functions of the power equipment and the associated protection and control system.

Details about connection and physical location are not as important unless they serve the purpose of communicating function. For example, in Figure 10, the CT polarity marks indicate the direction of the current that a protective element is oriented to, thereby implying a function. Symbols very similar to Figure 2 and Figure 3 can be seen in Figure 10 which is an example of an SLD. The challenging task behind the SLD is to include all the necessary data while keeping the diagram easy to read. Therefore the single line may rely on non-intuitive symbology to represent devices since communicating function is so important.

Circult Breaker Bushing Current Transformer with Polarity Protective Relay

Figure 2: Examples of Symbols Used on One Line Diagrams

Typically, single line or one line diagrams are used to document the configuration of the electrical high voltage circuit of a substation. Symbols are used to depict the high voltage equipment including: transformers, generators, circuit breakers, fuse, air break switches, reactors, capacitors, instrument transformers, and other electrical equipment. The connections between these pieces of electrical power equipment are shown by solid lines.

On these diagrams the three phase equipment and connections are shown with a single line, thus the basis for the diagram name. Single phase equipment may have the same symbol as a three phase device but will be specifically designated with the phase to which it is connected. Since three phase devices can be connected in a delta, phase to phase connection, or a wye, phase to neutral connection, symbols are included that indicate the type of connection. This can be a vector representation of the connection or may be indicated by the winding symbol itself.

Vector Representation Delta Winding Symbol Wye Winding Symbol

Figure 3: Three Phase Connection in a Single Line Diagram

In some cases a key or basic substation SLD will be used to show just the electrical configuration of the high voltage equipment in the substation. The equipment is shown in the basic physical arrangement but when there are difficulties in showing the

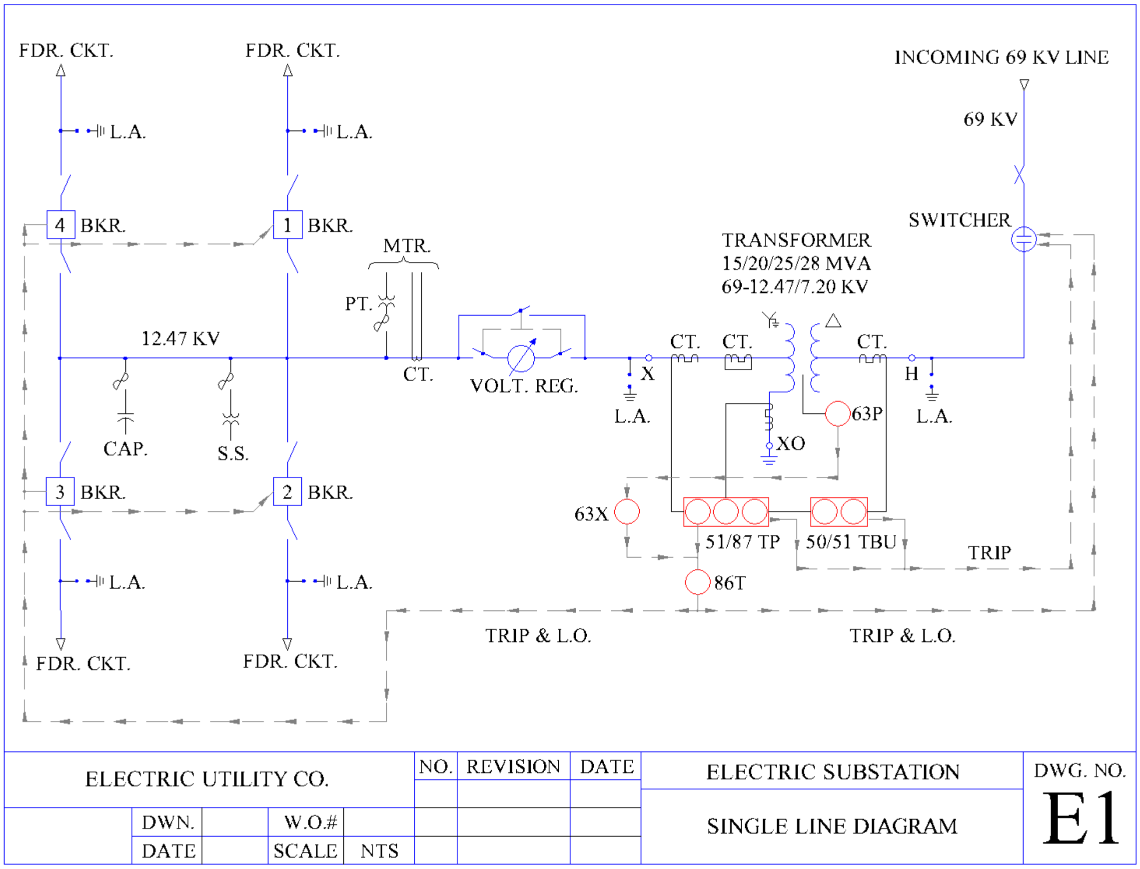


Figure 4: Example A of a Single Line Diagram

equipment in the correct physical orientation and showing the equipment in the correct electrical configuration then the correct electrical configuration is given priority.

Beyond the documentation of the high voltage equipment's configuration, typically some of the control and protection systems are shown on the SLD in a basic form. The most common additional system to be depicted on the SLDs are the current and voltage transformer circuits. Both the primary and the secondary of these circuits are shown. In both cases only half of the secondary circuit is shown. The polarity or delivery half of the circuits for relay operation, not the return circuits, are shown. The secondary circuits for the current transformers are typically shown with solid lines between the devices. To distinguish difference between the lines for the high voltage circuit and the current transformer circuit, the high voltage circuit is shown with a wider solid line than the current transformer circuit. The devices connected to the current and voltage transformer circuits are often shown with a circle large enough to contain a function number or acronym. The function numbers and acronyms are listed in the IEEE standard C37.2-2008.

4.1. Single Line Diagrams and IEC 61850 Process Bus

Application of IEC 61850 process bus requires a rethinking of how relay circuits are to be shown on an SLD. The merging unit (MU) in a process bus implementation takes analog inputs of voltage and current and digital inputs and converts them to IEC 61850 protocol. The output is a data stream over a fiber optic connection either to data management equipment or directly to IEDs performing a protection function. In this case, the physical connections to the MU shown on an SLD are unlikely to convey any functional information because the fiber optic connection can carry data concerning voltage, current or digital inputs to the MU. Knowing what CTs and VTs are feeding an IED can help indicate the protective functions it is performing. With an MU, you can only tell the set of data that may be feeding the IED, not what data it is using. The protective functions that the IED is performing will not be obvious from the connection alone. What follows are two examples of how to depict the process bus on SLDs.

4.2. Single Line Process Bus Example A

Previously, there was a one-to-one relationship between the analog measurement (CT or VT) and the input to the IED. Therefore simply showing a connection from a CT to an IED was not only a representation of the physical but also the functional, whatever functions the IED performed had to be based on the analog input. Now, an MU can have multiple analog signals input to it and then have a single physical output – a fiber optic cable. So a simple way of showing this is to be consistent with the physical representation, namely CT and VT connections are shown going to the MU but to add text to the fiber input to the IED so the analog input can be followed back to the MU so the function of the IED can be more obvious. An example of this approach is shown in Figure 5. The MU is labeled as MC#2 and the inputs shown are phase current (CP), ground current (CG), and phase voltage (VP). The IED labeled as 6CB32 is using VP while 3T4 is using CP, CG and VP.

4.3. Single Line Process Bus Example B

Another proposal for representation of the process bus on the SLD is to depict the MU as an optical auxiliary transformer. This retains the practice of showing a one-to-one relationship between analog measurement and the input to the IED. So the function of communicating the analog voltage or current data to protective relays could be shown as in Figure 6.

These symbols would reflect the physical connection to the current and voltage inputs but would depict the output as data to the subscribing IEDs. Therefore one MU may have both a voltage and current input with output to numerous IEDs. The input to each of these IEDs would be shown separately for each current or voltage. Figure 6 shows the current data output from an MU. If this is interpreted as a physical depiction it would seem that there were numerous physical connections when in fact there may be a single fiber connection from the MU to the control building. In addition, because it is current data it is not delivered serially to the IEDs as it would if it were a CT, rather, the data is delivered in parallel to the IEDs. Labeling would allow the association of the function to the correct MU. In Figure 6, the MU has multiple current and/or voltage inputs therefore labeling will need to address this. Here, it is current element 1 (C1) of merging unit C12 (MUC12) that is being used. A more detailed representation of the physical connections from the CTs and VTs to the MUs would be shown on the AC schematics and the physical connection from the MU to the IEDs could be show on a process bus architecture drawing.

4.4. Control Functions on the Single Line Diagram

It has been common to show the function of the basic protection circuits and sometimes the control circuits on the SLD by connecting the protective relay circles that enable other devices with dashed lines. These are the circuits of the response actions, trip and close, which are automatically performed by the protective relays. An arrow at the receiving end of the dashed lines indicates the direction of the action. The devices that trip or close the high voltage fault interrupting device have dashed lines to the symbols for those devices. These “control lines” can be seen in Figure 4 pointing at the circuit breakers in the drawing. This method of depicting the relay logic on the SLD has limitations. The conjunction of two control lines typically depict an OR junction, meaning that either incoming action would result in the same resulting action. The depiction of the logic requiring multiple control actions to be enabled at the same time to accomplish a resulting action, an AND gate, is difficult to depict with this type of documentation. In spite of the shortcoming of this method of logic depiction it has been used for many years and continues to be used.

The advent of user modified control logic in microprocessor based relays challenges the application of this type of relay logic depiction on SLDs. When the logic of the protection or control circuit is no longer limited to the results of wiring individual relay functions together but is the composite of the user defined logic internal to the relay devices and the external wiring between devices the limitation of the dashed lines to depict the overall protection circuit logic has become unacceptable for many users. The same evolution in protective relay logic also increased the importance of having a method of detecting the basic overall logic on one diagram. Prior to the user defined logic in microprocessor based relays, the control schematic provided this overall logic diagram because the logic

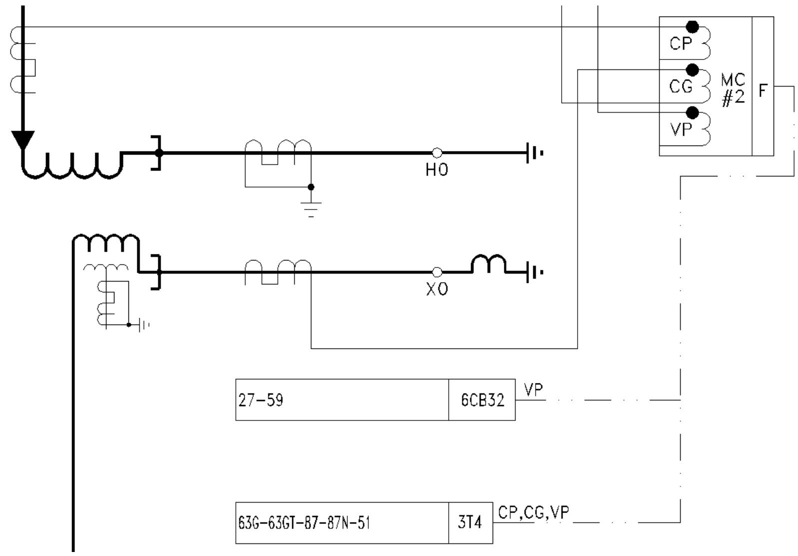
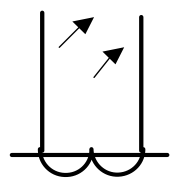
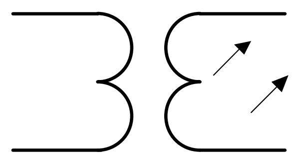


Figure 5: Example A of Merging Unit on Single Line



Current data from merging unit.



Voltage data from merging unit.

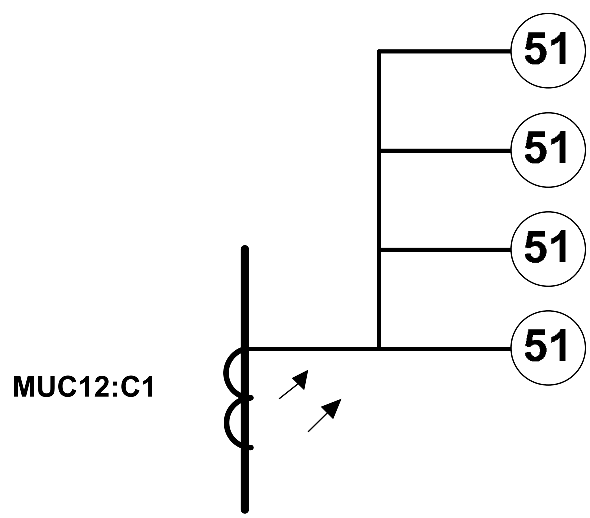


Figure 6: Symbols for Current and Voltage Output of a Merging Unit
and Example B of Current Data Connection to IEDs

was created by the wiring of individual functions together. With the advent of the microprocessor based relay, one output contact can be the composite result of the operation of multiple measuring devices combined with timer and multiple conditional situations. None of this internal complex logic is shown on the typical control schematic As a result of these two factors, the limitations of the legacy documentation system and the need to document the internal relay logic along with the external logic, has driven many utilities to change the way that protection relay logic is depicted on the SLDs.

One method that has been adopted by some utilities is to depict the basic protection relay logic on the SLD using the traditional Boolean logic symbols or some variation of these symbols. By using Boolean logic, more complex logic can be depicted than what could be depicted using the dashed line with the arrows and both logic internal and external to the programmable relays can be shown on the same diagram. To facilitate the SLD being understandable by a larger audience at least one utility has adopted symbols used on some generating plants drawings. These symbols and the more traditional symbols are shown in Figure 7.

Figure 8 shows a section of a substation SLD using logic symbols to portray the way the protection and control circuits for the tripping and closing of a circuit breaker are configured. The circuit breaker has two trip coils so the logic for each is shown separately. Both the control logic that is accomplished by inter-device wiring and logic that is accomplish by the custom programming of microprocessor based relays are shown on the same diagram. Referring to Figure 8, the logic inside the dashed box labeled (1M63)62BF5 is custom programmed logic whereas all of the other logic is accomplished with inter-device wiring. The logic shown for device (1M63)62BF5 is a simplification of the complete logic. The complete logic for this device can be shown on the control schematic for the breaker failure protection. It is important to link the inputs and outputs of this device to the external logic shown on the SLD. There is no local area network (LAN) used for the protection and control circuits at the substation shown in Figure 8. If there was a LAN the protection and control logic accomplished with signals communicated over the LAN are shown on the same diagram.

The more complex logic like that used in a transmission line pilot scheme are shown in symbols like Figure 9. Figure 9 is the logic for a permissive over reaching transfer trip scheme using relay to relay digital communication. To simplify the logic for the SLD some of the details of the logic are left out. Some examples of that simplification are the showing of just Zone types and not the individual elements that are combined by logic to detect faults in a Zone and the absence of the timing functions involved in the echo back keying of the permissive trip signal circuit.

With the logic for the protection and control circuits in addition to the primary power circuits, and the current and voltage circuits being shown on the SLD; the SLD can be used to understand the systems being applied in the substation. The SLD is also a critical link between the schematic diagrams and the relay settings documents in trouble shooting protection and control circuits.

