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Substations – Volume XII – Auxiliary Systems

Instructor: Lee Layton, PE

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
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Substation Design
Volume XII
Auxiliary Systems

Table of Contents

This series of courses are based on the "Design Guide for Rural Substations", published by the Rural Utilities Service of the United States Department of Agriculture, RUS Bulletin 1724E-300, June 2001.

Preface

This course is one of a series of thirteen courses on the design of electrical substations. The courses do not necessarily have to be taken in order and, for the most part, are stand-alone courses. The following is a brief description of each course.

Volume I, Design Parameters. Covers the general design considerations, documents and drawings related to designing a substation.

Volume II, Physical Layout. Covers the layout considerations, bus configurations, and electrical clearances.

Volume III, Conductors and Bus Design. Covers bare conductors, rigid and strain bus design.

Volume IV, Power Transformers. Covers the application and relevant specifications related to power transformers and mobile transformers.

Volume V, Circuit Interrupting Devices. Covers the specifications and application of power circuit breakers, metal-clad switchgear and electronic reclosers.

Volume VI, Voltage Regulators and Capacitors. Covers the general operation and specification of voltage regulators and capacitors.

Volume VII, Other Major Equipment. Covers switch, arrestor, and instrument transformer specification and application.

Volume VIII, Site and Foundation Design. Covers general issues related to site design, foundation design and control house design.

Volume IX, Substation Structures. Covers the design of bus support structures and connectors.

Volume X, Grounding. Covers the design of the ground grid for safety and proper operation.

Volume XI, Protective Relaying. Covers relay types, schemes, and instrumentation.

Volume XII, Auxiliary Systems. Covers AC & DC systems, automation, and communications.

Volume XIII, Insulated Cable and Raceways. Covers the specifications and application of electrical cable.

Chapter 1
AC Auxiliary Systems

Substation AC auxiliary systems are typically used to supply loads such as, transformer cooling, oil pumps, and load tap changers, circuit breaker air compressors and charging motors, outdoor device heaters, outdoor lighting and receptacles, control house equipment, and motor-operated disconnecting switches,

Designing an AC auxiliary system requires tabulating the connected kVA of all substation AC loads and apply a demand factor to each. Demand kVA is used to size the auxiliary transformer. Load diversity and load factor need not be considered in this case. In auxiliary transformer sizing you should examine the substation growth rate. If expansion is planned in the near future, consider the estimated demand load of the expansion in the transformer size. If expansion is in the far future, it may be economically advantageous to plan for the addition of a transformer at expansion time.

In small distribution substations one auxiliary transformer is usually sufficient. As substation size increases, customer load criticality increases. A decision has to be made as to redundancy of substation auxiliary services in light of economics and customer requirements. Large transmission substations, servicing large load blocks, and distribution stations, should have dual feeders serving two separate auxiliary transformers. When dual feeds are selected, locate two separate, independent sources so the loss of one will not affect service of the other. Designate the least reliable as the alternative supply. A popular option to consider in this case is the use of a tertiary winding of the power transformer as a normal source.

An alternative source could be a distribution feeder at a customer service level, 480 or 240 volts, single or three phase. Depending on auxiliary secondary voltage level selected, this could eliminate one transformer. The auxiliary source could be either overhead or underground distribution lines. When undergrounding within the substation property, even from an overhead source, direct-buried conduit is recommended. A spare, capped, conduit should be installed to minimize down time if a cable failure occurs.

Some low-voltage loads have to be maintained at all times such as,

- Battery chargers which, through the batteries, supply breaker trip and close circuits as well as communication circuits
- Transformer cooling
- Power circuit breaker compressors and motors
- Trouble light receptacles in the station yard
- Security lighting

- Breaker control circuits
- Fire alarm circuit
- Electric heating
- Substation automation circuitry

Critical loads for each station should be determined. These loads should be served from a panel fed from the normal source and representing the minimum load for transfer to alternative supply.

Secondary Voltage Level

Several secondary voltage or utilization levels are available for AC auxiliaries. For the purposes of standardization, on a given power system it is best that only one level be selected. This is not a limiting rule, however. An exception could be justified. Possible secondary voltage levels as illustrated in Figure 1 are as follows:

1. 480/240 Volts, Three-Phase Delta

Three-phase transformer fans and oil pumps need to be specified at 480 volts. In practice, the units are rated at 460/230 volts, but this is inside the NEMA plus 10 percent voltage requirement. Other loads may be specified at either 480 or 240 volts, single phase. This system is ungrounded and should be used with a ground detection system so that a “fault” or one leg of the system will cause an alarm. The system should trip when a second leg on the system is grounded.

2. 480/277 Volts, Wye Connected, Three-Phase, Four-Wire

Three-phase transformer fans and oil pumps need to be specified at 480 volts. In practice, the motors are rated 460/230 volts, but this is within the NEMA plus 10 percent voltage requirement. The advantage here is that luminaires can be equipped with 277-volt ballasts, saving lighting transformer costs over use of more common 120-volt lamped luminaires. Convenience receptacles are fed through small dry-type 480-120 volt transformers.

3. 208/120 Volts, Wye-Connected, Three-Phase, Four-Wire

Three-phase 208 volts or single-phase 120 volts or a combination of the two can be used for transformer cooling. Combination power and lighting panels can be used, resulting in reduced labor and material costs. This saving could be offset by higher conductor costs as compared to the 480-volt system. Receptacles can be served with 120 volts directly.

4. 240 Volts, Three-Phase Delta

Three-phase transformer fans and oil pumps need to be specified at 240 volts. In practice, the motors are rated at 230 volts, but this is inside the NEMA plus 10 percent voltage requirements.

This system is ungrounded and should be used with a ground detection system so that a “fault” on one leg of the system will cause an alarm. The system should trip when a second leg on the system is grounded.

5. 240/120 Volts, Delta-Connected, Three-Phase, Four-Wire

This is the most common level in use in moderate-size substations. One phase of the auxiliary transformer is center tapped to obtain 120 volts. Combination panels can be used, and 240-volt single-phase loads can be served.

6. 240/120 Volts, Open Delta-Connected, Three-Phase, Four-Wire

This is essentially the same as the closed delta connection except only 58 percent of the kVA capacity of the three transformers can be used. This configuration will provide construction economy for a medium-size installation or for temporary use. With single-phase units, the third transformer can be added in the future for increased kVA capacity. It is frequently used for construction power where both three-phase and single-phase supplies are required.

7. 240/120 Volts, Single-Phase, Three-Wire

This is “residential” service but applicable to small substations. Common panels can be used, with two available voltages.

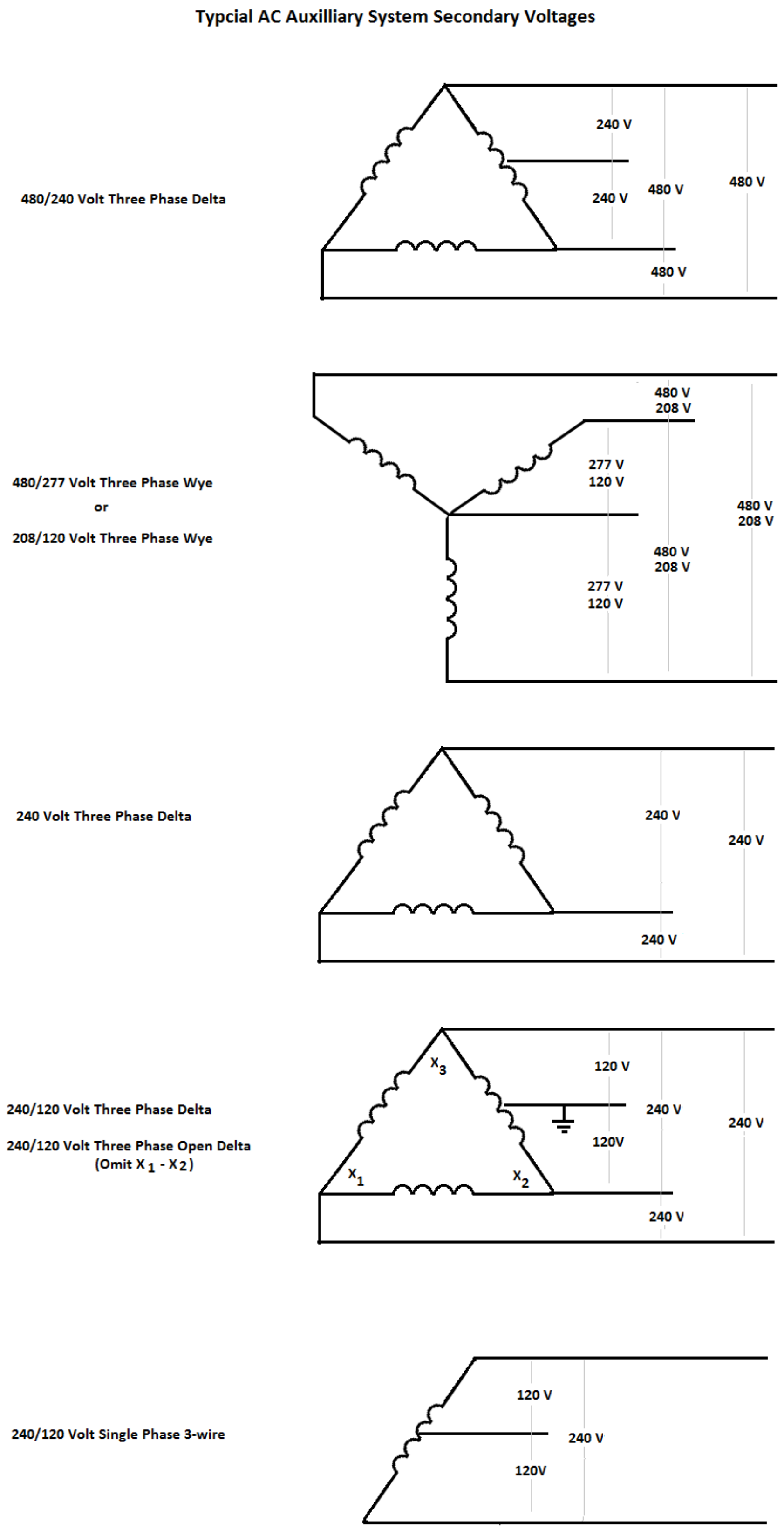

Typcial AC Auxilliary System Secondary Voltages
480/240 Volt Three Phase Delta
240 V
240 V
480 V
480 V
480 V
480/277 Volt Three Phase Wye
or
208/120 Volt Three Phase Wye
480 V
208 V
277 V
120 V
480 V
208 V
480 V
208 V
277 V
120 V
240 Volt Three Phase Delta
240 V
240 V
240 V
240/120 Volt Three Phase Delta
240/120 Volt Three Phase Open Delta
(Omit X 1 - X 2)
X3
X1
X2
120 V
240 V
240 V
120V
240 V
240/120 Volt Single Phase 3-wire
120 V
240 V
120V