Even though there are commonalities between all single diagrams, any two SLDs from different organizations can look very different. Figure 10 is another example of an SLD

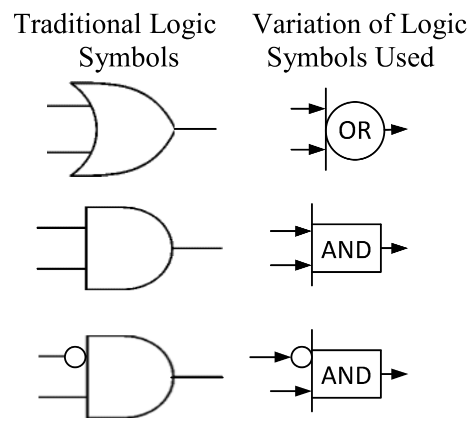


Figure 7: Diagram Comparison of Logic Symbols

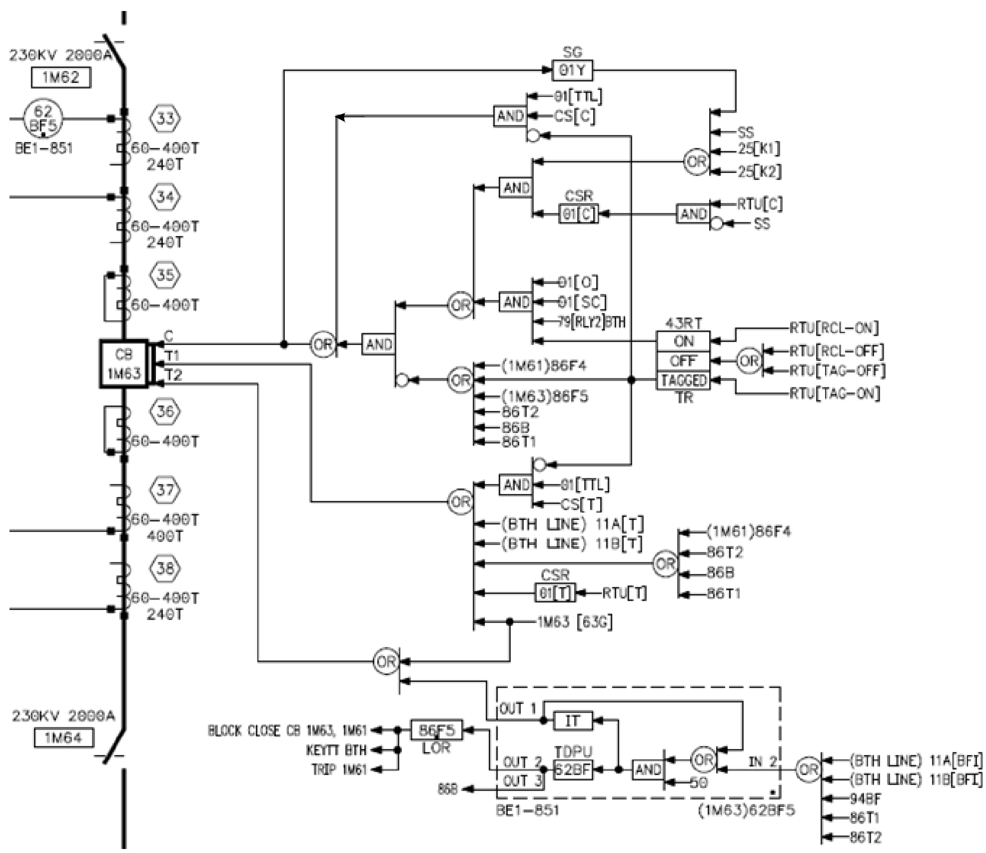


Figure 8: Section from Substation Single Line

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but it emphasizes the digital inputs and outputs to each relay along with the use of different texts and additional symbols such as the trip and close descriptions.

But even with these differences, single line diagrams summarize both the power system to be protected and the controls that will operate the power system. The next level of detail of power system relaying is found in the AC and DC schematics. The AC schematics detail the power system being protected and how it is being measured. The DC schematics detail the controls that operate the power system.

5. AC Schematics

AC Schematics, which are also called AC Elementary Diagrams or Three Line Diagrams, will show all three phases of the primary system individually. Examples of this can be seen in Figures 11, 12 and 13. Similar to the one-line, the location of all significant equipment will be shown. Bushings are identified on circuit breakers and power transformers. The drawing will also include equipment continuous thermal ratings, circuit breakers in amperes, transformers in MVA. An example of this transformer information can be seen in Figure 12. Detailed connections to all equipment utilizing AC inputs will be shown as well. These detailed connections often include terminal numbers. The example figures do not include all terminal numbers for the sake of readability.

5.1. Instrument Transformers

5.1.1. Voltage Transformers (VT) or Potential Transformers (PT)

The AC schematic will show the point on the high voltage system where each VT is attached and provide both primary and secondary connection details for each of the phases. Details will typically include winding ratios, number of primary and secondary taps, polarity marks, nominal voltage ratings, and winding configuration (e.g. delta, grounded wye). If secondary fuses are used, their location and size would also be shown.

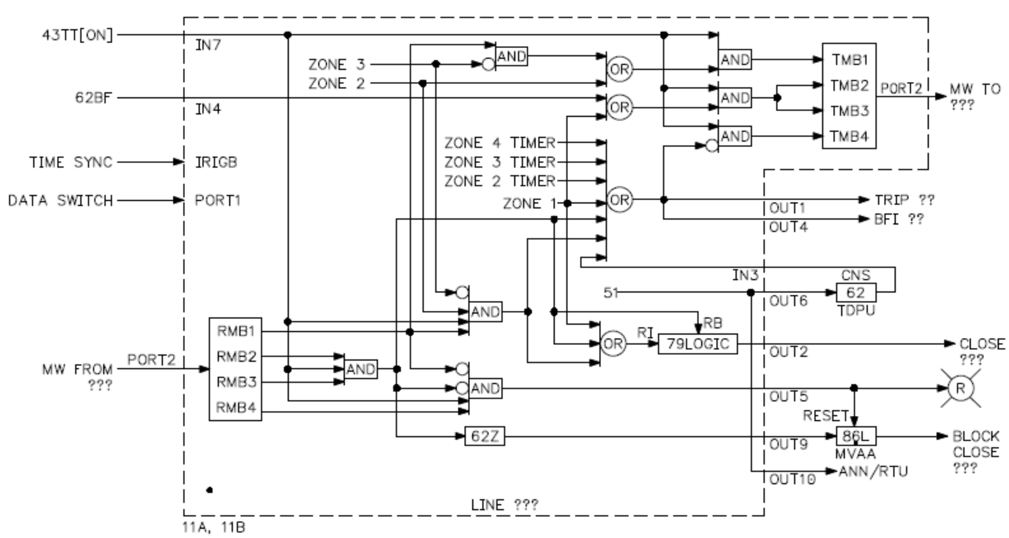

Figure 9: Line Relay Symbol for Substation Single Line Diagram

It is also common practice to include secondary wire names, for example P1, P2, P3, and P0 for the three secondary voltages and neutral of a grounded wye source as shown in Figure 11. This may be used as a source to supply protective relaying and metering equipment.

5.1.2. Current Transformers (CT)

Multi-ratio current transformers are commonly used for protective relay applications. CT location, full and connected ratios, polarity, and winding configuration (e.g. delta or wye) will be indicated on the drawing. Nominal secondary current rating (commonly either 1A or 5A) will also be shown along with secondary wire names, for example C1, C2, C3, and C0 for the set of CTs connected in a wye configuration on Figure 11.

5.2. Protective Relays

Protective relays that are applied to monitor changes in the AC system will be shown on the AC schematic connected to current and voltage transformer secondary outputs. Diagrams must show detailed connection information that follows manufacturer recommendations to insure correct operation. If a circuit is protected with a number of single function devices (these would typically be electromechanical relays) it is important to show current and voltage connections to each of the elements that make up these relays. This connection to individual current elements can be seen in Figure 13 between the 50/51TBU and 51/87TP coils in the AC Current Elementaries.

This detail should include terminal numbers, polarity marks, and any other important information that pertains to the AC inputs. This will provide valuable information regarding input quantities specifically used by the relay elements as well as information about directional sensitivity (if applicable). When microprocessor relays are used, internal relay program parameters will determine how secondary input quantities will be measured as well as the directional sensitivity of specific elements. Additional information will be required on this drawing if it is needed to detail exact functions that are in use.

Another vital function of the AC schematic is to show how the AC current and voltage circuits can be isolated for testing. Detailed information regarding the wiring and operation of these test switches are included in these schematics and an example can be seen in the lower left corner of Figure 11. Here current test switch 6 TC clearly shows the terminal point number and what each test switch does on operation. For example, test switch 1-2, when opened, will short the circuit from point 2 to point 4. This level of detail is needed to insure that testing can be done easily and avoids errors while testing.

5.3. Metering Functions

Metering information generally required for utility operations may include voltage, current, power (both Watts, and Vars) as well as other values. Present microprocessor relays are often capable of providing this information with acceptable accuracy. Discreet metering devices including panel meters and transducers are often no longer required. If metering functions are to be included in a microprocessor relay these functions could be indicated on the AC schematic drawing or even the single line diagram. This is one place where the effect of microprocessor relays on schematic representation can be seen. With the use of these relays to perform metering functions, it is no longer necessary to carefully detail all the transducers needed to perform the same functions.

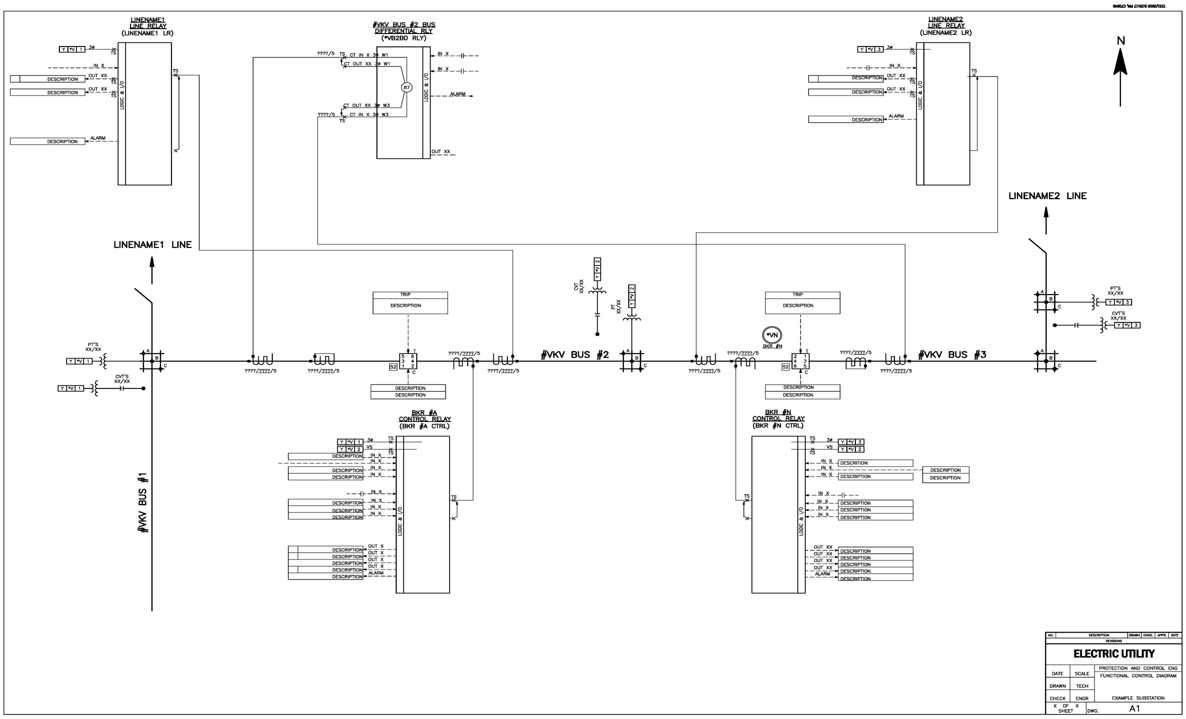

Figure 10: Example B of Single Line Diagram

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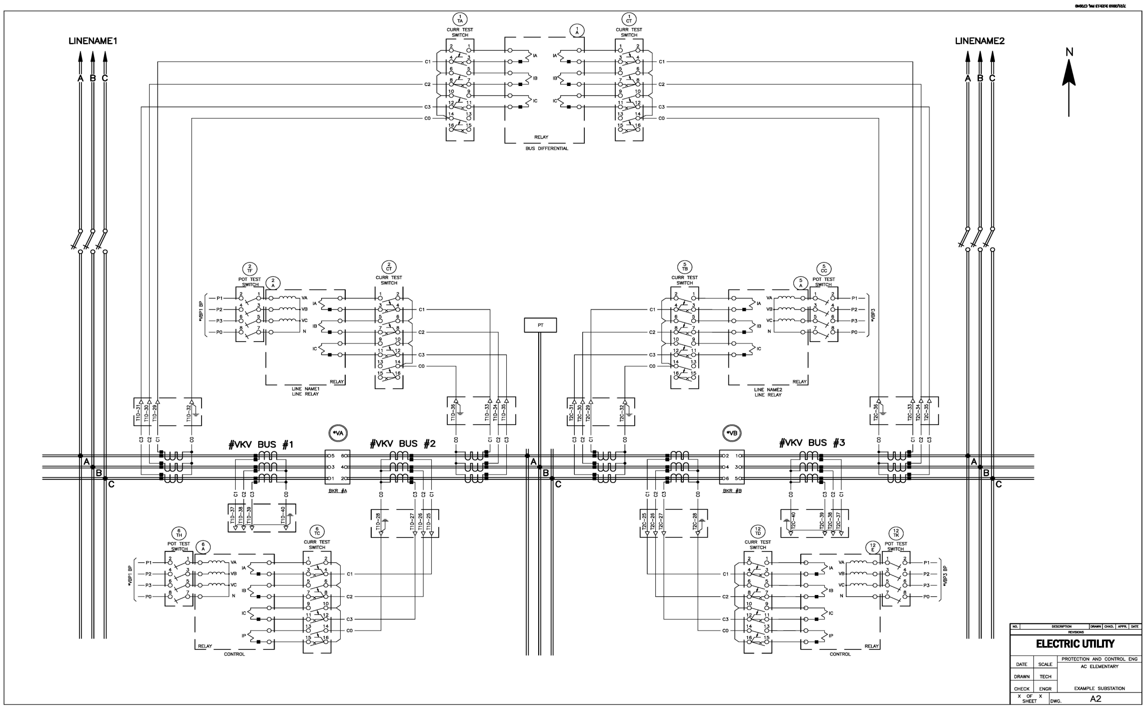