Figure 1

Transfer Scheme

Where two sources, normal and alternative, are feeding substation auxiliaries, a means to transfer from one to the other has to be established. At an attended station this can be a manual transfer arrangement. Automatic transfer has to be provided at an unattended station. Transfer is done on the secondary side for equipment economy. Article 700 of the National Electrical Code (NEC) outlines general requirements for this type of scheme. A typical configuration is shown in Figure 2. Transfer switch selection is an important factor in the system design. Operation should be *break before make double-throw* operation to prevent shorting the two sources. Mechanical interlocking should be provided to ensure the switch can be in only one of the two positions. The switch should have an ampere withstand capability for faults at points A, B, and C of Figure 2. The fault at C will be highest, the feeder impedance to B and A limiting the fault current to an amount below that at C. The auxiliary system in Figure 2 assumes transfer of all loads. The full load current of the 150 kVA transformer is 360 amperes, so a 400-ampere switch would be selected.

Assuming a 250,000 kVA source, two 500 kcmil, 10-foot long feeders per phase to the switch, and 4 percent transformer reactance, the fault current is approximately 10,000 amperes. This value is well within manufacturers' standard ratings for 400-ampere full load transfer switches.

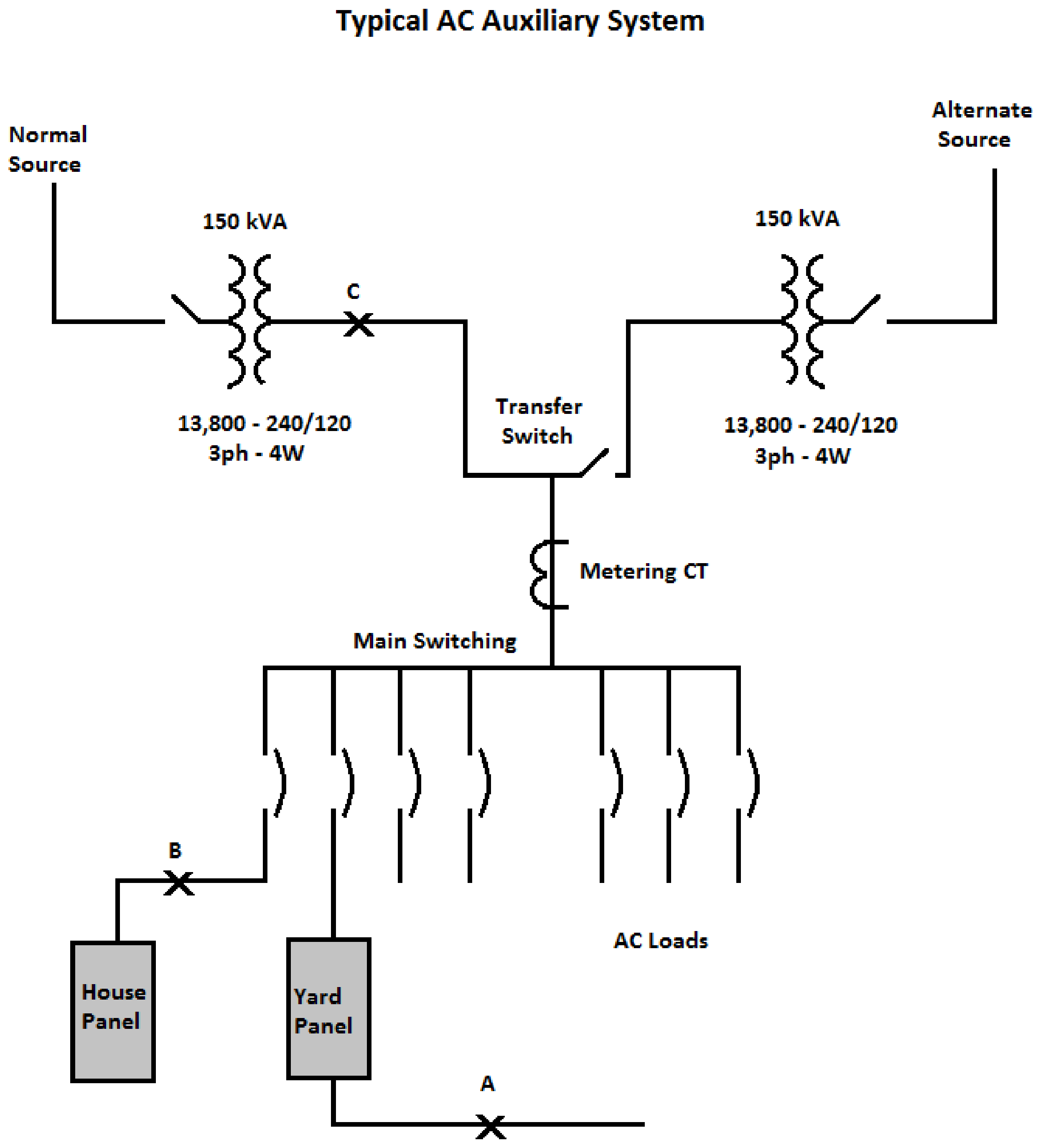


Figure 2

Automatic transfer switches are built to detect emergency conditions and transfer to the alternative supply when the normal supply falls to 83 percent of rated voltage. Return to normal supply is accomplished through an adjustable time delay at approximately 92 to 95 percent of rated voltage. A variety of accessories are available with transfer switches. Manufacturers' data is readily available, and the engineer should consult such data when specifying a transfer switch. Provide means to alarm for loss of voltage from either source.

The determination of fault currents in three-phase AC auxiliary systems is just as basic as the determination of load currents in sizing circuit breakers or fuses. The protective device has to operate or open during faults as well as carry load current during normal conditions or equipment damage could result. The symmetrical short circuit (fault) current is computed using,

$$\mathbf{I_F = \frac{kV_{Line-to-Line}}{\sqrt{3} * Resistance_{Ohms}}}$$

Ohms reactance is the total reactance of all current-carrying parts from the source to the fault.

In Figure 2 the 250,000 kVA source has a reactance of 0.00023 ohms. The 150 kVA transformer reactance is 0.0023 ohms, the current transformer 0.0005 ohms, the 10-foot cable about 0.001 ohms, and so forth. All reactances are totaled for the calculation.

The *asymmetrical fault current* is a function of the fault circuit X/R ratio. A multiplying factor (1.7) for the asymmetrical current is satisfactory for auxiliary power system calculations.
Fuse and circuit breaker manufacturers have handbooks with X, R, and Z values for transformers, current transformers, cables, etc., together with methods for determining protective device ratings based on estimated fault currents.

Equipment

The standards applicable to auxiliary transformers include,

- ANSI Std. C57.12.25, "Pad-Mounted Compartmental-Type, Self-Cooled, Single-Phase Distribution Transformers with Separable Insulated High-Voltage Connectors; High Voltage, 34500 GRD Y/19920 Volts and Below; Low Voltage, 240/120 Volts; 167 kVA and Smaller— Requirements."

- ANSI Std. C57.12.26, "Pad-Mounted Compartmental-Type Self-Cooled, Three-Phase Distribution Transformers for Use with Separable Insulated High-Voltage Connectors, High Voltage, 34500 GRD Y/19920 Volts and Below; 2500 kVA and Smaller."

This type of transformer is good for large substation auxiliary service use. The increasing use of underground distribution has made these units readily available from major manufacturers.

Consider the feasibility of establishing substation auxiliary system voltage at the same level as that for serving underground customers. With this standardization, spare transformers can be stocked and both customer and substation service maintained at minimum cost.

Pad-mounted transformers can be purchased with fused switches on the primary side for transformer fault current protection. High-voltage fuses, in this use sized for full-load transformer primary currents, will inherently have sufficient current interrupting ratings to protect the transformers under fault conditions. Primary load break switches are also available.

If the normal and alternative sources are overhead, pole-mounted, and hook stick operated, fused switches are a possible solution to transformer primary protection. Underground cable is used for the connection from the switches to the transformer pad.

Pad-mounted transformers and the kVA ratings previously mentioned apply to a fairly large substation. For smaller installations, structure-mounted distribution transformers, properly applied, can be used.

Electrical Panelboards

The definition of a *branch circuit panelboard* in the NEC (Article 384) is one having more than 10 percent of its overcurrent devices rated 30 amperes or less for which neutral connections are provided. Additionally, the number of branch circuit devices in one enclosure is limited to 42 poles. Switchboards differ from panelboards in that switchboards are free standing. Front or rear access to line and load terminals are vendor options. Branches can be group mounted or individually mounted, with or without barriers.