Figure 11: Example A of an AC Schematic

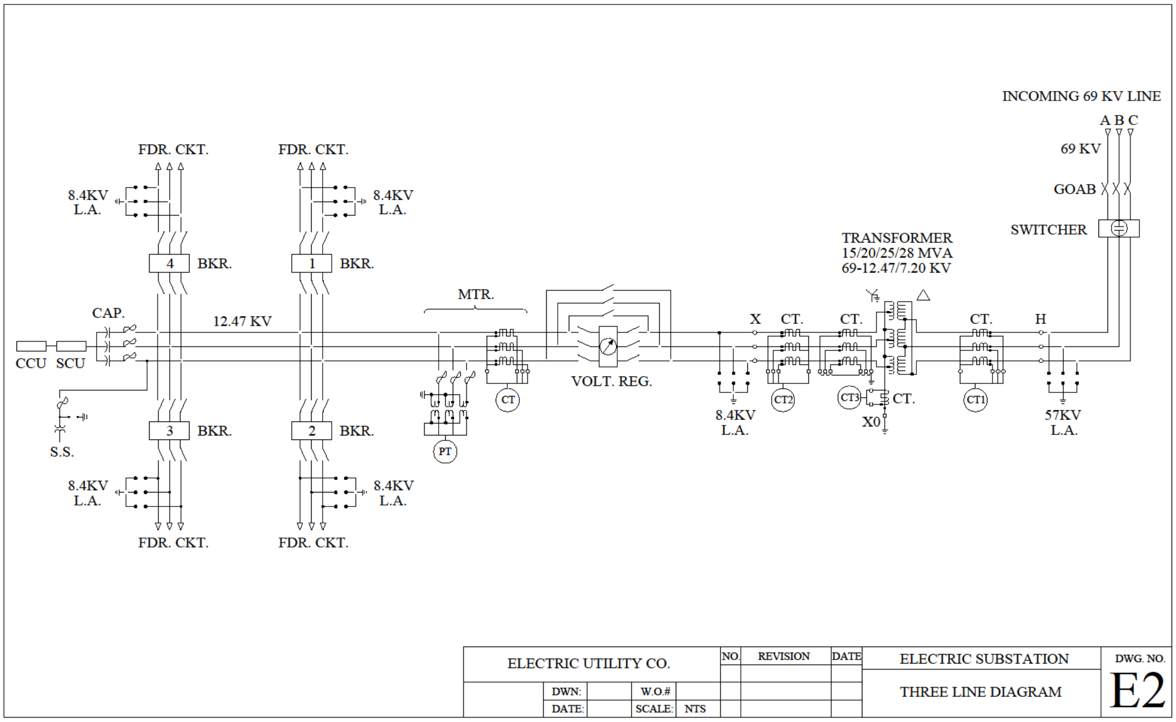

Figure 12: Example B of an AC Schematic

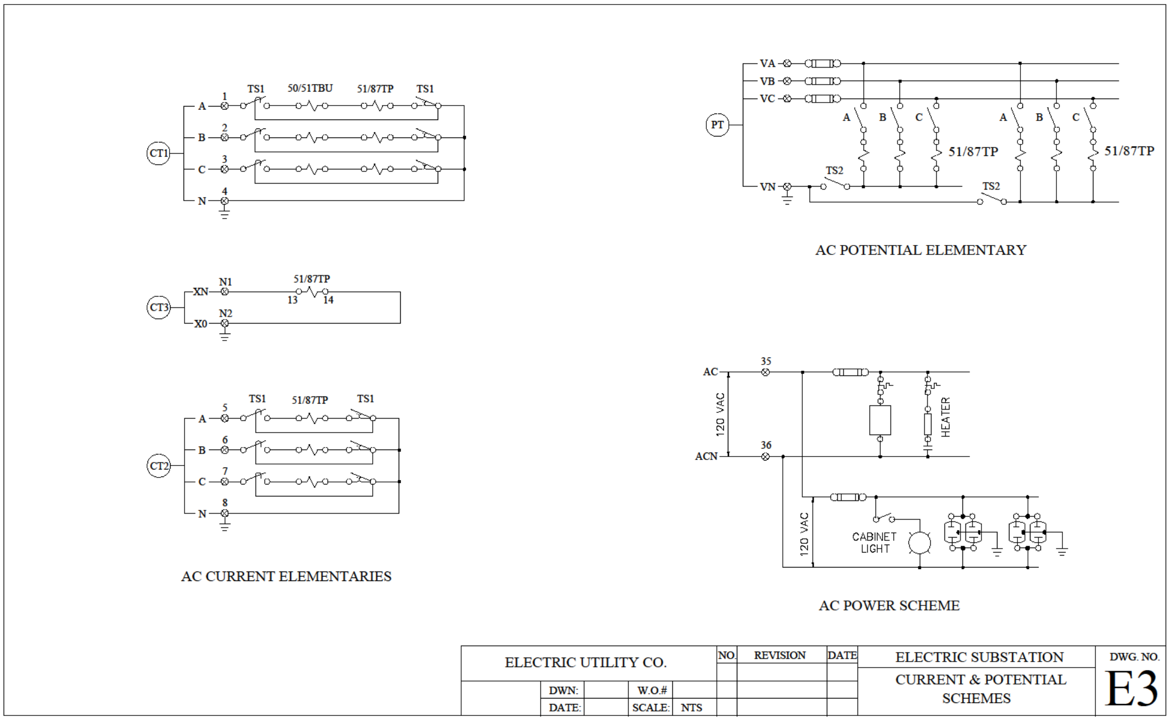

Figure 13: Continuation of Example B of an AC Schematic

6. DC Schematics

DC schematics, often referred to as elementary wiring diagrams, are the particular schematics that depict the DC system and usually show the protection and control functions of the equipment in the substation. It should be noted that sometimes the control functions are supplied by AC and are included in the elementary diagram (refer to Figures 16 and 18). One example of a DC schematic is a circuit breaker control schematic that shows the tripping and closing of the circuit breaker whether from controls or protective devices as well as the alarms for the circuit breaker. Examples of typical elementary diagrams are shown in Figures 14, 15, 16, 17, and 18.

Electric utilities have used elementary wiring diagrams to show their designs for many years. As the experience in using these drawings grew, practices common throughout the industry arose while at the same time utilities developed many standards regarding the details of the elementary wiring diagram that works best for them. Since the details in these standards often differ slightly but significantly from utility to utility, it is important to understand the standards when reviewing these types of drawings. As utilities have gone through some corporate changes through the years such as merging various companies, the selection of a common standard can often be a challenging process.

6.1. Common Practices

There are a number of common practices that are seen in DC schematics. If complexity of the system requires it, the devices controlling the equipment, like the two relays featured in Figure 14, may be shown on one drawing. The equipment being controlled would show up in another drawing, such as the switcher in Figure 15. The DC circuit is usually shown with the positive bus closer to the top of the page and the negative bus closer to the bottom. The general layout of these drawings is that the DC source is usually shown at the left end of the drawing and the initiating contacts are shown above the operating elements. For example, in Figure 15, when the contacts labeled 51/87TP close and the 89/a contacts are closed then positive DC at the top is connected "down" to the trip coil (TC) and the switcher is operated.

There are also functional similarities with the AC schematics. Similar to AC schematics, the DC schematics will include the rating for circuit elements such as fuses, heaters and resisitors. For example, in Figure 16 we see that FU-1 is rated at 20A, that HTR2 is rated for 300W at 240V and that a 7500Ω resistor is needed when connected to 250VDC. And just like the AC schematic, the location of test switches are shown in detail so outputs and inputs can be isolated for testing. Refer to Figure 15 and the test switches for the outputs of relays 87TP and 50/51TBU.

Figure 16 provides examples of the transition that schematics make between the functional design and the physical design. Near the center of the figure is the number 13 just above the text "79 "NLR21U"". Note that 13 is repeated to the right next to the contact labeled R2 and to the left next to the contact labeled C1. The repetition of 13 is not needed on this schematic to communicate that all these points are electrically the same, this fact can be easily seen in the drawing. However, 13 is also used in the physical design shown in the wiring diagrams. Terminal blocks will be marked with this number and in this

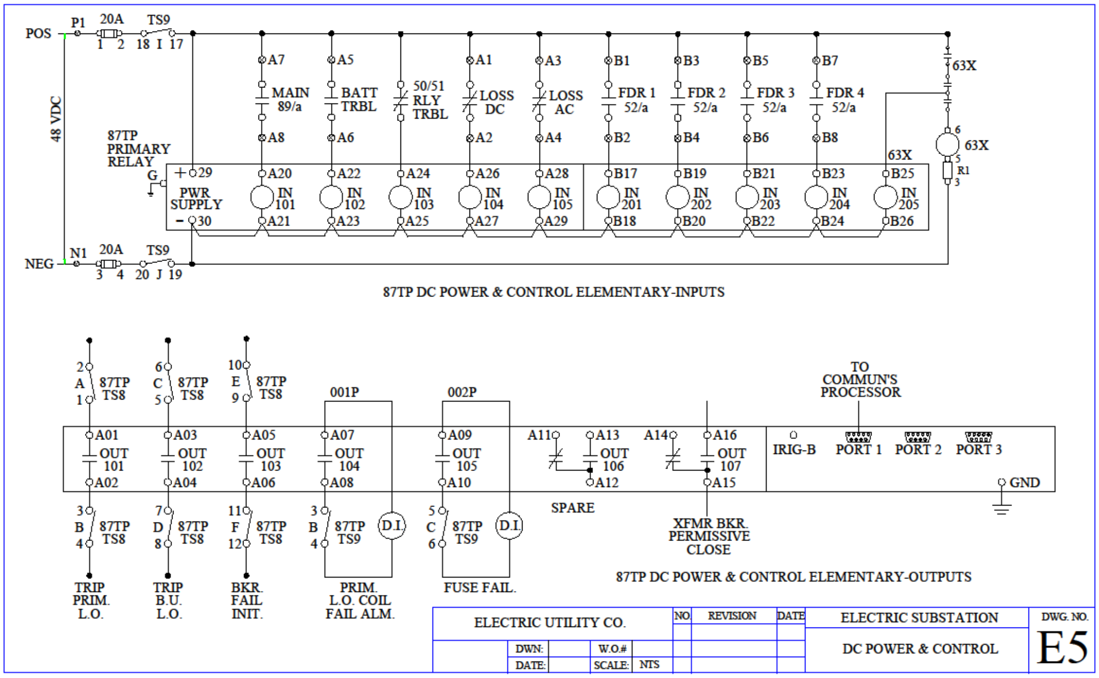

Figure 14: Example A - DC Schematic of Relays Operating Switcher in Figure 15

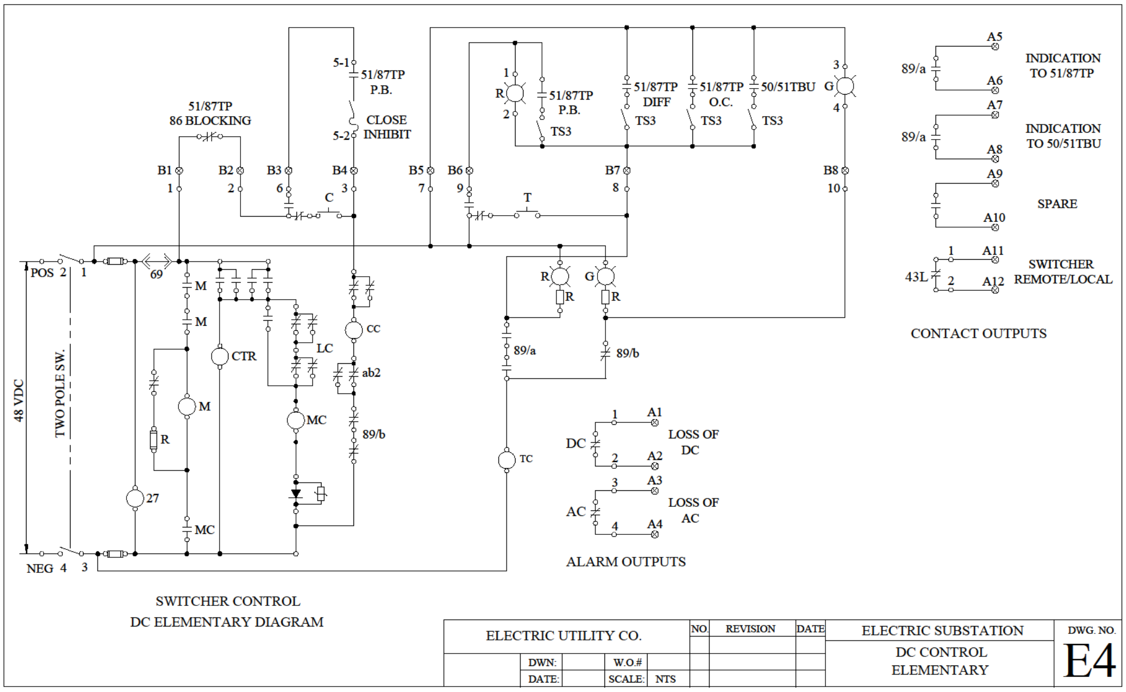

Figure 15: Example A – DC Schematic of Switcher Operated by Relays of Figure 14

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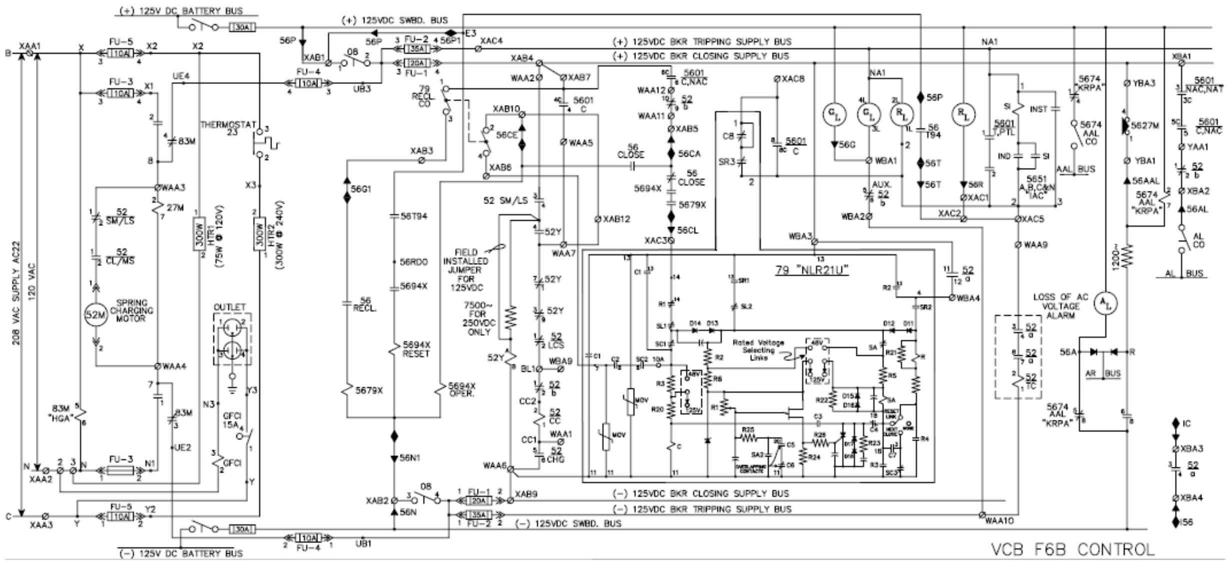
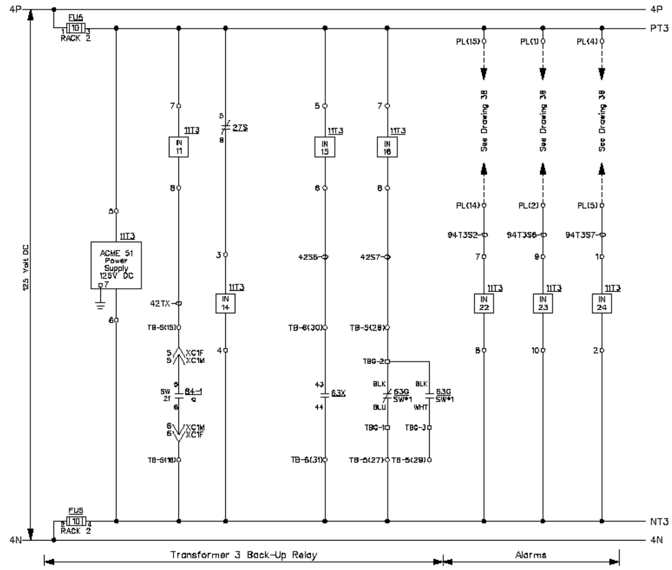


Figure 16: Example B of a DC Schematic



11T3
ACME 51

Connections	Name	Function
7o—□—o8	IN11	SW 23 Close Position
9o—□—o10	IN12	SW 23 Open Position
1o—□—o2	IN13	SW 23 Trip Coil Monitor
3o—□—o4	IN14	Loss of Emergency Station Power
5o—□—o6	IN15	SW 23 Lockout, Urgent SF6 Alarm
7o—□—o8	IN16	SW 23 Low SF6 Pressure Alarm
5o—□—o6	IN21	
7o—□—o8	IN22	Transformer 3 Device Alarm
9o—□—o10	IN23	Transformer 3 Gas Alarm
1o—□—o2	IN24	Transformer 3 Moisture Alarm
3o—□—o4	IN25	
5o—□—o6	IN26	
7o—□—o8	IN27	
9o—□—o10	IN28	
1o—| |—o2	OUT11	Trip SW 123
3o—| |—o4	OUT12	Close SW 123
5o—| |—o6	OUT13	
7o—| |—o8	OUT14	
9o—| |—o10	OUT15	
1o—| |—o2	OUT16	
3o—| |—o4	OUT17	
5o—|/|—o6	ALARM	

Figure 17: Example C of a DC Schematic

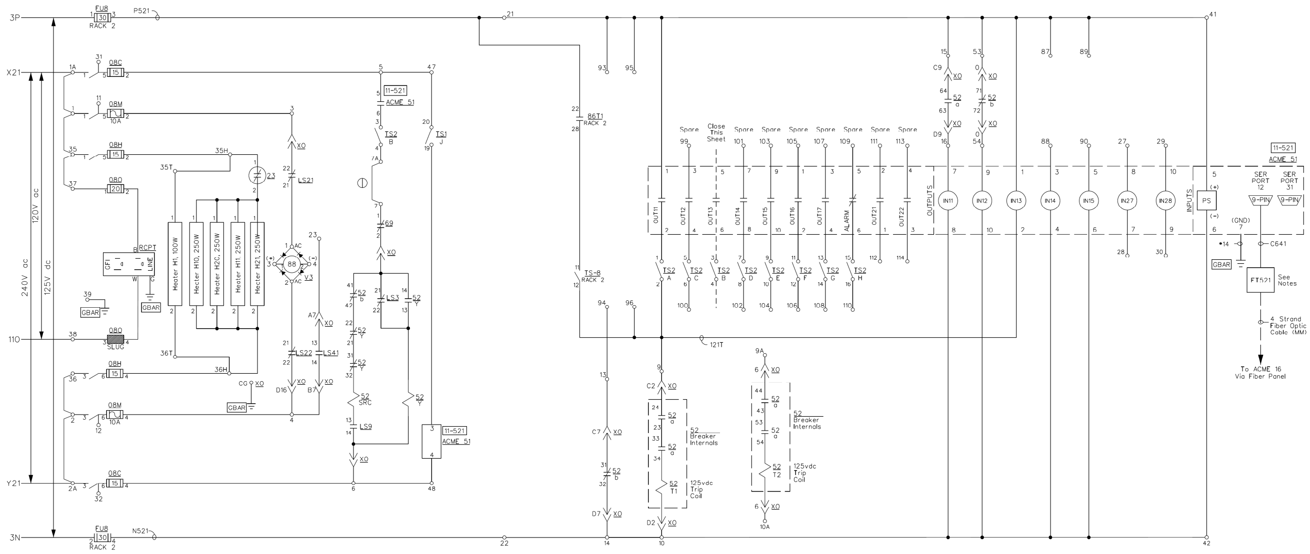


Figure 18: Example D of a DC Schematic

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application, it is an indication that all the points are electrically the same and can be identified by the same 13 on this schematic.

6.2. Unique Standards

Figure 16 provides examples of standards that have been developed regarding the details of the design. For instance, the black triangles and diamonds throughout the drawing have specific meanings regarding the disposition of the wires. They symbolize transitions from one location to the next. Care must be taken to appreciate the difference between the black triangle symbol used to indicate transitions and the black triangle symbol used in the lower right to indicate a diode.

Other examples from Figure 16 of unique standards include the use of the symbol ~ for ohms and the use of the circle with a line through it for terminal points. Though these symbols may be explained in a key somewhere on the drawing this is not always the case.

6.3. DC Schematics and the Microprocessor Relay

Today a new challenge is occurring as utilities have moved from their traditional designs using electro-mechanical relays to designs using microprocessor relays and advanced communications systems. The basis of the problem is the design of the protection system has moved from a hardware based system to a software based system with little experience in the best methods to document these designs. Documentation of the logic in microprocessor relays adds one level of challenges and the advent of schemes that use relay to relay communication connections and protocols, such as IEC 61850, add another level of challenges.

As with traditional designs, utilities will continue to document the hardware connection on the elementary wiring diagram. Since microprocessor relays are so powerful and flexible a new emphasis rises to show not only what the protection design is but also what it is not. In other words, the documentation needs to capture the IED resources available if the design ever changes and new resources (IED inputs and outputs) are required. One useful table generally included on a DC schematic or one-line would be a table of the inputs and outputs on a microprocessor relay, indicating which were being used (labeled with associated function) and which were available. This table is handy in tying the required functionality of the settings and logic to the physical wiring and the settings of the relay. This table is shown in the right of Figure 17. Another approach, shown in Figure 18, is to show all the available relay inputs and outputs in a graphical form on one drawing.

The connections showing the output and input contacts will be shown on the schematic diagrams but the issue remains how one documents what is happening within the programming. Several alternatives will be presented that have worked for other utilities. One of these alternatives may appear to be the best choice or a combination of approaches may work. It is also noted that these alternatives are not all-inclusive and a better idea may be developed. The alternatives that will be briefly discussed include hardware only documentation, software shown as part of the traditional elementary diagram, and showing a logic diagram on the elementary.

The first approach is to document only the hardware that is connected on the relay. In addition to showing the specific contacts that are used in the design, labels could be used that may show small details regarding the contact such as '51' for overcurrent relay contact. The major issue with this approach is the possible lack of sufficient information regarding the design. For simple designs, the label of the contact may be enough but if this approach is chosen for complex designs, then additional documentation will need to be supplied. One option would be to include more information on the relay setting sheet or some other type of documentation that goes with the relay. The additional document could include a verbal description of the relay logic that allows one to understand when the contact will operate. Logic diagrams could also be used as the additional documentation to show how the design is developed. One advantage to this approach is it keeps the elementary wiring diagram simple for those who do not require the details. For those that need the details, they can obtain it from the additional documentation. Another advantage to this approach is the flexibility improvement for most organizations. The changes of elementary wiring diagrams often require a process of obtaining approvals that hinders making changes often. One of the advantages of using microprocessor relays is the ease in changing the design if improvements can be made. If no wiring changes are made, then the use of additional documentation or setting sheets to document the changes is often less strenuous than changing elementary wiring diagrams.

The second alternative is to show the details of the logic in the form of the elementary wiring diagram. So, similar to the wiring diagram, if logic is using an "OR" function then the variables are shown in parallel. If an "AND" function is used then the variables are shown in series. The difficulty in this alternative is distinguishing between hardware connections, which feature physical contacts, and the logic, which depicts logical outputs as contacts. Therefore it may be beneficial to use different colors or line types for software logic.

One other alternative is to use logic diagrams on the elementary wiring diagram. Logic diagrams are a graphical display that shows what is happening in the logic of the relay or communications system. Logic diagrams will be discussed in more detail in a later section of this report.

6.4. DC Schematics and IEC 61850 Station Bus

Early applications of relay protocols provided engineers with basic tools for substation automation, but they were often limited in functionality. Several are proprietary and for that reason, one must reference the vendor manufacturer's relay manuals for schematic representation methods. IEC 61850 differs from other standards/protocols because it comprises several standards describing client/server and peer-to-peer communications, substation design and configuration, and testing.

IEC 61850 provides a method for relay-to-relay interoperability between IEDs from different manufacturers. With the open architecture, it freely supports allocation of C37.2 device functions. What makes it unique is that the station bus described by IEC 61850 operates digitally over a secure Ethernet based network sending protective relay messages called Generic Substation Events (GSE) or Generic Object Oriented Substation Events (GOOSE) between relays (and other IEDs) on that network. Because of this feature, it eliminates most dedicated control wiring that would normally be wired from relay-to-relay (i.e. a trip output contact from one relay to the input coil of another relay).

Due to this digital communication between relays, a typical DC schematic diagram alone is not an adequate method for describing the system. Therefore IEC 61850 GOOSE messages (signals) are best represented in a point-to-point list or spreadsheet format (e.g. a bus differential relay would subscribe to all associated feeder protection relays on that bus, or a main-tie-main relay group would subscribe to each other to perform breaker interlocking). This point-to-point (publisher/subscriber) list is not maintained by a computer on the Ethernet network, but instead a protective relay engineer uses a System Configurator software tool to program each IED to subscribe to each other depending on the protection scheme. It is possible for one IED to communicate the same protective message to several other IEDs at the same time. The IEDs, once programmed to communicate with each other, will manage the messages they have been programmed to receive and transmit.

7. Logic Diagrams

The logic diagram used in the representation of power system relaying usually refers to:

- A system representation using symbols or diagram other than electronic or electrical power system symbols.
- A system representation using some terminology close to computer science field or programming language.
- A statement or representation or presentation of a scheme that can be transferred from hardware installation to software program.

There are many ways of presenting logic diagrams for power system relaying schematics. Presented here is a limited list of these approaches with some examples. Though they are similar, they are not the same as the logic diagrams used in computer science or mathematics fields because those fields have broader and more in depth explanation of logic diagrams. Here are a few that are commonly used in power system relaying :

7.1. Timing Diagram

This type of logic representation is very useful if the scheme is very time dependent.

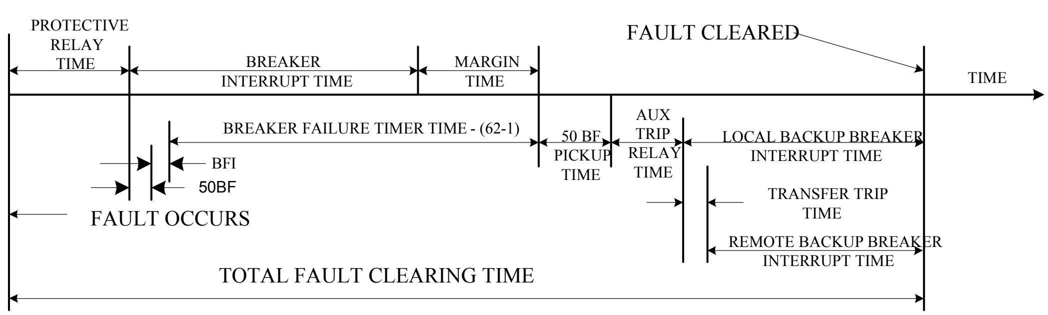
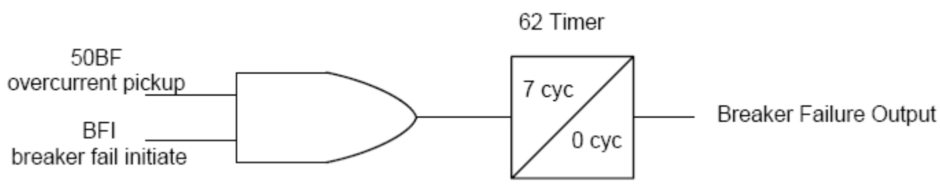


Figure 19: Timing Chart of Protection Element

7.2. Boolean Logic Diagrams

AND, OR, XOR, NOT TIMERS, and COUNTERS are featured in Boolean Logic Diagrams. It is the most common and very useful in detailing the overall scheme but very hard to use to summarize a more complex scheme;



50BF Overcurrent Pickup	BFI Breaker Fail Initiate	62 Timer Expires	Breaker Failure Output	Comment
0	0	0	0	
0	1	0	0	
1	0	0	0	
1	1	0	0	
1	1	1	1	

Figure 20: Boolean Logic with Associated Truth Table

7.3. Karnaugh Map

It usually goes together with the creation of a State Diagram.

F= ABC			AB (50BF Overcurrent and 50BFI inputs are ON)			
			00	**01**	**11**	**10**
C	62BF Timer Expires	**0**	0	0	0	0
		1	0	0	1	0

Figure 21: Karnaugh Map of Protection Element

7.4. Structured Text

It looks very similar to a programming language code/syntax. The functionality may be limited to what is provided by the device manufacturer. Usually it is used in conjunction with Boolean logic to allow the use of a simpler model in a complex scheme.

```
IF BF_Initiate=1 AND BF_Overcurrent=1 THEN
        BF_Timer_Start:=1;
ELSE BF_Timer_Start:=0;
END_IF;

(* When BF_Timer_Start=1 start Time Delay Pickup logic with 7 cycle/ 117ms
and the output is pulsed for 1 cycle / 17ms  *)

IF BF_Timer_End=1 THEN
        BF_Output:=1;
ELSE BF_Output:=0;
END_IF;
```

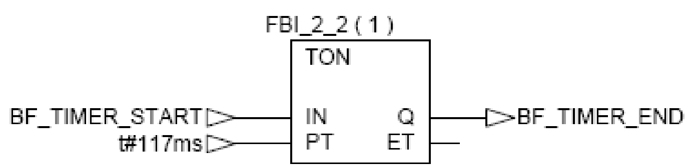


Figure 22: Structured Text with Boolean Logic

7.5. Functional Description

It is a description of a scheme in a few sentences. In a complex scheme, this becomes too hard to describe in a paragraph. For example, a scheme that is very dependent on timing or previous states of system may be very difficult to understand in 1 or 2 sentences.

"Breaker Failure Output shall pickup after a PRESET time delay pickup. The timer is only started and running when breaker failure initiate and overcurrent condition are picked up. If the inputs drop off before the time delay pickup has expired the output shall not pickup."

7.6. Flowchart

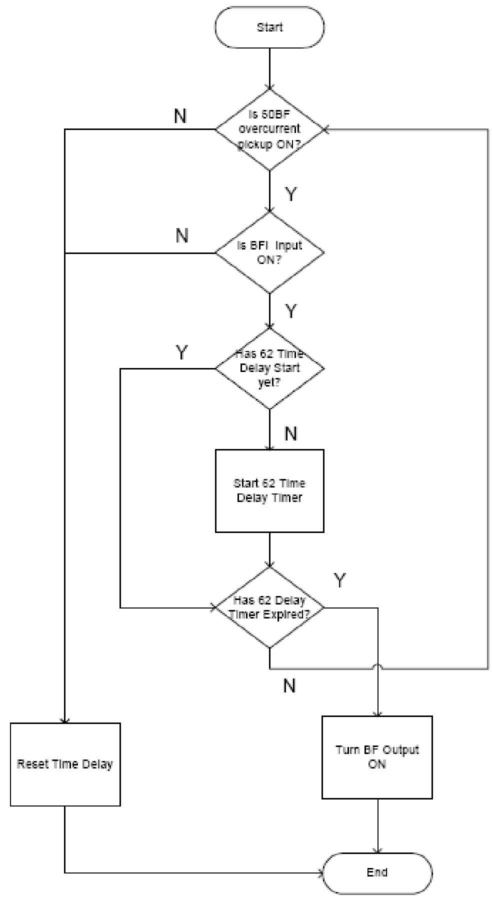


Figure 23: Flowchart of Protection Element

All the preceding logic diagram examples represent or describe the same scheme using different type of logic representation. This breaker failure logic is borrowed from IEEE C37.119 section 7.1, Figure 2. Each representation has strengths and weaknesses and some need to be used in conjunction with other methods.