Enclosures should be specified NEMA 1, general service for indoor use, or NEMA 3R, raintight for outdoor use. Panelboards are available for flush or surface mounting, with fusible or circuit breaker branch circuits. Main breakers, if required, can be furnished.

For lighting circuit service exclusively, in a moderately sized installation, a circuit breaker panelboard offers the advantage of switching the lights, thereby eliminating light switches. For exterior lighting, the engineer may consider mounting a weatherproof three-pole magnetic contactor fed from an adjacent outdoor panel.

Lighting and Heating Equipment

Outdoor lighting serves two basic purposes: substation security and safety. Depending on the area, certain luminaires may be used during hours of darkness for substation security. These are photoelectrically controlled. A microwave tower could require FAA lighting. This would also be controlled photoelectrically. Lamps for outdoor use are essentially incandescent, mercury, or sodium lamps. Except for an unusual condition, the lamps presently in use on a given system should continue in use, simplifying inventory. The unusual condition could be a new large substation where a different source is desirable and a separate, on-station inventory can be kept.

Luminaires for substation use, from the basic flat dome reflector to Illuminating Engineering Society (IES) pattern refractors, are available. Pole-top or bracket mountings can be used. The engineer, with the proper vendor data, can develop a lighting layout to satisfy the purpose required. The basic requirements are one or two foot-candles in equipment areas. Convenience receptacles should be in equipment cabinets and also strategically located to serve 50-foot extension cords with trouble lights. Convenience receptacles in the substation yard should have ground fault interruption protection.

Indoor lighting should be designed for maximum operator convenience. Luminaires should be located to adequately illuminate relay and control panel fronts. With fluorescent units, 4-foot lamps are recommended, since storage is easier than for 8-foot lamps. Provide duplex receptacles for extension cord lights for initial panel interconnection work, relay setting, and plant maintenance.

Provide control house electric heating for comfort and freeze prevention. This can be done with ceiling or wall-mounted electric unit heaters and/or electric baseboard heating units. Provide powered roof ventilators along with floor-level, manually operated wall louvers to provide for three to five air changes per hour. Louvers should be provided with fusible links as a means, in case of fire, to keep damage to a minimum. Gravity roof ventilators should always be installed to prevent concentration of hydrogen in battery rooms.

Air conditioning of the control house, where required, is best provided by packaged through-wall units. Packaged through-wall units pump an energy-efficient heating/cooling option for most climates and can have supplemental resistance heat. Built-in resistance heaters are provided in some to provide all-season use.

Chapter 2

DC Auxiliary Systems

Substation DC auxiliary systems are typically used to supply loads consisting, relaying, supervisory, alarm, and control equipment, emergency control house lighting, and circuit breaker trip and close circuits. A substation DC system consists of a battery of suitable voltage (number of cells) and suitable size (ampere-hour capacity) connected in parallel with a control bus together with properly selected voltage-regulated charging equipment.

At a single location where two distinct DC voltages are required, i.e., possibly 48 volts for microwave and 120 volts for substation operation, two separate batteries and chargers is one option. Tapping a larger unit to obtain the smaller voltage is not recommended. Another option to obtain different DC voltages is a DC-to-DC converter. This is usually used for small loads and is available from the manufacturer.

The charging equipment consists of a full wave rectifier with regulated output voltage. Normally, the charger operates continuously to furnish direct current to the control bus for steady loads such as indicating lamps, holding coils, and relays, plus a small current to maintain the battery at full charge. Intermittent loads of short duration such as tripping or closing of circuit breakers or automatic operation of other equipment is handled by the charger within the limits of its capacity. Any excess load is supplied by the battery, which is automatically recharged when the intermittent load ceases. Should the AC input to the charger fail, the battery carries the entire load.

The control bus may be a DC bus in a switchgear assembly or, in the case of a large substation, a DC or group of DC panels. DC voltage requirements for solid-state relaying, event recorders, data acquisition, and other such devices are generally below the voltage levels for circuit breaker trip coils. Some types of equipment are provided with individual rectifiers, rack mounted, changing 120 volts, 60 hertz AC, to 12, 24, or 48 volts DC. If the AC supply fails, static switching changes the source to the main DC batteries and required DC converter. An alarm indication is provided to indicate this status. Other equipment is designed to be fed directly from the main batteries with AC/DC converters to supply the static device voltage.

Two of the most important components of a substation DC system are the main battery and charger and these components must be sized correctly. Under sizing could possibly mean a circuit breaker reclose failure and undue service interruption. Over sizing, while not damaging, is expensive. However, the cost of the supply is a fraction of total substation cost, and the economics should be balanced with reliability. At a minimum, the main battery should be sized to allow normal substation operation for 8 hours.

Types of Cells

Before determining the cell ampere-hour rating, the type of cell for the particular application has to be selected. Once a battery is installed for stationary service, it stays in place for up to 30 years. Interchangeability on the system is unnecessary. The types of secondary cells readily available today are:

1. Lead acid
2. Nickel cadmium (NI-CAD)
3. Lead calcium

A brief description of the three predominant types follows. In the case where no standards are established, select battery type based on:

- First cost
- Years of float life
- Annual depreciation
- Number of deep discharges required over the life of the battery

Lead Acid Cell

This cell has a positive plate of lead peroxide and a negative plate of pure sponge lead. The electrolyte is dilute sulphuric acid. Open circuit voltage of a fully charged cell is a nominal 2.25 volts; voltage varies depending on electrolyte strength and cell temperature. Battery condition can be determined with a hydrometer using,

$$\textbf{Cell Volts} = \textbf{S.G.} + \textbf{0.84}$$

Where:
S. G. = Specific gravity of the electrolyte

The specific gravity of the electrolyte varies with cell temperature, so a thermometer should be a part of the maintenance kit. The higher the temperature, the lower the specific gravity. Battery ratings are usually specified at 25C. Temperature correction curves are included with the battery manufacturer’s instruction manual, as are charge and discharge curves.

Nickel Cadmium

This cell has a positive plate of nickel hydrate and a negative plate of cadmium sponge. The electrolyte is a solution of potassium hydroxide with a specific gravity from 1.160 to 1.190 at 25C. Open-circuit voltage may vary from 1.30 to 1.38 volts. The cell voltage is 1.4 volts fully charged at 25C. The specific gravity of the electrolyte is constant regardless of charge state.

The nickel cadmium battery has the advantages of infrequent maintenance requirements, absence of corrosive fumes, immunity to inadvertent overcharge, and the reduced derating required for ambient temperatures below 25C. The absence of corrosive sulphuric acid fumes allows for the installation in cubicles, a possible advantage in some installations. The primary reason for the lack of greater use of NI-CADS for main substation batteries is initial cost.

Lead Calcium

This cell is similar to the lead acid type with the exception of the addition of approximately 0.8 percent calcium to the lead grid for additional strength. This alloy also greatly reduces cell internal losses.

Typical Loads and Duty Cycle

To accurately specify a battery and associated charger, the DC load has to be accurately defined. Each single item of equipment connected to the DC system has to be individually tabulated with the following pertinent data included:

- Voltage
- Current requirement
- Duration of operation
- Frequency of use

The last two items constitute the duty cycle.

DC voltages of 24, 32, 48, 120, and 240 are normally encountered in substation design. For the purpose of this course, a 120-volt battery with a nominal voltage per cell of 2 volts and 60 cells will be considered in the following discussion. A final voltage of 1.75 per cell or 105 volts for the battery will complete our model.

DC system loads consist of both continuous and intermittent loads. Continuous load typically involves the battery 3- to 8-hour ratings. It consists of indicating lights, relays, and any other equipment continually drawing current from the DC bus. Emergency lighting consisting of circuits energized during an AC outage plus certain communication circuits involving the 1- to 3-hour rating.

Intermittent or momentary load, constituting relay and breaker operation, involves the 1-minute battery rating. The duration of breaker operation may be only a few cycles, but the battery voltage drop will be essentially the same after 1 minute. A typical duty cycle will have the breakers tripping at the beginning of the cycle and closing at the end of the cycle. If two or more breakers are to operate simultaneously, the total current determines the 1-minute rating.

The sizing of DC cables and cabinets is done in the same way as for AC services. The only exception is that no demand factor should be applied to connected loads. Voltage drop should be held to within 3 percent. Special consideration of short-circuit capacity is not a factor in a DC auxiliary system.

Equipment

Lead batteries are rated in ampere-hour capacity at an 8-hour rate to 1.75 volts average at 25C. Consider the following example of a system with the following duty cycles,

- Ten 40-watt, 120-volt lamps - 3 hrs. 3.5 amperes
- Relays and panel indicating lamps - 8 hrs. 5.0 amperes
- Communications - 3 hrs. 5.0 amperes
- Three simultaneous Breaker Operations - 1 min. 100.0 amperes

From vendor data, a cell of seven plates will furnish approximately 200 amperes for 1 minute to 1.75 final volts. The ampere-hour capacity of the selected unit at the 8-, 5-, 3-, and 1-hour rates is about 145, 130, 115, and 80, respectively.

This example, duty cycle is only to serve as a numerical example of battery selection. For the 120-volt system, 60 of the lead calcium cells would be connected in series.

Satisfactory battery life and service are more dependent on the design and specification of the charging equipment than on any other external factor. The most costly and complicated charger is not necessarily the best selection. Shunt wound DC generators were used for years for charging batteries, but frequent adjustment was required and recharge capability was slow. For substation service, bridge rectifiers are used. Tube type is still in service, but new installations are being specified with solid-state devices. The ampere capacity of the charger can be determined using,

$$\mathbf{A = L + \frac{1.1 * C}{H}}$$

Where:
A = Charge capacity (amperes)
L = Continuous load (amperes)
C = Discharge (amperes hours)

H = Recharge time (hours)

Consider the following example of how to select a battery charger based on the data from the previous battery selection example.

DC Lights 3.5 Amperes	-	3 hrs.	10.5 AH
Communications 5.0 Amperes	-	3 hrs.	15.0 AH
Breaker operations 100.0 Amperes	-	l min.	1.7 AH
Panel load 5.0 Amperes	-	8 hrs.	40.0 AH
Total 67.2 AH			

$$A = 5 + \frac{1.1 \ast 67.2}{8}$$

A = 14.24

The next largest standard size charger should be selected. If the charger is to be operated at altitudes above 3,300 feet and above 40C ambient, check vendor data for correction factors. The example illustrated here is only to demonstrate a method for battery selection. Also consider substation expansion in initial battery/charger selection.

Single- and three-phase AC inputs at standard voltages are available. Chargers are commercially available with standard and optional devices to indicate status and to alarm unusual situations, mainly AC failure. Refer to vendor data to determine the required devices pertinent to the particular situation under consideration. If the selected charger uses a cord, cap, and receptacle for AC supply, specify a locking cap and receptacle.

Also determine if the battery charger is to function as a *battery eliminator*. This would allow the battery to be disconnected for short periods to allow maintenance on the battery without disrupting 120-volt DC service. Many of the newer electronic and microprocessor devices require a relatively stable DC supply, with a minimal AC compound associated with the DC supply. The battery while connected into the DC system provides this filter. If the battery is disconnected, the battery charger filtering may be inadequate to prevent damage to the relay DC input filters, causing the relays to be damaged. In such cases where the battery charger is to be used as a battery-eliminator type of charger, compare the AC ripple component specifications on the DC equipment inputs with the ratings for the battery charger.

The substation DC auxiliary system should be an ungrounded system with fuse or circuit breaker panels for DC service. The trend is to use circuit breaker panels. It is recommended that the positive and negative legs of the DC system be run in separate PVC conduits from the battery to the first fusible disconnect. This reduces the possibility of the positive and negative legs of the battery becoming shorted together with no means of clearing the short circuit. Also, the battery charger should be specified with a ground detection system so positive or negative grounds are detected.

Relay panels having solid-state equipment cannot sustain voltages higher than 140 volts DC without possible relay damage. When the battery is being recharged or equalized, the DC terminal voltage could be in excess of 140 volts. In this case install a 50/60 cell switch and do the recharging at the 50 cell position. Additionally, circuit breaker operation can cause transient voltage spikes that could possibly damage equipment connected to the DC bus. Install a surge rectifier across the battery to drain the surge energy to ground. These features are usually not available from battery charger manufacturers so it is recommended that they be installed in the battery room on a wall-mounted wood panel. Figure 3 illustrates a simplified diagram of a DC system with these features.

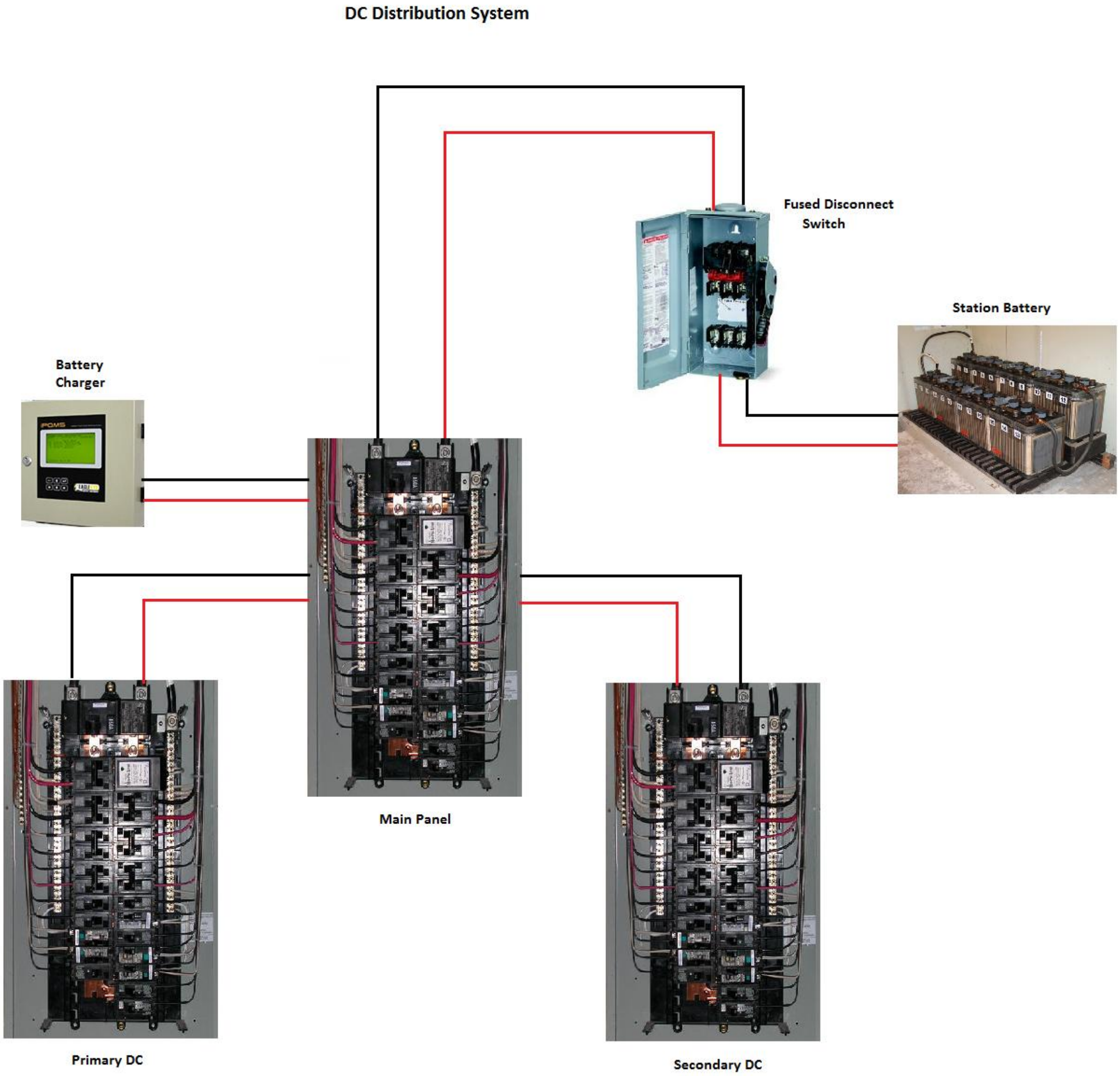


Figure 3

Many utilities will remove one or two cells from the battery bank to avoid the problem of overvoltage while the battery is being equalized. Complete an evaluation to guarantee the values of current, load, and power supply will stay in specified levels during the process.

Chapter 3
Substation Automation

Substation automation is the use of state-of-the-art computers, communications, and networking equipment to optimize substation operations and to facilitate remote monitoring and control of substations cost-effectively. Substation automation uses intelligent electronic devices in the substation to provide enhanced integrated and coordinated monitoring and control capabilities. Substation automation may include traditional SCADA equipment, but more often encompasses traditional SCADA functionality while providing extended monitoring and control capabilities through the use of non-traditional system elements.

In the traditional SCADA system, a host computer system (master station) located at the energy control center communicates with remote terminal units located in the substations. RTUs are traditionally "dumb" (non-intelligent) devices with very limited or no capability to perform local unsupervised control. Control decisions are processed in the master station and then carried out by the RTU through the use of discrete electromechanical control relays in the RTU. Analog telemetry information (watts, VARs, volts, amps, etc.) is generated by discrete transducers whose outputs are wired into the RTU. Device status (breaker position, load tap changer position, etc.) is monitored by the RTU through sensing of discrete contacts on these devices. Monitored data is multiplexed by the RTU and communicated back to the master station computer in the form of asynchronous serial data.

Substation automation systems do include many of the same basic elements as the legacy SCADA system but with significant enhancements. A central operations computer system generally provides the master station function. Legacy RTUs may be incorporated into the automation scheme, particularly in retrofit situations, but are generally replaced with intelligent programmable RTUs and other IEDs in an integrated LAN. Legacy transducers are replaced by IEDs that provide not only the traditional analog signals, but a number of additional data values that can be useful to operations, engineering, and management personnel. IEDs communicate with RTUs and local processors via a substation LAN with an open communications protocol, thereby eliminating discrete transducer analog signals. Programmable logic controllers (PLCs) may be included, discretely or integrated into the intelligent RTU, to provide closed loop control and control functions, thereby eliminating the need for many electromechanical relays and interlocks.

The integration of IEDs in the substation has been a major challenge for electric utilities and equipment suppliers. The primary obstacle has been the lack of standards for LAN communications protocols, with manufacturers opting for proprietary protocols that require costly interface modules for protocol conversion. Strides have been made in recent years to resolve the protocol standardization problems, and some de facto standards have emerged. The trend will continue toward more vendor-independent substation network environments as these standardization efforts move forward and as the level of standards support improves among IED manufacturers.

Open vs. Proprietary Systems

All exchange of data among networked computers and devices may be thought of as part of a network architecture, that is, a framework that provides the necessary physical and communications services to facilitate data exchange. Any number of internally consistent architectures can be chosen to permit the desired communications; however, many are proprietary. Proprietary networking solutions can prove to be highly effective and efficient from a functional standpoint, but they are not compatible with a multivendor environment that many end users now demand.