7.7. Logic Diagram Considerations

Logic diagrams are now an integral part of schematic representations arriving with the usage of microprocessor relays. Relay manufacturers had predefined logics in their equipment but sometimes additional logic equations are needed to customize the protection, automation and control functionality of the relay. But this customization and expansion of logic has requirements. The additional drawings that need to be created, maintained, and versioned increase as the system becomes more complex.

When deciding the amount of detail to be included in the logic diagram one has to take into account the following factors:

- The number of pages added into the drawing sets. For example, one logic page that covers several pieces of equipment vs. one logic page for each piece.
- The amount of duplication from manufacturer instruction manual. Is there copyright issues?
- The location of the logic diagram to be added. Will it be in the DC schematic page of the relay or its own page?
- The amount of functions to be tested. Is a logic diagram needed for testing the output contacts, alarm/target LED, Trip equation, control and automation of a function?
- The testing of the functions. Do we test gate-by-gate, test the flow chart, or timing test?
- Verification of the logic diagram representation with the relay configuration/setting/native file. While it is important to choose a presentation method of logic that provides a simple and clear representation of the scheme, similar to AC and DC schematics, the representation must enable testing or verification of the intended scheme. Hence it may have to be a combination of several different types of logic diagrams so it can be understood and verified easily.

One of the most challenging parts of using logic diagrams is creating them. The following practices that help with logic diagram design/creation include:

- Logic drawing tools integrated with the setting software.
- Logic simulator to test logic design and do timing chart for testing purposes.
- Logic drawing export format that is compatible with standard CAD software.
- Consistent usage of gate symbol, font formatting, line weight and keeping it clean and simple. An example is shown in Figure 24.

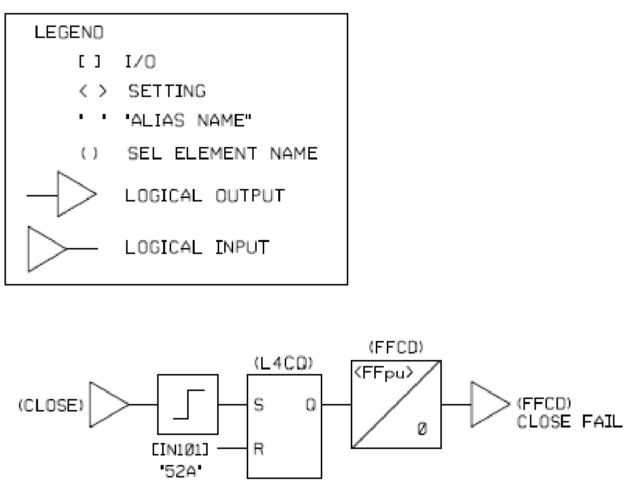


Figure 24: Logic Diagram Legend and Example

- Use of grouping /title-box within the logic diagram such as TEST SWITCH LOGIC and SYNC CLOSE used in the following example. Grouping can be based on functionality for example EMS vs. local, protection vs. automation, etc.

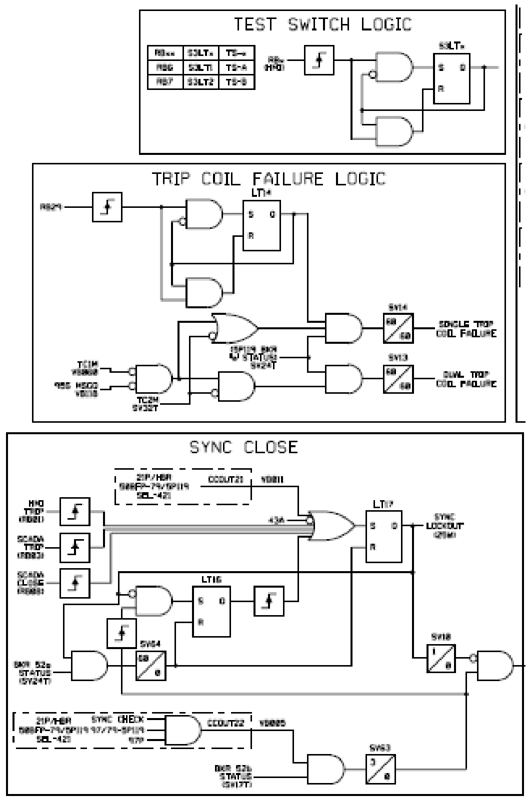


Figure 25: Logic with Title Box

- Show page reference in DC schematic that points to the logic page (show where Boolean bit comes from)
- Use of versioning system to version custom logic/setting vs. standard logic/setting and reference it in the relay configuration file and vice versa.
- Use of a single spreadsheet as a map of all the bits being passed around in the system similar to Figure 26. A reference to the equipment and page number where the bit is being used.

GOOSE MESSAGES OUT TS LI VERIFIED IN RECEIVING ARCH ONLY RELAY EVERIFIED IN SOURCE RELAY QUICKSET

INITIATING RELAY	dataset name		CCOUT##	ELEMENT	Test Switch	TEST SW	97 SWITCH	BKR/MOD	FUNCTION	COMMENTS	CI 21P/ABC 50BFP- 79/9P999 Relay-Type-A	CI 21S/ABC 50BFS/9P999 Relay-Type-A
87T2P_Relay Type - C	GooseDSet2		A2.phsA.C\	A AMPS						A AMPS ,		
87T2P_Relay Type - C	GooseDSet2		A2.phsB.C\	B AMPS						B AMPS ,		
87T2P_Relay Type - C	GooseDSet2		A2.phsC.C\	C AMPS						C AMPS ,		
87T2P_Relay Type - C	GooseDSet13		MsgQuality	Goose Message Quality						Goose Message Quality ,	CCIN111	CCIN111
87T2P_Relay Type - C	GooseDSet2		PhV.phsA.(	VOLTAGE						VOLTAGE ,		
87T2P_Relay Type - C	GooseDSet13		S1LT2	97T2P					S	97T2P STATUS,		
87T2P_Relay Type - C	GooseDSet13		S3V1T	86T2	TS-A	S3	97T2F	BK	T	86T2P TRIP, BFI, RECL WAIT, BKR 5P	CCIN050	CCIN050
87T2P_Relay Type - C	GooseDSet13		S3V2T	86T2	TS-B	S3	97T2F	BK	T	86T2P TRIP, BFI, RECL WAIT, BKR 5P121 w/89 TR2		
87T2P_Relay Type - C	GooseDSet13		S3V3T	86T2	TS-C	S3	97T2F	MO	T	86T2P TRIP, MOD TR2		
87T2P_Relay Type - C	GooseDSet13		S3V4T	86T2	TS-D	S3	97T2F	BK	T	86T2P TRIP, BFI, BKR TR2		
87T2P_Relay Type - C	GooseDSet13		S3V7T	PB-T				MO	T	PB-T TRIP, MOD TR2		
87T2P_Relay Type - C	GooseDSet13		S3V8T	PB-C				MO	C	PB-C CLOSE, MOD TR2		
87T2P_Relay Type - C	GooseDSet2		TotVAr.inst	MVARS						MVARS ,		
87T2P_Relay Type - C	GooseDSet2		MsgQuality	Goose Message Quality						Goose Message Quality ,		
87T2P_Relay Type - C	GooseDSet13		S2LT1							DIGITAL WATCHDOG PULSE		

Figure 26: Spreadsheet as Bit Map

8. Other Forms of Documentation

Along with the drawings needed to detail the protective relaying system, there is a host of drawings and documents needed to detail the power system and the system infrastructure that protective relaying is a part of. Though not specific to protective relaying or not graphical representations, the following documents prove invaluable to the effective application of a protective relaying system.

8.1. Wiring Diagrams and Rack Layouts

Wiring diagrams are the physical representation of the system and are often used to construct the wiring of the panel. Therefore they must match as closely as possible what the equipment looks like. Because it is based on the physical state, the needs for the representation of power system relaying do not differ significantly from the other installations such as controls or communication.

A strictly visual representation of the wiring required quickly becomes complex due to the sheer number of cable and wire connections required. This approach not only depicts the termination of each wire but how each wire is routed between the termination points on the rack and sometimes termination points on other racks. Figure 27 is an example of one of these types of wiring drawings which were aptly named “spaghetti diagrams” .

A different approach is shown in Figure 28, where only the routing of the wires in cables from equipment on other drawings is shown. Wires from each cable are drawn and documented with their wire labels as they are terminated in terminal blocks. In this diagram, wires from terminal blocks to equipment are shown as call-outs. For example, at the left of the drawing is device PSU which has a terminal marked L with a call-out labeled TBB3-21. To the right of PSU is a terminal block labeled TBB3 and on its terminal 21 is a matching call-out labeled PSU-L.

A more systematic method is to keep track of point to point wiring using some form of tabular format. This can be accomplished in various forms. Figure 29 shows a detail from one form of this approach which is a wiring drawing that consists of a panel layout showing the location of each device. These drawings generally provide a view of the rear

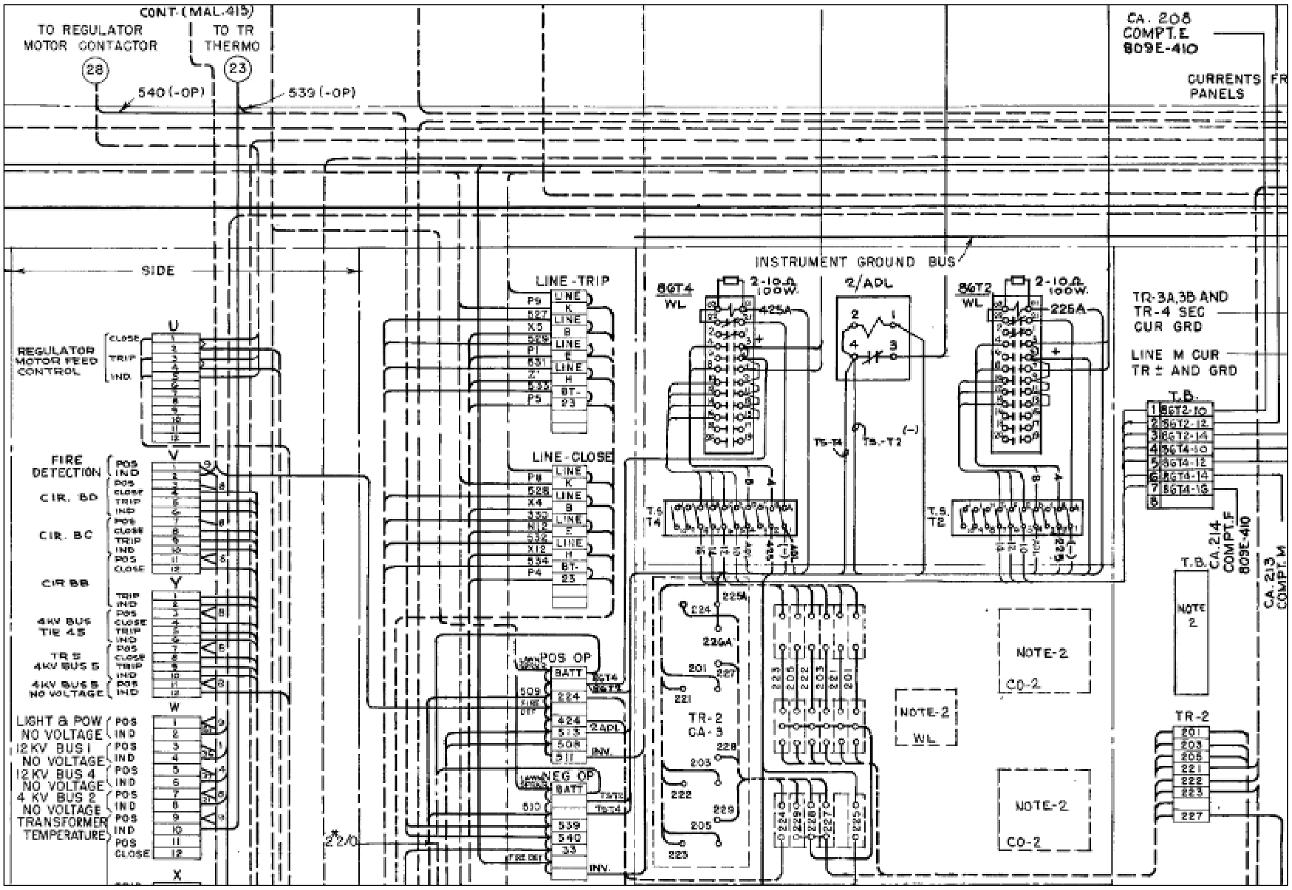


Figure 27: Detail of Wire and Routing Diagram

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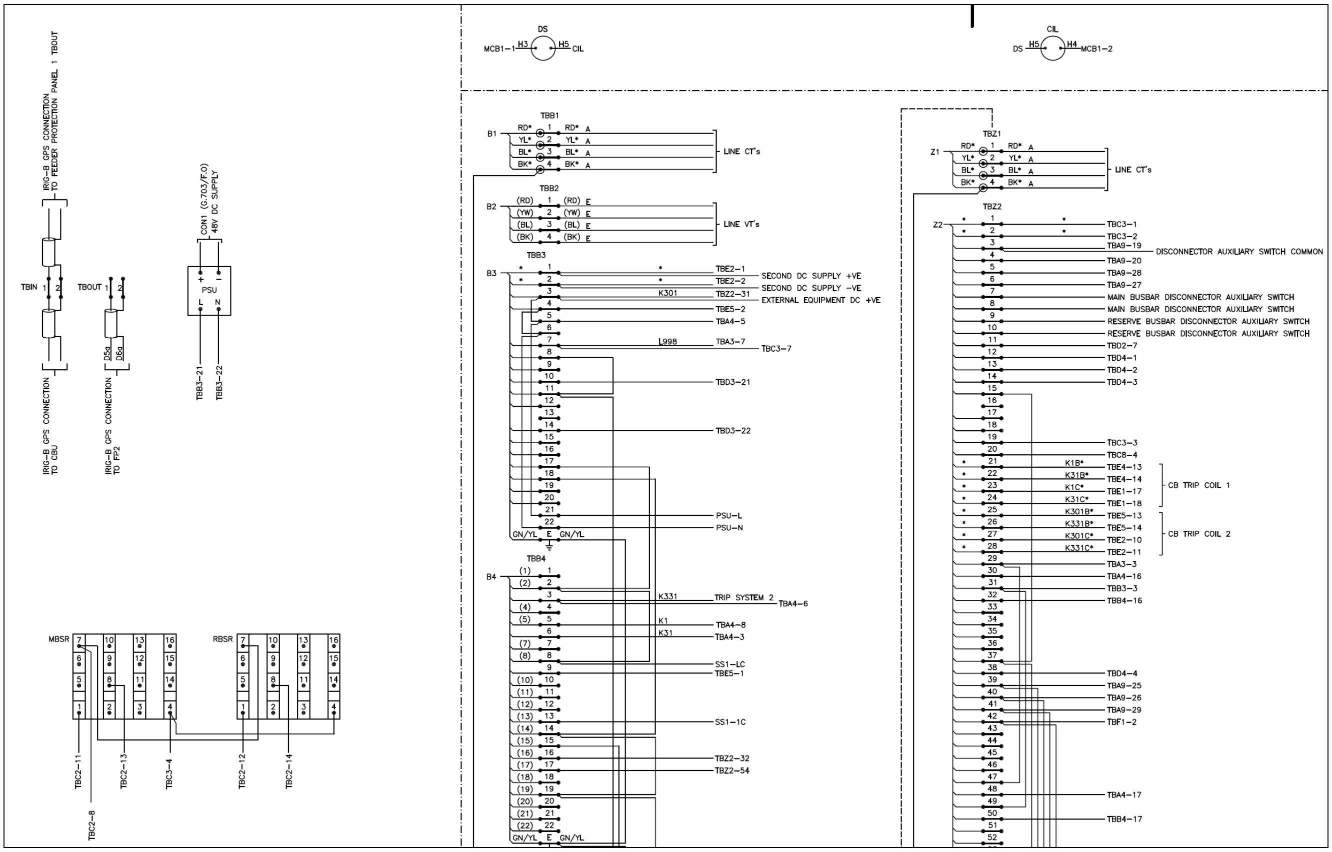