In a proprietary network, the network vendor is in control of what features are supported within the network. A vendor can decide not to support certain features, support them incompletely, or require the purchase of expensive upgrades to implement those functions. But proprietary networks do have the advantage that the user has access to a single point of contact and responsibility at the system vendor for all network functions, and these networks are generally guaranteed to "plug and play" without the user having to be concerned about architectures and protocols. A cautionary statement for proprietary systems is needed here. If or when the vendor or his product becomes obsolete, ensure someone will handle support services for this network. An escrow account for the source code of the system is a good starting point. This allows future modifications to the system without having to re-engineer the entire system.

In a network based on open products and standards, the user is no longer dependent on a single vendor to provide the functions and features needed or desired. The user also has the advantage of being able to solicit competitive prices among equipment vendors rather than being locked into one source of supply. But in an open environment, the user has to take responsibility for overall network functionality, and has to take care in the selection of protocols and equipment to ensure "plug-and-play" compatibility.

Two widely accepted open system architectures are the International Organization for Standardization (ISO) Open Systems Interconnection (OSI) 7-layer model, and the Transport Control Protocol/Internet Protocol (TCP/IP) model. TCP/IP was originally developed for the ARPAnet, now called the Internet, but has been widely used in local area networks. A more recent development is the Utility Communications Architecture (UCA), which is a family of OSI-compliant protocols developed by EPRI for use in electric utilities.

Substation Automation Architecture

The basic architecture of a utility automation system can be viewed as a multi-layered stack (Table 1).

Table 1
Substation Automation Architecture

Information Infrastructure Layer	**User Interface**	**Applications Layer**
	Applications	
	Data Repository	**Presentation Layer**
	Data Repository – Substation Host Processor Interface	**Transport Layer**
Data Acquisition and Control Layer	**Substation Host Processor**	
	Substation Host Processor - IED Interface	
	LAN	**Data Link Layer**
	IED's	
	Substation Field Equipment	**Data Link Layer / Physical Layer**

At the bottom of the stack are the electrical power substation field devices (transformers, breakers, switches, etc.). The top of the stack is the user interface where data and control prerogatives are presented to the end user, which in this case would be a human operator. The intermediate layers may be implemented with discrete elements or subsystems. In some cases, several levels may be combined into one, or even eliminated altogether.

The overall architecture can be viewed as two layers, each made up of several sublayers. The first or lowest layer, the *data acquisition and control layer*, is made up of substation-resident equipment. The second or highest layer, the utility enterprise, can be viewed as the *information infrastructure layer*. This course focuses on the substation-resident data acquisition and control layer.

Data Acquisition and Control Elements

Substation automation may take many different forms and levels of sophistication, depending on the philosophy of the implementing utility and the specific application. For instance, a single serial data interface between a SCADA RTU and an electronic recloser would be an example of a relatively simple and limited application. A fully automated substation with digital relays, electronic reclosers, and programmable logic controllers, all sharing a common network with a substation host processor and man–machine interface, would represent a relatively sophisticated application. Figure 4 shows the major data acquisition and control elements found in substation automation and their typical relationship to each other and to the corporate data infrastructure.

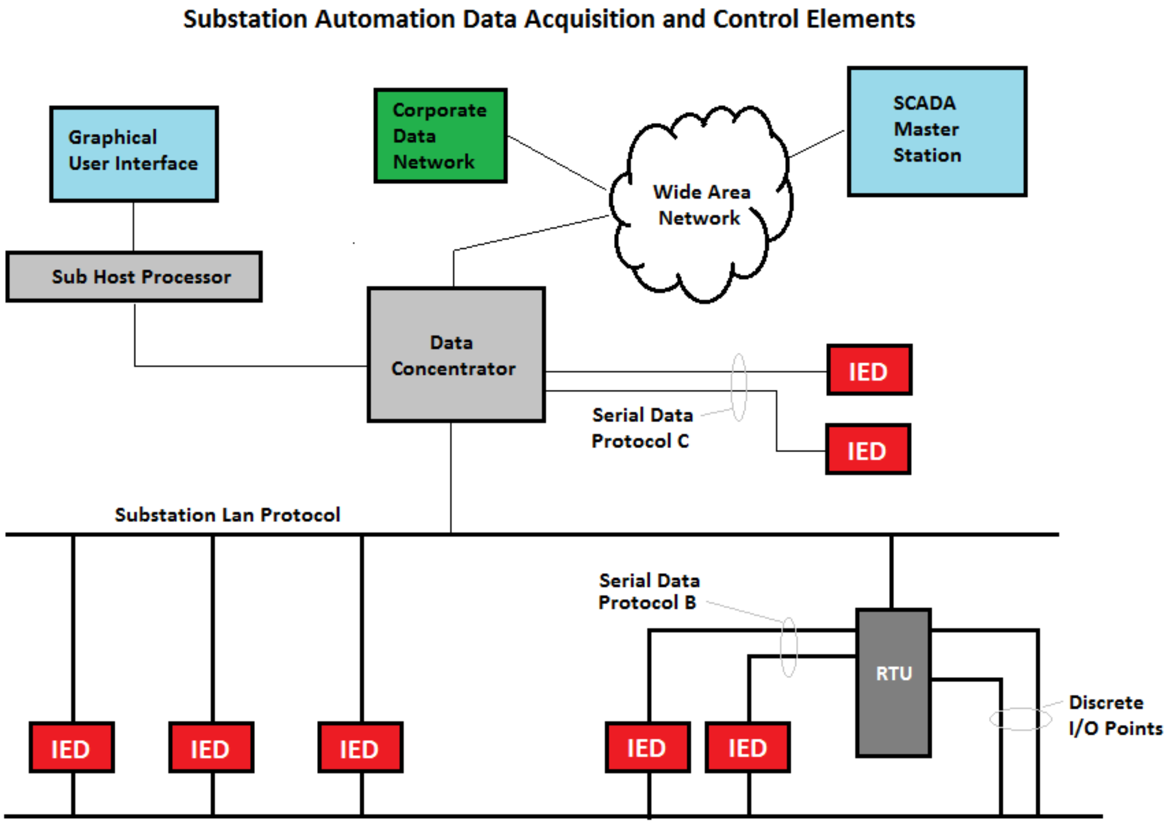


Figure 4

Regardless of the size and complexity of the network, the basic elements of substation automation are generally those described in the following subsections.

<u>Substation Host Processor</u>

The substation host processor serves the following functions in the substation automation system:

1. It provides local data storage for data acquired from the field devices.
2. It provides a local human–machine interface, allowing a human operator to locally access system data, view system status, and issue system control commands.

3. It can, if necessary, perform logical data processing and closed-loop control algorithms.
4. It serves as a gateway for communications between the substation and the control center (SCADA host).

The substation host processor may be a single computer, such as a PC, or multiple computers in a networked or distributed computing environment. The substation host processor should be based upon industry standards and have to have strong networking ability. A Windows-type graphical user interface should be provided.

For smaller substations, a single non-redundant processor should suffice. For larger and more critical substations, a dual-redundant processor with automatic failover is recommended. The level of redundancy called for will vary by application, depending on what functions the host processor is providing, the level of electromechanical backup employed, and the operational risks and implications related to an extended failure of the processor.

Intelligent Electronic Devices

Examples of IEDs are electronic multifunction meters, digital relays, programmable logic controllers (PLCs), digital fault recorders, sequence of events recorders, voltage regulators, capacitor bank controllers, and electronic reclosers. Intelligent SCADA RTUs and PLCs can also be considered IEDs but are typically categorized separately.

Many IEDs perform two functions within the substation. First, the IED provides its primary design function such as relaying, capacitor control, or voltage regulation. But by virtue of the fact that many of these IEDs have built-in instrument transformers, or are otherwise connected to the potential transformer (PT) and/or current transformers (CT) circuits of the substation, the IEDs also calculate and provide a large amount of power system data.

Data available from IEDs includes but is not necessarily limited to the following information:

1. Power flows (kilowatts, kilovars, power factor, phase angle, kilowatt-hours, kilovar-hours)
2. Other electrical data values (amperes, volts, symmetrical components)
3. Fault current (per phase, ground, waveform capture)
4. Relaying targets
5. Sequence of events
6. Oscilliography

Data is retrieved from the IED by the substation host processor and/or a local RTU digitally via a serial data port or other network interface. This eliminates the need for discrete analog tranducers, accomplishing a significant reduction in space and wiring, which can also lead to cost reductions, particularly on new (as opposed to retrofitted) substations.

A single IED can often deliver hundreds of data values even though the utility user is only interested in a small subset of the total data set. The ability to filter the data reported by the IED has been limited as a result of both hardware and protocol-related issues. The goal is to provide the capability to filter or "mask" certain data registers at the IED level, as opposed to making this function protocol or host-dependent.

IEDs should be individually addressable, preventing the need for a dedicated communications channel for each IED. IEDs should support open protocols such as,

- DNP 3.0,
- ModBus,
- ASCII,
- UCA 2.0,
- IEC 870-5-101 or 103, or
- TCP/IP.

An important design consideration in development of IED interfaces is the data acquisition method. For example, the IEDs may be polled by the host device for changes (report by exception), or the IEDs may be sequentially scanned (full data dump). In the more common instance of a full scan, it is important to quantify any limitations on the maximum allowable latency of the data (the time required for changes to appear in the host processor or data repository). These issues may play a role in the selection of IEDs and/or the communication protocol and method.

Programmable Logic Controllers

PLCs may be considered IEDs, but are often considered as a separate class of device. Most IEDs are designed to provide a primary function, such as reclosing, voltage regulation, relaying, or revenue metering, while also offering ancillary system data that has some additional benefit to the utility. PLCs, on the other hand, are more generic and can perform a wide variety of automation functions on a user-programmable basis.

PLCs have traditionally been used in industrial applications such as assembly line automation. PLCs have also been widely used in power generating station distributed control systems, but have only recently been applied in electric utility substations. One of the reasons for the lack of penetration by PLCs into the substation data acquisition and control industry was that PLCs have only recently begun to be manufactured to rigorous substation environmental and electrical standards, such as ANSI Std. C37.90a surge withstand capability. Another recent development is that, with the advent of faster microprocessors, PLCs can now perform sophisticated control procedures fast enough to meet the requirements of substation protective relaying.

PLCs are now finding applications in substations that were traditionally the realm of legacy SCADA RTUs. PLCs can provide the same monitoring and supervisory control functions as an RTU. But PLCs offer the advantages of lower costs than RTUs in some configurations, and ladder logic programmability not available in the legacy RTUs. In an attempt to combat the influx of PLC products into their traditional markets, RTU manufacturers have begun to offer lower cost RTUs with intelligent programmable features. The increased intelligence and programmability of the RTU compared with the PLC’s same features should make the defining border between the two obsolete.

In addition to providing traditional SCADA functions, PLCs are being used by utilities for a wide variety of automation functions:

- Reclosing
- Auto-sectionalizing
- Power line carrier automatic check-back schemes
- Transformer LTC control
- Capacitor controller
- Local HMI for alarm annunciator, metering indication, data logging, and events recording
- Breaker control, especially for more complex operations such as tie breakers
- Breaker tripping for more complex schemes requiring a significant number of inputs

The programmability of PLCs lends to the development of schemes that were previously considered very difficult to actuate. If the input can be obtained, the ladder logic to make decisions regarding the input can be written to produce an output. Future additions to the substation may also be made simpler since the substation wiring is made easier and logic may be readily changed with the use of PLCs.

Some utilities, because of the complexity of their control schemes, have used PLCs as a control device between relays and breakers to provide tripping and closing of the breakers. While this is not generally recommended, the use of PLCs minimizes installation time because of reduced wiring and control checkout since the logic for any scheme may be entered into the ladder logic.

Data Concentrator

Data concentrators are often the sole communications integration point within the substation. The data concentration function is primarily the integration of multiple incompatible IED protocols for presentation to an external host under a single unified protocol.

The role of the data concentrator is changing with the advent of UCA. UCA will allow for direct communications to all IEDs, regardless of whether the communication is internal or external to the substation. But data concentrators may still be desirable for bandwidth efficiency in low-bandwidth wide area telecommunications links.

Substation Local Area Network

The substation LAN provides a means of physical data transfer between intelligent devices in the substation. There are two main distinctions between various LAN types: access method and physical media. The access method, physical media, and transmission rate of the network in megabits per second (Mbps) will also dictate the maximum distance between communicating devices (nodes).

The *physical media* used in LANs include coaxial cable, UTP (unshielded twisted-pair) copper, and optical fiber. Optical fiber, because of its immunity to electrical effects, has distinct advantages in an electrical substation environment. Coaxial cables and UTP can experience loss or corruption of data messages as a result of electrical transients. Even though protocols at various layers can mitigate some of these adverse effects, it is recommended that fiber-optic media be used to connect all IEDs engaged in protection functions.

The *access method* can take various forms. The most common methods are *carrier sense multiple access with collision detection* (CSMA/CD), token ring, and token bus, and the Fiber Distributed Data Interface (FDDI), although a number of vendor-proprietary schemes are also in use. In selecting an access method, the designer has to consider the expected loading of the network, whether or not a deterministic access method (see below) is required, desired data rate, and the physical distances between nodes or communicating devices. Networks that use CSMA/CD are generally referred to as Ethernet networks, although this is not always true.

Ethernet is actually a proprietary access method developed by Digital Equipment Corporation, but was the basis for the IEEE 802.3 networking standards. CSMA/CD is a broadcast access method where multiple devices contend for access to the same communications medium in a bus architecture. It is a nondeterministic method, meaning that the amount of time required for a message to be sent and received cannot be accurately determined, and is best applied in lightly loaded networks. Its non-deterministic behavior is a disadvantage for time-critical automation tasks like closed-loop control. CSMA/CD is supported under UCA 2.0.

Token ring (IEEE Std. 802.5) is the most commonly used token passing access method. Unlike CSMA/CD, this method is deterministic because token passing among communicating devices is used to govern access to the communications medium. Token ring is supported under UCA 2.0. Token bus (IEEE Std. 802.4) is a bus access method like CSMA/CD, but uses a token passing arrangement for deterministic medium access. *Token bus*, like token ring, is supported under UCA 2.0, but is less commonly used than token ring or CSMA/CD.

The *Fiber Distributed Data Interface* (FDDI) is described in ANSI Std. X3T12 and is supported within UCA. The physical medium used is optical fiber, as opposed to coaxial cable UTP. Dual 100 Mbps fiber rings are included, allowing for rerouting of data around a fiber fault. FDDI is primarily used as a backbone network to connect multiple lower speed LANs in a large building or campus environment, so would be less commonly used in a substation environment. Also, with the advent of 100 Mbps CSMA/CD, asynchronous transfer mode switching and synchronous optical network technology, FDDI usage should wane in the coming years.

ATM is dedicated-connection switching technology that organizes digital data into packets and transmits them using digital signal technology. Due to ATM's ease in implementation by hardware, faster processing speeds are possible. ATM runs on a layer on top of SONET. SONET is the U.S. (ANSI) standard for synchronous data transmission on optical media. This standard ensures the interconnection between networks and that existing conventional transmission systems can take advantage of optical media through tributary connections.

Utilizing this technology can bring data speeds of 155.520 Mbps or 622.080 Mbps or faster. These two technologies are a major component of broadband ISDN (BISDN). FDDI usage should wane in the coming years because of this technology.

Communications between intelligent devices in the substation may take the form of synchronous or asynchronous serial connections rather than a LAN connection. Most RTU vendors, for instance, offer serial ports on their RTUs for interfacing to IEDs with standard protocols. The most common standard serial interfaces are RS-232, RS-422/423, and RS-485. Like LANs, these standards define a physical and electrical interface and do not imply a particular protocol. The industry's most common serial interface standard, RS-232 is defined by ANSI/TIA/EIA Std. 232-E. It defines the interface between data communications equipment (DCE) and data terminating equipment (DTE) employing serial binary data exchange. RS-232 signals are generally limited to 50 feet or less without the use of special low-capacitance conductors.

The RS-422/423 standard serial interface is defined by ANSI/TIA/EIA Std. 422 that extends the transmission speeds and distances beyond RS-232. It provides for a balanced voltage interface with a high noise immunity. RS-423 is the unbalanced version.

The RS-485 standard serial interface is defined by ANSI/TIA/EIA Std. 485. It provides for a balanced voltage interface similar to RS-422, but uses tri-state drivers for multidrop or "daisy-chained" applications. Because of its multidrop capability, this is the most common serial interface in substation data communications.

Communication Protocols

For two devices to communicate successfully, not only they have to share a common physical interface and access method, but they have to also share a common protocol. A protocol is a formal set of conventions governing the formatting and relative timing of message exchange between communicating systems. The careful selection of communication protocols is essential for the successful deployment of substation automation systems. The prevalent approach among equipment manufacturers is to support several standard protocols. One RTU vendor, for example, offers the end user a menu of 34 different protocols for the RTU-to-IED interface port, and a single RTU can support up to four of these protocols simultaneously.

The ISO-OSI 7- layer model is not described in detail in this course due to the complexity of the subject. The reader is only exposed to the application layer.

Protocol Descriptions:

- IEC 870-5, developed by IEC Technical Committee 57 Working Group 3, answered the need for a protocol standard for telecontrol, teleprotection, and associated telecommunications for electric utility systems.
- DNP 3.0, developed by GE Harris Canada, was established to minimize the creation of new protocols used to communicate between SCADA devices. The protocol is designed for data acquisition and application control in the electric utility field. This protocol is maintained by the DNP Users Group.
- ModBus (ASCII and RTU) were developed by Modicon. These protocols define a message structure that controllers are able to recognize and use; the protocol forms a common format for the layout and contents of data messaging.
- Manufacturing Message Specification (MMS) is an internationally standardized messaging system for exchanging real-time data and supervisory control information between networked devices and/or computer applications in a manner that is independent of the application function being performed or the developer of the device or application. MMS is an international standard (ISO 9506) that is developed and maintained by Technical Committee Number 184 (TC 184), Industrial Automation, of the International Organization for Standardization (ISO).
- Landis & Gyr 8979 is another standard byte-oriented protocol commonly used in the utility marketplace.

While there are “standard” protocols available, many of these are dynamic in that continuing development and enhancements are taking place. Several versions of a particular protocol may exist in the marketplace. Two devices that claim support of the same protocol may indeed support different versions or revisions of the protocol, resulting in some lack of interoperability.

To avoid such problems, it is incumbent on the design engineer to research and understand the history of the selected protocol, whether multiple versions exist, and what continuing development, if any, is taking place. The designer should also be informed as to any proprietary modifications to the standard protocol that may have been incorporated by potential equipment suppliers as a means of optimizing its implementation with their devices.

The best way to avoid unforeseen protocol interoperability problems is to implement pre-engineered "plug and-play" interfaces. Equipment manufacturers should be required to demonstrate plug-and-play interoperability between the specific devices in question, not just general compliance with a protocol, either through factory testing or in actual field installations. If a new and untried interface is undertaken, the utility should place the burden for protocol emulation and development on a single entity. This will typically be the RTU manufacturer (in the case of RTU-to-IED interfaces) or the data concentrator manufacturer (in the case of multiple protocol integration).