Figure 28: Detail of Wiring Diagram with Callouts

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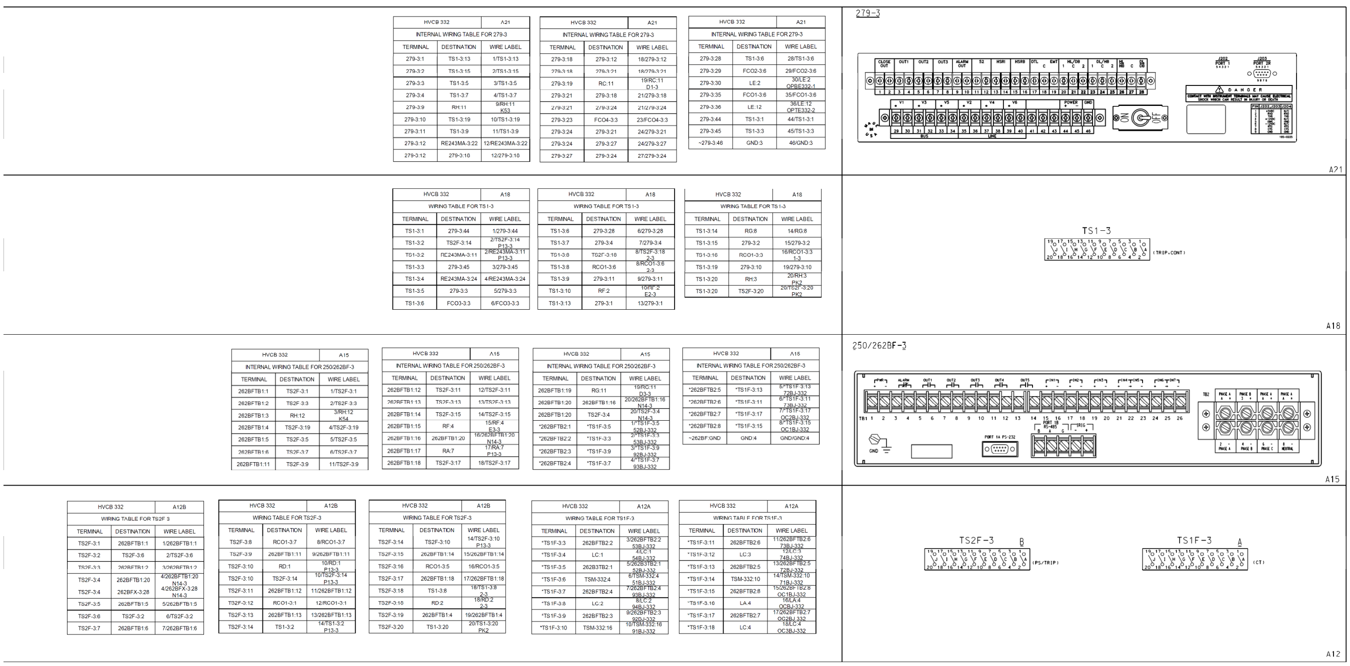

Figure 29: Detail of Wiring Diagram with Connection Tables

of each relay or other device showing the terminals used for the attachment of the external wiring to the device and all communication ports and terminals are depicted for each mounted device. Near each of these views is a table listing all of the connections made to each of these devices. Discrete terminal blocks can be replaced by a table listing the terminations made to that particular block. For example in Figure 29, referring to the "Internal Wiring Table for 279-3" Terminal 279-3:28 shows a destination of TS1-3:6. Just below and to the left is "Wiring Table for TS1-3" and for terminal TS1-3:6 which shows a matching destination of 279-3:28. Both tables are adjacent to rear views of their corresponding devices and the locations of the terminals are easily identified.

To carry this concept further, the drawing is eliminated altogether and replaced with a series of tables that serve to itemize all of the point to point wiring. The information contained on such a table can be whatever is needed but would at least contain information defining the "from" point, the "to" point, unique wire identification, and the point locations. The advantages of this approach should be fairly obvious. The final form of this concept is to eliminate the need for a wiring drawing and simply keep track of the wiring using a table. A spreadsheet accommodates this form well. It is easy to produce and updates are quick. The disadvantage of the spreadsheet approach as compared to the approach that uses more physical details is that the spreadsheet can be more difficult to use for troubleshooting and repairs.

8.2. Front View Rack Layout Diagram

For quick reference to device arrangements and layouts on racks, the front view rack layout diagrams are handy to have. An example of the rack layout diagram is shown in Figure 30. Often, these drawings are used to construct the rack and so are often drawn to scale however sometimes they are not scaled. In this example, the layouts, which are drawn to scale, would be helpful to engineers in determining availability of rack spaces for future design. Also documented are the type of devices mounted on the rack and sources for power supply. Sometimes a bill of the rack materials may be included on the drawing. This bill of materials provides detailed descriptions of the equipment on the rack or panel. From this information the equipment can be ordered.

8.3. Communication

Communication systems of electric utilities have become increasingly critical to electric system protection, operation and maintenance. For fast tripping and clearing of system faults, communication-aided relaying has become a common protection scheme particularly in line protection. Control centers are dependent upon reliable communication channels to remotely operate substation circuit breakers and switches, telemeter electrical quantities of the electric system, and monitor substation alarms. Maintenance engineering has also become increasingly dependent to communications for remote access to intelligent electronic devices such as relays, remote terminal units, digital fault recorders and revenue meters. Because of the increasing dependency on communication systems, electric utilities are managing their communication assets through proper documentation with drawings and databases.

Documentation of a substation has to address the internal and external communication circuits and the nature of the data that is being communicated. For the purposes of this paper, the area of communication has been split into three areas: internal

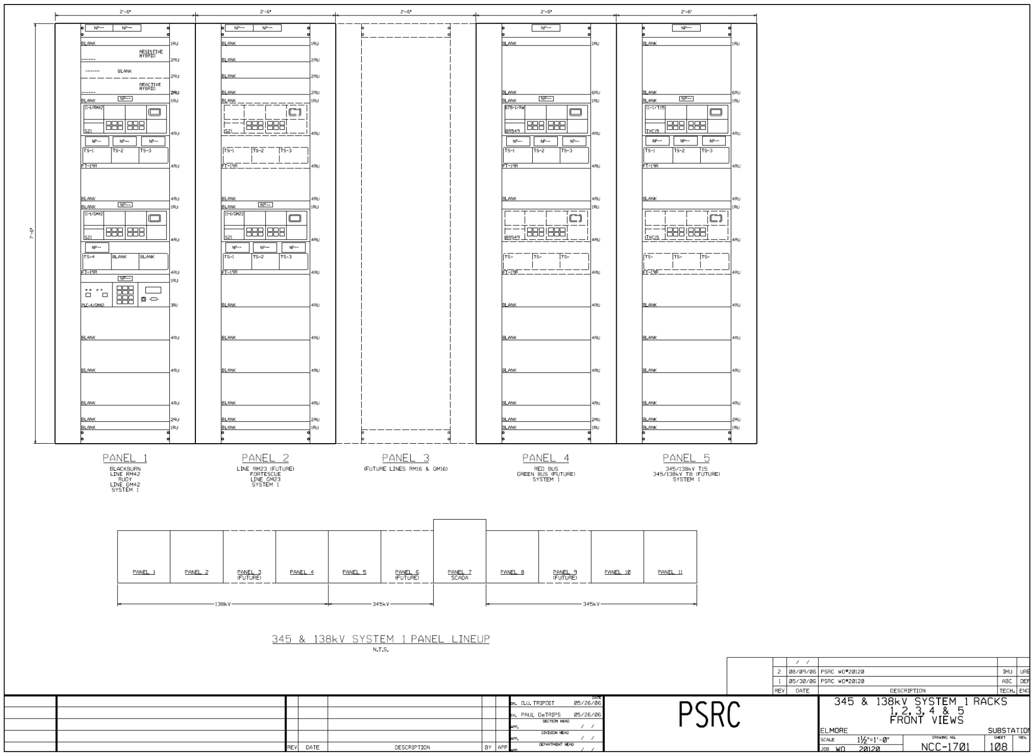

Figure 30: Front View Rack Layout

communications – the communication system design internal to the substation that feeds into the external communications and documents relay-to-relay communications; SCADA – details of the documentation unique to SCADA data; and external communications – inter-substation communications and the details of the communication media used. Note that these three areas of communication are all integrated with each other and there is overlap between these areas.

8.3.1. Internal Communications

IEEE Std C37.1-2007 discusses the importance of block diagrams, with the new revision underway addressing the communication block diagram in more detail. The communication block diagram provides a similar function for the communication system as the substation one line provides for the electrical design. Before any communication design begins, all of the internal and external connections to IEDs should be put on a drawing. These circuits include:

1. Remote SCADA communications to one or more entities and/or utilities for operational data
2. Remote communications to one or more entities and/or utilities for non-operational data
3. Inter-substation protective relay communications via various transport methodologies:
    a. Dedicated fiber using proprietary communications
    b. Serial multiplexed signals to a SONET ring
    c. Power line carrier
    d. Ethernet
    e. Leased telco circuits
    f. Radio/microwave circuits
4. Local telco circuits for substation phone and/or data circuits
5. Revenue metering data circuits

Entities involved for each of these circuits can be one or more utilities, power plants, and independent system operator.

The communication block diagram should detail the following connections for each IED:

1. Device designation
2. Device part number (optional)
3. RS-232 serial communication ports with connector type (terminal block, DB9 male/female) and port number with front or rear indicated as necessary
4. RS-485 serial communication ports with connector type (terminal block, DB9 male/female) and port number or terminal block number with front or rear indicated as necessary

5. Ethernet ports with connector type and speed (RJ45: 10/100BaseTX, 10/100/1000BaseTX; ST, MTRJ, LC: 10BaseFX, 100BaseFX) and port number with front or rear indicated
6. IRIG-B port with connector type (coax, terminal block) and modulation, with port number or terminal block number with front or rear indicated as necessary

Device designations can use device number 16 when appropriate. C37.2-2008 added device number 16 to refer to data communications devices and lists suffixes to identify the functions. The first suffix indicates whether the device is serial (S) or Ethernet (E). Subsequent suffixes indicate the following functions: security processing (C), firewall (F), network managed (M), router (R), switch (S) and telephonic (T). Device designations on the block diagram should match those assigned on nameplates and drawings to provide consistency across the design documentation.

The communication block diagram should connect communications ports together, with cable types indicated by line type and/or line annotation. Organization of the communication block diagram is very important, as the diagram can quickly become a mess of lines that is difficult to read and understand. Care should be taken when splitting apart the drawing into different drawings for time signal distribution, Ethernet, and serial connections, as this duplicates some similar information shown on various drawings and can be prone to error. The diagram should mimic system architecture and the physical installation if possible, so devices located in adjacent panels are shown adjacent on the drawing.

Figures 31, 32, and 33 are examples of block diagrams. Figure 31 shows a small, simple block diagram for a metering system connected to a generation plant with IRIG-B connections and network connections shown.

Figure 32 shows a detail from a larger, more complex conceptual block diagram for a complete substation automation system without IRIG-B distribution shown. This drawing was completed at the conceptual design stage, well before any detailed design was started. Some protective relay communications is shown. Note the use of device number 16. For example, 16ERFCM indicates an Ethernet router, managed, with firewall and VPN for cyber-secured communications.

Figure 33 is a detail from an even larger, more complex block diagram for part of a substation automation system that shows IRIG-B distribution. At the point of the design process, Figure 33 had not yet captured the protective relay communication requirements.

8.3.2. SCADA

SCADA is an important part of substation control and protection and its integration to protective relay schematic is very common. The SCADA equipment discussed in this section is referred as Substation Remote Terminal Unit / RTU. This section does not cover the SCADA – Energy Management System that is the SCADA master at utilities control/operation center. The schematic representation at the substation drawings typically ends at the telephone/communication circuits going back to the external communication system.