Utility Communications Architecture was developed by EPRI based on the ISO/OSI standards for data communications. The overall goal of UCA is to provide interconnectivity and interoperability between utility data communication systems for real-time information exchange. UCA employs the Manufacturing Messaging Specification (MMS) to define the language, semantics, and services for real-time data acquisition and control throughout general utility operations. Both the ISO/OSI and the TCP/IP networking models are currently supported under UCA. UCA Version 1.0 was adopted in 1991, providing a suite of selected protocols, with MMS as the recommended protocol for real-time data acquisition and control applications. But UCA 1.0 lacked detailed specifications of how the protocols would actually be used in field devices. UCA Version 2.0 addresses this problem.

Automation Acronyms

See Table 2 for a list of commonly used communications acronyms used in substation automation.

Table 2
Common Telecommunications Acronyms

Acronym	Description
Asynchronous Transfer Mode (ATM)	A communications transmission and switching standard for carrying broadband signals at speeds up to 2.2 gigabits per second. Combines techniques of time division multiplexing and packet switching.

Carrier Sense Multiple Access with Collision Detection (CSMA/CD)	A LAN contention-based access-control protocol technique (Ethernet); defined in IEEE Std. 802.3.
Data Circuit-Terminating Equipment (DCE)	Formerly known as data communications equipment; network-embedded devices that provide an attachment point for user devices.
Data Terminal Equipment (DTE)	The computing instrument, apart from any device used to perform the analog transmission and reception of data; examples are computers, RTUs, and PLCs.
Fiber Distributed Data Interface (FDDI)	Shared-medium, ring topology LAN that operates at 100 Mbps. It is ANSI Std. X3T9.5, using fiber-optic cable as the medium.
HMI	Human–machine interface.
Intelligent Electronic Device (IED)	Electronic equipment that provides monitoring and controlling capabilities.
Ladder Logic	Industry-standard symbology used to document relay logic control systems. Logic lines are drawn horizontally, similar to the rungs of a ladder.
Legacy	Existing implementation of an application or project; it does not refer to trials.
Local Area Network (LAN)	A group of computers connected over a common medium within a building.
Master Station	The “central host” computer in a SCADA system.
Open Systems Interconnection (OSI)	An international standard describing seven layers of communication protocols (physical, data link, network, transport, session, presentation, and application) that allow many dissimilar information systems including computers, workstations, PBXs, etc. to be interconnected.
Programmable Logic Controller (PLC)	Electronic device that can be programmed using a specific language via a computer.

Remote Terminal Unit (RTU)	An electronic device used to control and monitor Input/Output points within an overall system and to communicate the derived data to a master station or other "host" unit.
SCADA Supervisory Control and Data Acquisition;	Used by utilities and other process-oriented operations to collect data from machinery that may be located over a widespread area. A basic SCADA system consists of two types of devices "master" and "remote." The master resides at a centrally manned location while the remotes are generally placed at unmanned locations. Communication between master and a number of remotes can be via telephone-like circuits, radio channels, or fiber-optic communications media.
SONET	Synchronous Optical Network; standard for optical transport formulated by the Exchange Carrier Standards Association (ESCA) for ANSI; essentially a standard for Broadband Integrated Services Digital Network transmission facilities.
Token Bus	A networking standard that uses a bus configuration and a broadcast messaging system. Token bus networks use a token-passing scheme to determine which node has the network access.
Token Ring	A LAN that uses the token-passing access method and that supports 4 Mbps or 16 Mbps baseband communications in a physical star and logical ring arrangement.
Transport Control Protocol/Internet Protocol (TCP/IP)	The main transport protocol used on the Internet for connectivity and transmission of data across heterogeneous systems. It is an open standard that is available on most UNIX systems, VMS and other minicomputer systems, many mainframe and supercomputing systems, and some microcomputer and PC systems.
Utility Communications Architecture (UCA)	Developed by EPRI based on the ISO/OSI Standards for data communications.
UTP	Unshielded Twisted Pair.

Wide Area Network (WAN)	A computer network interconnected over distances beyond a city or metropolitan area.

Chapter 4
Communications

Since substations are part of large interconnected power systems, methods of voice and data transmission among the various system parts are necessary to maintain satisfactory operation and control. Communication systems are used in protective relaying schemes to initiate tripping control schemes of power circuit breakers; in supervisory control systems to operate remote equipment, for transmission of data indicating equipment status and system conditions, and for voice communications for system operation and maintenance.

Table 3 matches the various substation communication applications with the most appropriate communication method.

Table 3
Substation Communications Methods vs. Applications

Applications	**Methods**					
	Power Line Carrier	**Audio Tone**	**Microwave**	**Fiber Optics**	**Wire Line**	**Satellite (VSAT)**
Relaying	✓	✓	✓	✓	✓	
SCADA	✓		✓	✓	✓	✓
Voice	✓		✓	✓	✓	
Telemetering	✓	✓	✓	✓	✓	

Communications Applications

Applications for communications mediums include relaying, SCADA, telemetry, and voice.

Relaying

Many relay schemes now in use require information to be exchanged among all the terminals on a transmission line to effect high-speed tripping over 100 percent of the line. Since these terminals are often many miles apart, some form of two-way communication channel has to be established between them. The information to be transferred is relatively simple two-state data in most cases and can utilize the more basic forms of modulation.

SCADA

Most utilities have a centralized energy control center from which the electric power system is remotely operated. It is usually expected that circuit breakers and tap changers will be monitored and controlled, generation monitored and controlled, capacitor banks may be monitored and controlled, alarms reset, and miscellaneous other on/off-type functions effected over distances ranging from a mile or less to hundreds of miles.

The energy control center receives various types of data from the power system. This data includes breaker status, tap changer position, amps, volts, watts, VARs, and other quantities, both digital and analog. Again, the data travels over distances ranging from a few miles to several hundred.

In most modern energy control centers, the remote data monitoring and system control functions for substation applications are performed by a SCADA system. These systems consist of a central host computer system at the energy control center, referred to as a master station, and RTUs located in the substations. There is a trend toward increasing intelligence at the substation level where the traditional RTU is being replaced with IEDs in a LAN arrangement. Regardless of the level of intelligence resident at the substation level, some form of real-time communication is required between the master station and the RTU or remote electronics.

Telemetering

In some instances where a computer-based SCADA system is not available or justified, it is desirable to transmit discrete power system data from the substation to the energy control system in an analog format. For example, analog quantities such as amps, volts, watts, or VARs may be required to drive a remote readout or chart recorder. Likewise, discrete system status values such as breaker position may be required to drive a remote annunciator. In these cases a communication method is required that can directly accommodate analog signals that may include scaled milliampere or voltage, or frequency-shift audio.

Voice

Power system operation and maintenance require the use of voice communication for daily operation and functioning of the power network. Voice communications are required between fixed points of operation and for mobile maintenance crews. The transmission of voice signals may take place via cable, radio, or the power system itself. The transmission facilities may make use of either leased systems or utility-owned facilities.

Communications Methods

Communications methods include,

- PLC
- Audio Tone
- Carrier
- Microwave
- Fiber
- Wire
- Satellite

Each of these is discussed in the following paragraphs.

Power Line Carrier

Power line carrier, one of the more common communication means found in power systems in the past, is now being displaced in many applications with fiber optics. But power line carrier may still be used for relaying and voice applications, and lower speed data.

Carrier signal frequencies range from 30 kHz to 500 kHz and are coupled directly to the power line through a coupling capacitor, a device that frequently doubles as a relaying and/or metering potential source. The signals are transmitted at a relatively low power level, 100 watts or less, typically 10 watts, and hence do not radiate appreciably from the power line. They have to be received in a similar way through a coupling capacitor connected to a carrier receiver at the other end of the line. See Figure 5.

To confine the carrier signal as nearly as possible to one line section and to keep the signal from being effectively shorted through the high capacitance of the station bus and connected transformers, *line traps* are installed on the station side of the coupling capacitor to block the carrier signal.

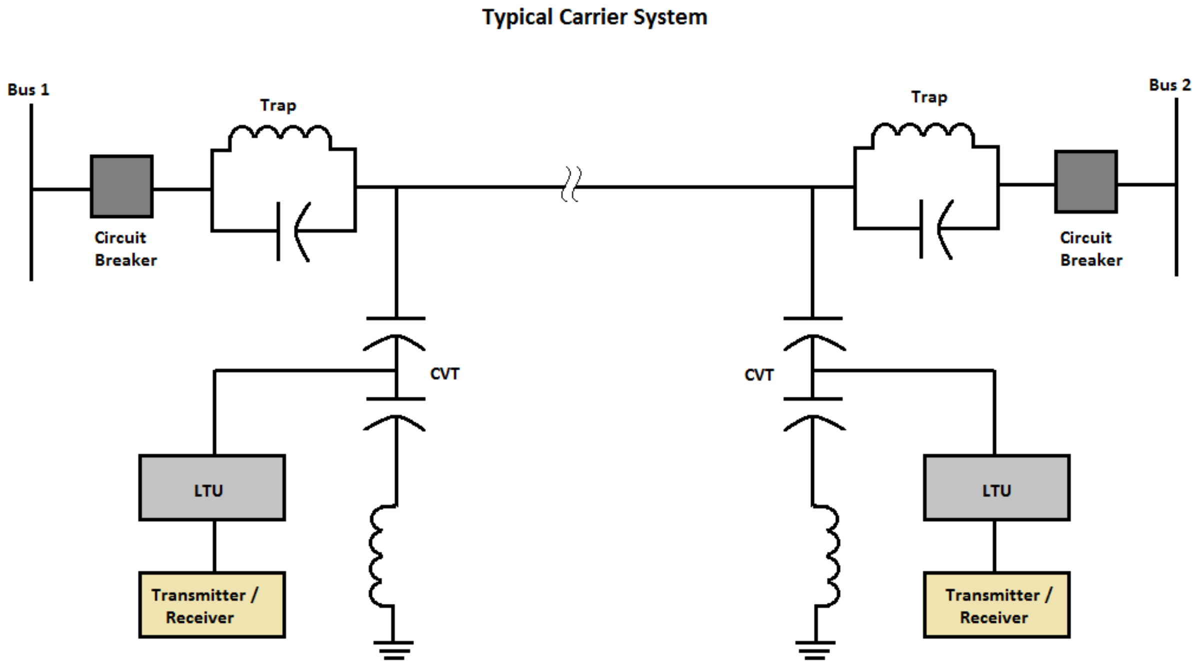


Figure 5

Line traps are generally simple parallel L-C resonant circuits with the inductance in series with the coupled phase of the line. This inductance is rated to match the BIL, through current capability and short-circuit withstand capability of any other major equipment on the line, and so is physically large.