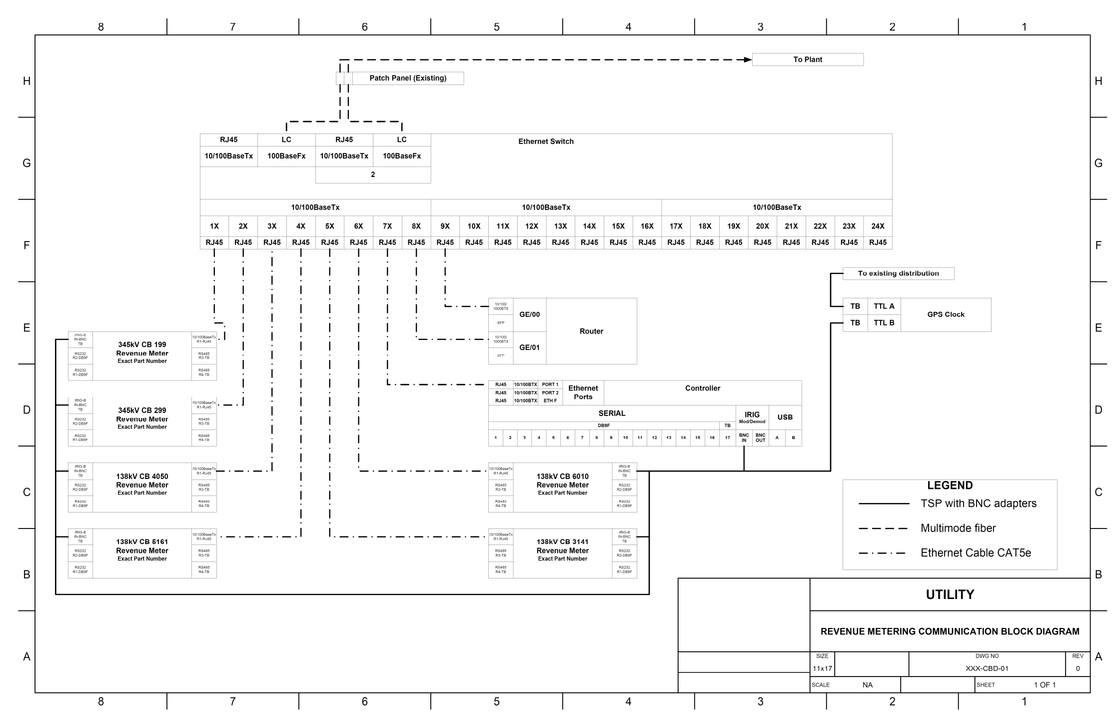

Figure 31: Example Block Diagram #1

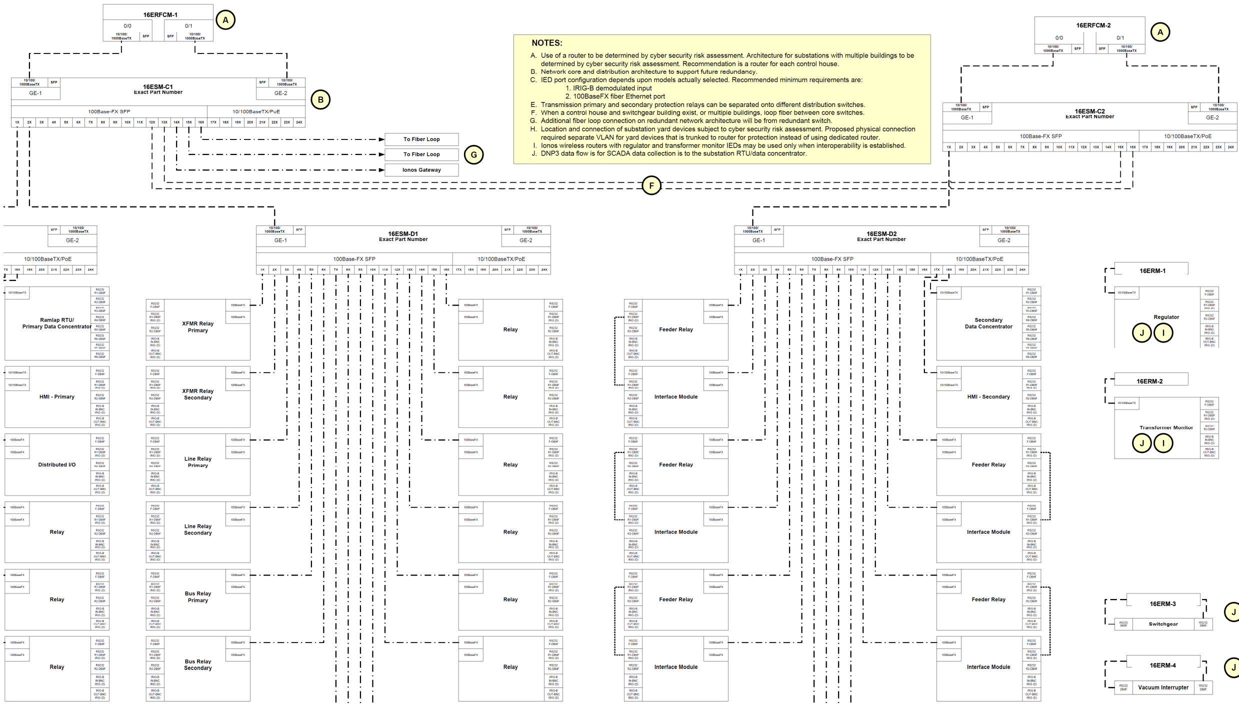

Figure 32: Detail from Example Block Diagram #2

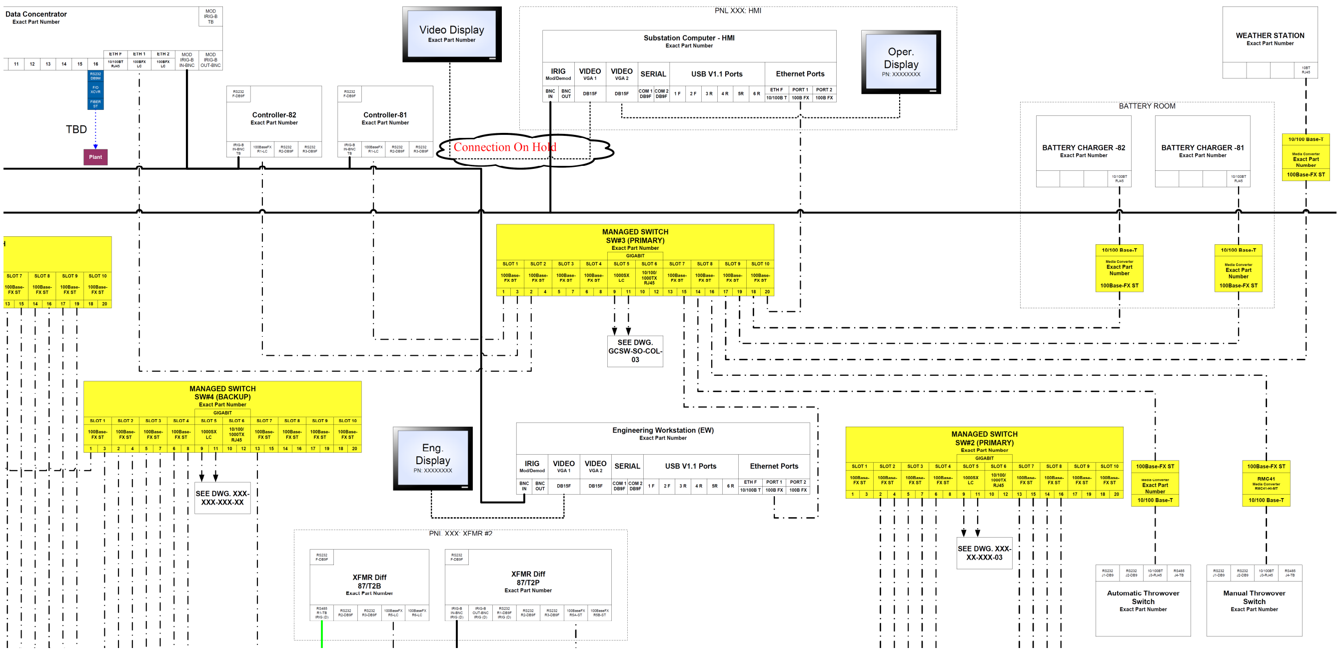

Figure 33: Detail from Example Block Diagram #3

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Some utilities have their own SCADA group that handles communication circuit/information document between the substation site and control center. It is not common to include this information in the substation schematic.

The following information is important to include in representing substation SCADA related control/equipment in the schematics.

- Functional/Network diagram (firewall, router, switch, IED, meters, HMI, transducers, multiplexer)
- Protocols (DNP3, Modbus, etc.)
- Communication interface/pin out (ie. RS 232, null modem, RJ45, Fiber optic, etc.)
- Port Communication setup (baud rate, stop bit, parity, etc.)
- Cyber-security critical infrastructure perimeter diagram
- Communication media (copper, fiber, microwave, etc.)
- Communication circuit ID and type (analogs, digitals, frame relay, T1, Sonet, etc.)

Where possible, SCADA related controls are to be identified in the schematic by unique box or text font for easy identification.

The same issues as in microprocessor relays are encountered in SCADA equipment. For example a Remote Terminal Unit sometimes has logic built in the programming. It is sometime difficult to decide how much of that program inside the RTU should be documented on the schematic diagram.

Many utilities use separate table/spreadsheet based documentation outside the schematic. Any pertinent information to protocol/s used in the SCADA system need to be documented either in this document or the schematic.

The SCADA design documentation is a combination of the communication block diagram and the SCADA point list. The SCADA point list is developed to show what points are mapped from the slave IEDs to the master IEDs or SCADA masters. IEEE Std C37.1-2007 discusses the concept of point count, but does not discuss the point list in detail. This will be accomplished in the ongoing revision to that standard.

The point list can be a valuable design control document as well as a testing document. The point list is usually in a spreadsheet format, with separate worksheets for:

- Cover sheet
- Connection sheet
- Status
- Control
- Analog inputs
- Analog outputs
- Accumulators

The cover sheet contains a revision block and site name. The connections worksheet can detail the communication settings for the ports being used in the system, with serial port and network port settings showing relevant information about the connection type. Serial connections can show baud rate, data bits, stop bits, parity, slave address, master address, and protocol. Network connections can show port speed, IP address, subnet mask, default gateway, master address, slave address, and protocol.

Each worksheet for data points has a different format, with appropriate columns depending upon the system functionality:

- Point number
- Point name
- Point description
- Alarm state
- On description
- Off description
- Comments
- Scaling (min, max, offset, counts)
- Units

Even with IEC 61850 substation automation systems, the point list can be a valuable tool to define what points are actually required from each IED and where that data goes. So the function turns into a design control document that IED configuration files can be created to match.

It may also be necessary to create a data flow diagram, either in spreadsheet or drawing format, so that the person programming the firewall/router knows what communication is explicitly allowed in the system. If in a spreadsheet format, placing the "data flow table" as a worksheet in the point list is an option. This table shows all IEDs as rows and columns, with cells filled in where a protocol connection is being used and indicates the port number or protocol. If in a diagram, it is important for the data flow to show at least the initiating connection and identify the protocol being used along with the associated TCP port number.

8.3.3. External Communications

Electric utility communication systems are typically unique and proprietary to the electric utilities that own them. Hence, approaches to documentation of these systems may vary from utility to utility. However, there are documentation approaches that are common among electric utilities such as communication system maps, drawings and diagrams, and databases of utility-owned communication assets, channels and leased lines.

- **Communication System Map**

A communication system map is useful in depicting a bird's eye-view of the electric utility's backbone communication system which is typically composed of microwave radios and fiber optic cables. The actual locations of major communication sites or terminals are typically indicated on the service area map of an electric utility as dots. Also shown are the backbone communication links between communication terminals, whether fiber cables or microwave hops. To differentiate the microwave radio and fiber optic systems, the dots and lines can be color coded. Other useful data that can be included on the map are the azimuths and elevation of microwave antennas, heights of microwave towers, lengths and types of fiber optic cables and other pertinent information peculiar to each terminal or site.

- **Communication System Layout Diagram**

The purpose of communication system layout diagram is to document all communication devices used at a communication site or terminal and to depict how these devices are interconnected with each other. The devices include microwave radios, fiber-optic multiplexers, digital access cross-connect switches (DACS), routers, channel bank assemblies (CBA) and T1 protection switches. An example of communication system layout diagram is shown in Figure 34. In this example, the communication terminal, located in a substation, directly supports a control center. As shown, the backbone-communication devices such as microwave radios and fiber optic SONET OC-3 multiplexer are documented and drawn to show how they are interconnected with other devices. As observed, the communication system layout diagram is a high-level representation of a communication system at a substation or communication terminal. Typically, interconnections between devices are shown at DS1 and higher levels of digital communication only.

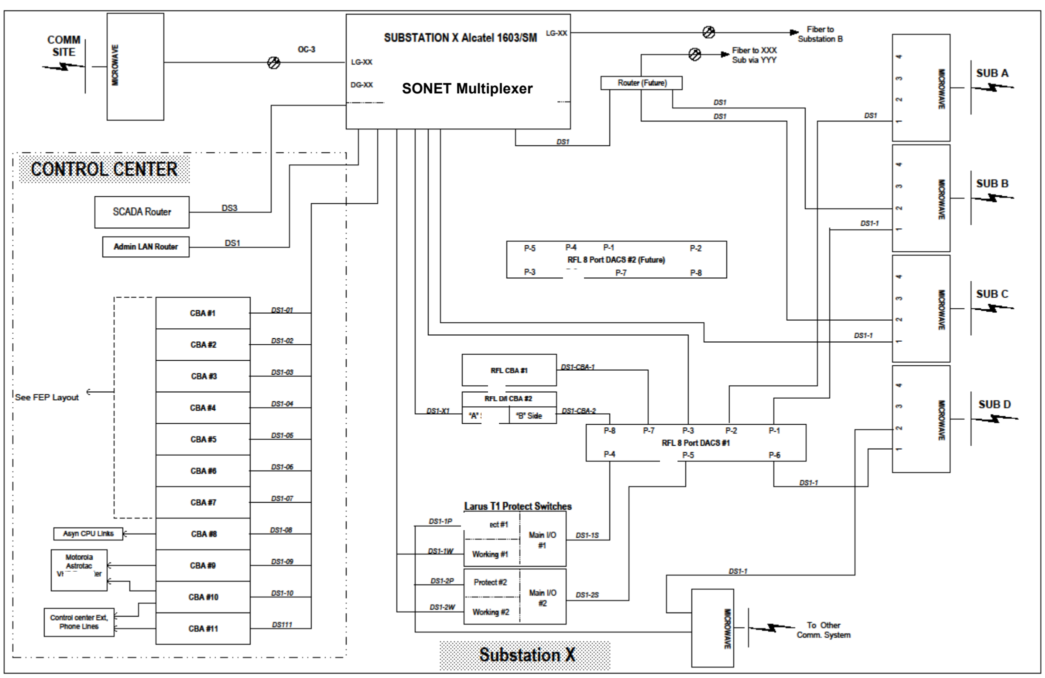

Figure 34: Communication System Layout Diagram

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- **Microwave Radio and Fiber Optic Communication Systems Diagram**

Figure 35 is an example of a microwave radio communication system diagram which documents and presents the components of microwave radios in a substation or communication terminal. Detail information relating to the antennas and waveguides are documented in this diagram. Specific parts of the antenna-waveguide system are documented for ease in maintenance. Block diagrams showing the types of radio transmitter-receiver, multiplexers and channel bank assemblies and their interconnections are presented. Also shown in detail is the 48Vdc power supply system that supports the radios.

The fiber optic communication system diagram documents terminal devices associated with fiber optic communications in substations. An example of this diagram is shown in Figure 36. As shown, fiber patch panels and their terminals are clearly indicated in the diagram. Communication devices and relays that use direct fiber communications are drawn showing their fiber optic ports and their fiber connections to and from the patch panels. Patch panel terminals are clearly indicated in the diagram. This information is very critical in trouble shooting of optical fibers.

- **Communication Channel Circuit Diagram**

One method of documenting communication channels is by drawing out the entire communication circuit between the communicating devices as shown in Figure 37. In this diagram, the devices that are communicating with each other are the RTU in a substation and the control center SCADA. As communication channel is routed through channel banks and digital access cross-connect switches, channel assignments and communication circuits are documented. Baud rates, connector types and communication protocols may also be documented on the diagram. Actual microwave hops and radio sites can be specifically indicated in the clouded microwave radio system.

- **Database Documentation**

For better accounting and management of electric utility assets, business applications such as asset management programs are commonly used in the industry. Communication system assets are entered and stored in the databases of these programs. Specific information of these devices including historical maintenance data are archived and managed in the database. This database is linked to financial database for tracking expenses of their maintenance.

Generic database or spread sheet programs may be also used to archive and document specific information or assets technical data. The advantage of using these applications is the greater flexibility for the users to create database fields as deemed necessary, and to design the report format as desired. An example of a report of a query from a database is shown in Figure 38. In this example, the cross-connecting channels to DACS Port 008 channels and circuit descriptions are documented. This database provides a convenient method for documenting, tracking and managing channels through a DACS system.

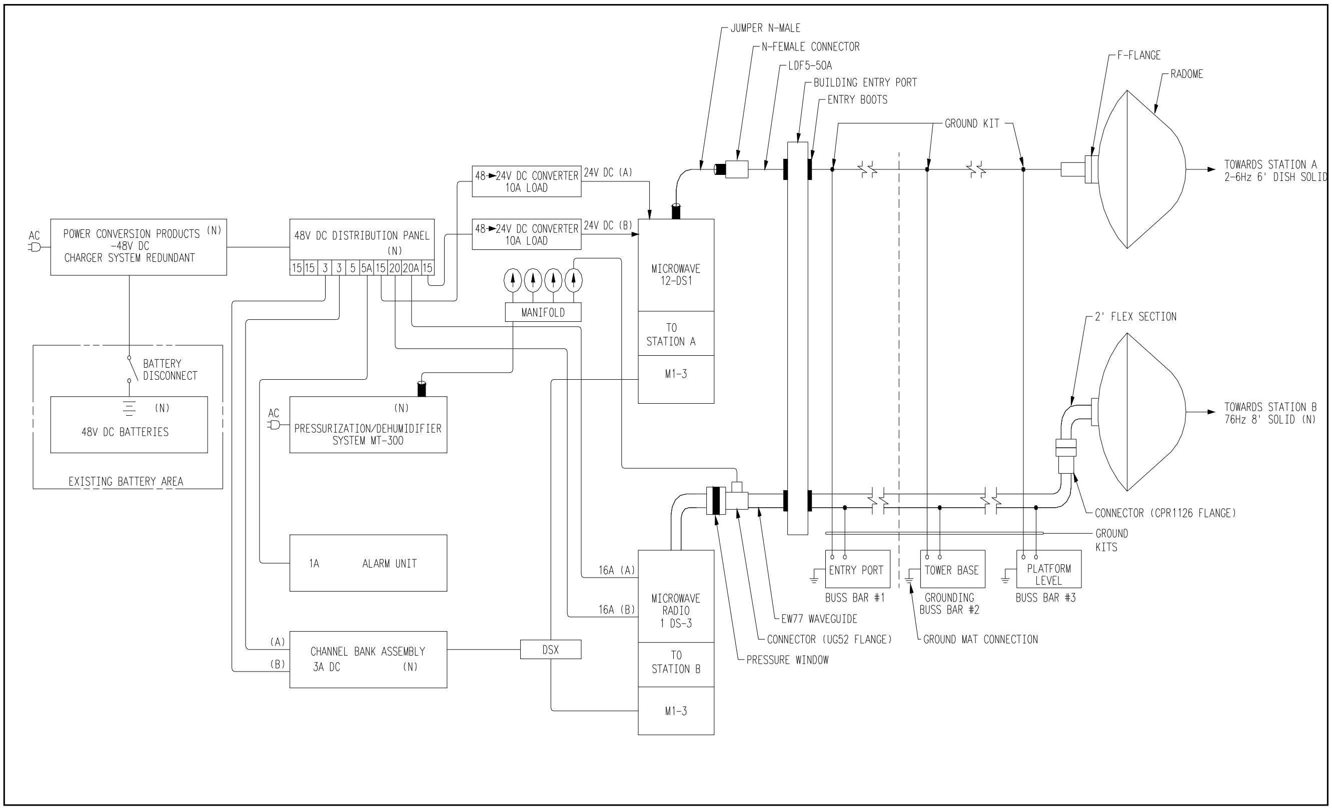

Figure 35: Microwave Radio Communication System Diagram

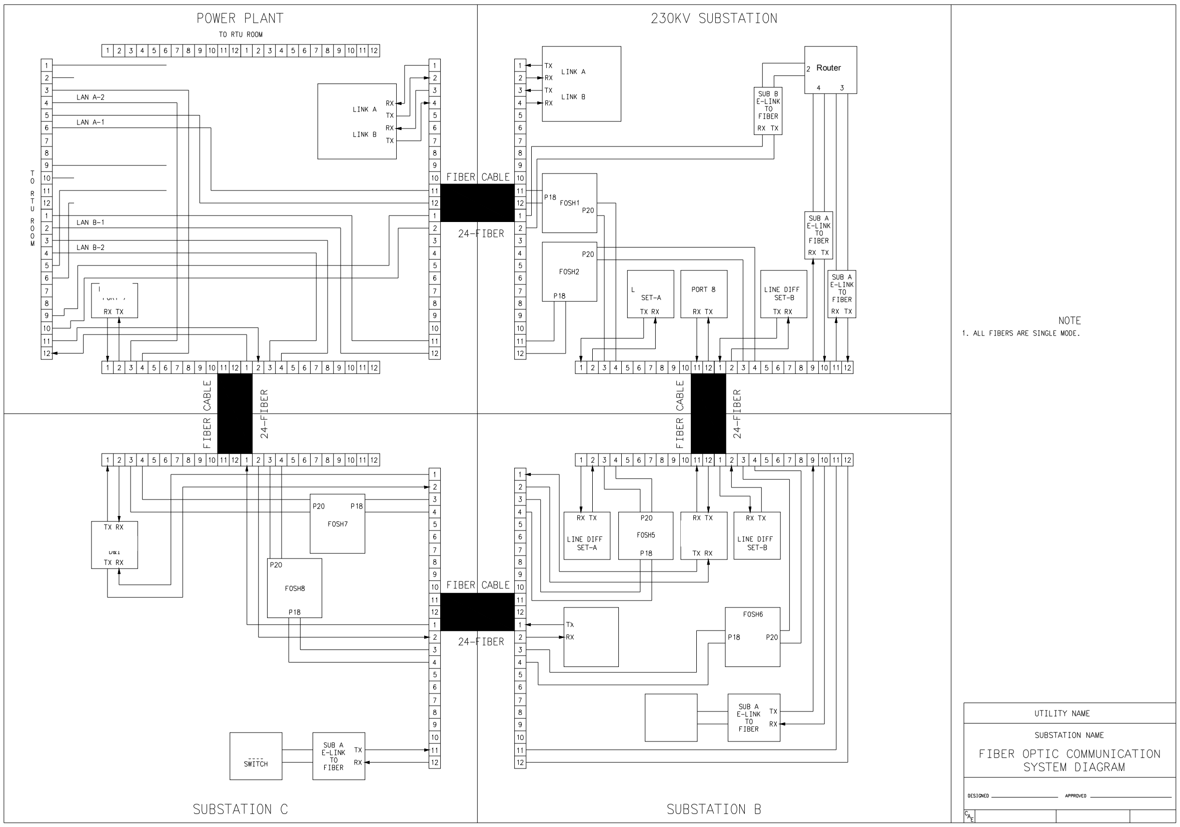

Figure 36: Fiber Optic Communication System Diagram

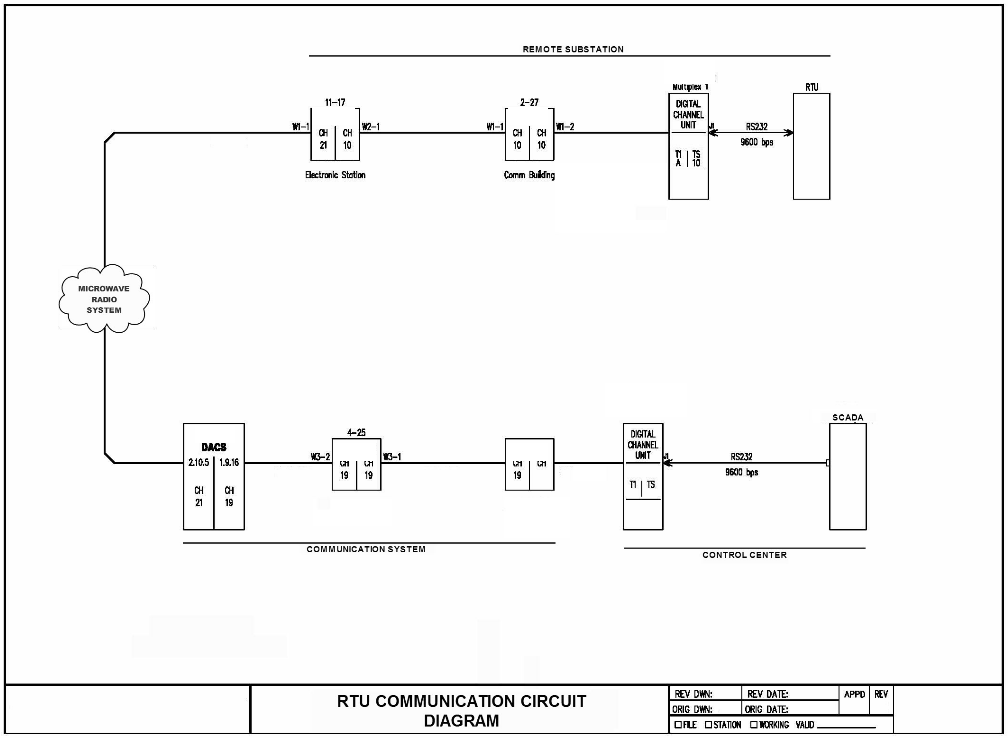

Figure 37: Communication Channel Circuit Diagram

8.4. Design Philosophy Document

The purpose of a design philosophy document is to provide a record of the application and design goals of a protective relay design and to and communicate these goals to affected stakeholders.

With the growing use of microprocessor relays, documentation within a DC schematic of the logic found within each relay has proven to be a challenge for many organizations. While the logic may be found in the relay's settings file, it is not commonly shown on drawings, nor are the design intent and considerations readily understandable from the end result.

Design philosophies, similar in content to a logic diagram, contain specific explanations of each logical equation programmed within the relay. The design philosophy explains the conditions that must exist for an anticipated output.

The use of design philosophies varies within each organization. A design philosophy may be used as a reference when applying a certain scheme, while other organizations have found value in ensuring each substation has its own copy that is updated anytime the schemes within the substation are changed.

DACS Ports for Substation X

DACS Port: 001

Channel Circuit ID Port Channel DSX

Port DSX: **2-01**
T1 ID: **SUB X – SUB Y 01** SUB Y RFL C3A to SUB X DACS Port 1

Term Equip: **MDR-6000**
Equip DSX: **1-28**

CHANNEL	CIRCUIT ID	PORT	CHANNEL	DSX
01				
02				
03				
04				
05				
06				
07	SUBSTATION Y PHONE EXT	004	12	2-04
08	SUBSTATION Y DATA EXT	005	13	2-05
09	SUBSTATION Y FAX EXT	006	14	2-06
10				
11				
12				
13				
14				
15				
16				
17				
18	SUB X-SUB Y DTT	007	22	2-07
19	SUB X-SUB Z DIST RELAY POTT & DTT	003	08	2-03
20	SUB X-SUB Z RELAY DIFFERENTIAL	008	10	2-05
21	SUBSTATION Y RTU (DNP)	005	19	2-05
22	SUBSTATION X RTU (DNP)	004	18	2-04
23				
24				

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Figure 38: Database Documentation of DACS Channels

8.5. Commissioning Documentation

In the paper "Lessons Learned From Commissioning Protective Relaying Systems", by Karl Zimmerman and David Costello, a number of observations are made regarding the process of documentation for commissioning purposes. The following are excerpts from the paper.

> *"As an industry, we have replaced detailed drawings with electronic settings files. In the past, detailed control schematics served as a visual description of our intended scheme. For a technician, the diagram did more than explain the circuit, it provided a troubleshooting and testing road map. Without this picture, a technician is forced to examine electronic settings files, interpret intended scheme operation, and assume what needs to be tested. Without it, a commissioning plan or checklist is replaced with "winging it." Our most critical commissioning tests are often done at the very end of a project, after many dates have slid except for the final in-service date, leaving precious little time for detail and our best efforts.*
>
> *Combine this with the use of protocols and features that may be new to a user. Protocols are often touted as revolutionizing, but regardless of how control logic is implemented, the protection system still needs to be documented, validated, and tested."*
>
> *"Many problems are created due to poor or incomplete documentation. Simply sending out settings and connection drawings is often not enough. For example, if an application includes programmable logic that resides in the relay, that logic must be described and documented. Sometimes this requires complete logic representation.*
>
> *1) Create the Documentation Necessary for the Application*
>
> *Examples of different methods of depicting relay settings logic include the following:*
>
> - *Word description*
> - *Control circuit representation of logic*
> - *Logic gates description of logic*
> - *"Ladder" logic*
> - *Relay settings*
>
> *All of these can be valuable tools, but the important thing is to provide adequate documentation for the specific application."*

9. Conclusion

The disruption to the established method of the schematic representation of power system relaying precipitated by the significant technological changes to power system relaying has brought to light issues that need to be addressed.

- Established methods have proven effective for supporting the safe and reliable installation and operation of power systems. The technological shifts may have changed how the system is documented but has no effect on the standing need for that safe and reliable system. The challenge has been that before changing the methods of representation, the best understanding of the established methods will ensure the most successful evolution to new methods. Unfortunately, the net loss of expertise challenges the continuation of best practices. Though this paper attempts to address this, it was observed that more papers like this will be needed.

- Due to the power and flexibility afforded by the microprocessor and communication technologies, products based on these technologies will be widely divergent in approach but with similar results. The natural advance is numerous divergent paths in communicating the operation of these products. This will require a close relationship between manufacturer and user to try to make these new products easier to assimilate into the existing methods of documentation.

- What makes this assimilation especially challenging is the subtly shifting roles of the documentation for relaying systems in establishing the quality of the power system's functional operation. The functions performed by relaying systems that use earlier technologies are defined more by the wiring than by the setting of the relay. Whereas the relay setting certainly determined how the system operates, there are more opportunities to effect that operation in the wiring. In these systems, schematics played an important role in the construction of the system. For, as stated, as one goes from single line to schematic to wiring diagram, the functionality becomes less apparent but the construction requirements become clear. Systems are constructed from wiring diagrams which are created in reference to the schematic. There is a direct line of determination from schematic to wiring to functional operation. In other words, the performance of the system is determined by the wiring which is determined by the schematic diagram. With this process, the quality of the system performance is determined by the quality of the wiring which is determined by the quality of the schematic. Any corrections to the wiring made during testing can be directly made to the schematics.

  Compare this with evolving technologies where the wiring is minimal and a greater portion of the systems operations are determined by the setting and configuration of the relays. The most commonly observed approach is to derive the settings based on studying the IED manual combined with the relay setting engineer's understanding of the functions needed derived from the scope of work and the one line diagram. Then, after the relay has been set, schematics are drawn based on the settings. These schematics may be made up of input/output assignments, logic diagrams, and IEC61850 message tables. To appreciate the difference in the process, this would be like wiring a panel and then basing schematics off the wiring. So the quality of the system performance is determined by the quality of the setting. And the quality of the schematic, used for troubleshooting and maintenance, is determined by the *translation* of the setting into a graphical representation. The process does not aid the engineering of quality into the system. The step of translating the relay setting into a graphical representation adds the opportunity of error which is not reflected in the setting. Now if a correction is made to the setting, it has to be translated into a graphical representation which is another opportunity for error.

What is needed to restore quality to the process would be software that could read the setting files and output these settings graphically. Of necessity, this would have to include relay to relay messaging.

- The change in relay technologies also changes the requirement for expertise to design and maintain relay systems. With the functioning of the relay system determined more by the relay setting than the wiring, this has an effect on the pool of resources that will be able to maintain the systems. Those systems whose function was determined more by wiring were represented by schematics similar to those used in many other devices and industries and the ability to read a schematic for a car's electrical system or an air conditioner, for example, would shorten the learning curve for people maintaining those relay systems.

  Emerging technology relay systems that rely more on relay settings, use the manufacturer specific programming along with industry specific protocols. Investments will have to be made to overcome the learning curve and additional knowledge and skills, such as familiarity with computer programming, would be beneficial. Those who manage these resources may have to turn to greater specialization among their maintenance resources between those who work on the relay settings and those who work on the equipment.

  Standardization is important in avoiding some of these challenges but this also depends on the universality of the standard. If the standard has to be revised for most applications then the need for new expertise is created.

It cannot be overstated how important it will be to the adoption of new relay system technologies that for the maintenance of these systems, documentation is available that emphasizes transparency to the functions the system is performing. It is crucial that the technology of power system relaying does not outstrip the industry's ability to safely, reliably and effectively implement these technologies into its daily operations.