Besides the line trap and coupling capacitor, there are several other components involved in tuning and matching the transmitter output to the power system.

A *Line Tuner Unit (LTU)* is a coupling capacitor that provides the path for the carrier signal to reach the power line itself. Since there are capacitive and inductive elements in the coupling capacitor and in the power system, a tuning network has to be provided to match the transmitter output impedance to the impedance seen at the coupling capacitor input. This device, the line tuner, comes in several different configurations, depending on the tuning method selected. In addition, the line tuner assembly contains protective elements such as a gap with capacitor and a grounding switch. The assembly may be mounted in the coupling capacitor base or in a separate weatherproof cabinet.

A *Hybrid Tuner* is a special transformer used to combine carrier transmitter and receiver inputs and outputs in such a way that transmitters and receivers may be connected to the same line tuner without mutual interference. A hybrid has one output and two inputs and is bi-directional so that the output may be connected to the line tuner and the inputs to a combination of transmitters and receivers without the receiver input being overloaded when the transmitter operates. Hybrids may be stacked; that is, one of the two inputs may be connected to another hybrid output resulting in three isolated inputs to the same line tuner. A limitation to this connection is that each hybrid reduces the power level by 3dB. Thus, two stacked hybrids result in only one quarter of the transmitter power reaching the line tuner from each hybrid terminal.

Various combinations of series and parallel connected capacitors and inductors are available for use with special tuning schemes or as additional tuning elements in the line tuner package and are known as *L/C Units*. In general, the manufacturer's recommendations should be followed in applying these units.

There are three basic methods of tuning carrier transmitters and receivers to the power line,

- Single-frequency resonant tuning,
- Double-frequency resonant tuning, and
- Wideband tuning.

A *single-frequency resonant-tuned* installation utilizes a combination of inductances and capacitances in the line trap and line tuner resulting in a combination frequency response that exhibits a single sharp peak centered about the selected frequency. Adjustment is available in both the trap and tuner, but both have to be ordered by specifying a range of frequencies according to the manufacturer's catalog data. Single-frequency resonant tuning is used less frequently as the available carrier spectrum becomes more crowded and it becomes more common to have several frequencies for multiple uses on a single line. Single-frequency tuning results in the lowest transmission losses, but is least flexible from the standpoint of subsequent additional carrier frequencies for control, telemetering, and relaying.

Figure 6 shows a typical graph of the frequency response for a Single-Frequency Resonant Tuning frequency resonant tuned installation.

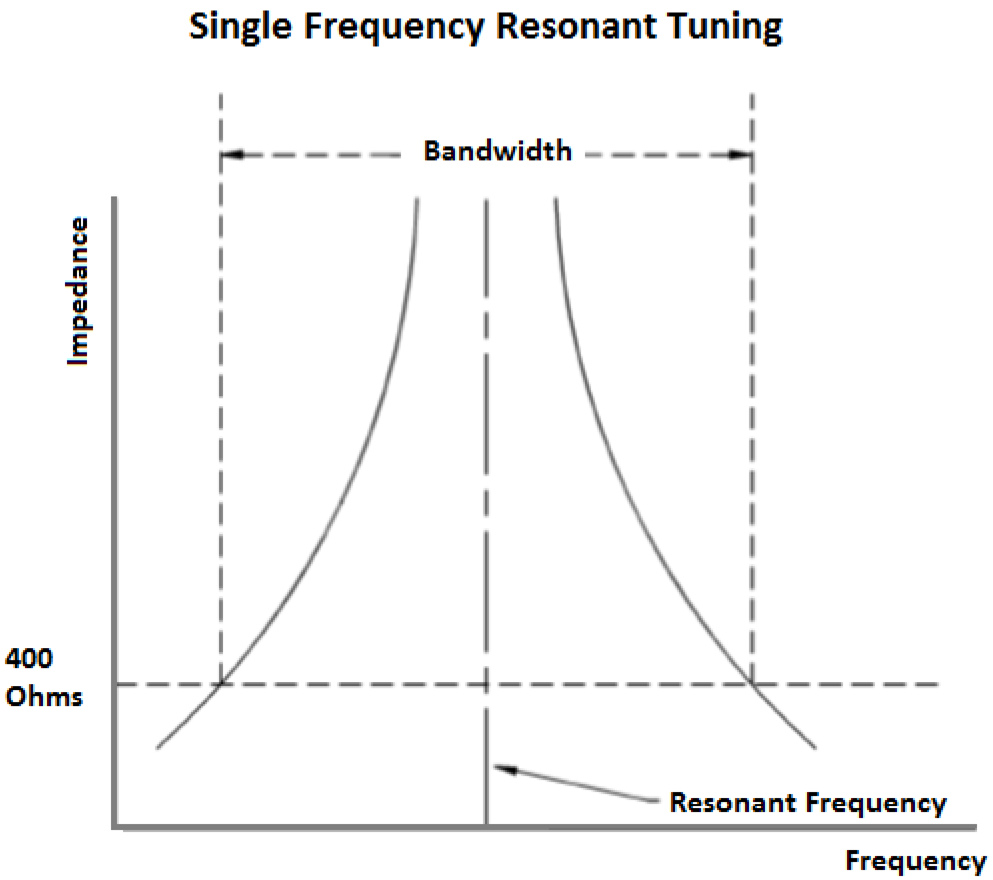


Figure 6

A *Double-Frequency Resonant Tuning* is a coupling method is identical to single-frequency tuning except that there are two closely spaced sharp peaks in the frequency response. The losses are somewhat greater, but the availability of two frequencies can compensate for this small disadvantage. In addition, it is possible to use as many as four frequencies if they are selected so that none is more than the manufacturer's tolerance away from a peak. This is done by using hybrids on each of the two frequencies. Figure 7 shows a graph of a typical double-frequency resonant-tuned system.

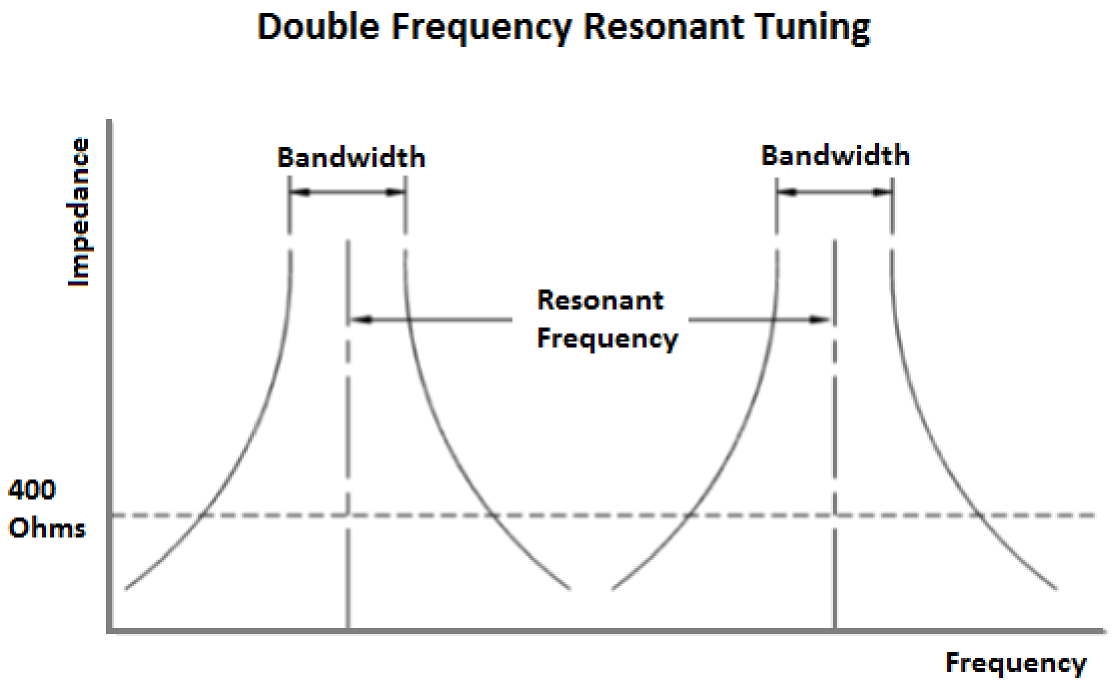


Figure 7

The frequency response of a *wideband tuning* package is a relatively low peak spanning a wide range of frequencies. The obvious advantage is that a number of frequencies may be fed through the same line tuner.

A disadvantage is greater attenuation in the tuning package through more leakage to the bus side and higher impedance in the tuning package. The wideband line tuner is a simple high-pass filter, and series L/C units are frequently used to separate the various transmitter–receiver combinations. Hybrids should still be used to separate transmitters and receivers. Wideband tuning is becoming more popular in spite of the increased losses because of the need to put more functions on a line as relaying schemes become more elaborate and remote control and data functions are added. Figure 8 shows a graph of a typical wideband-tuned system.

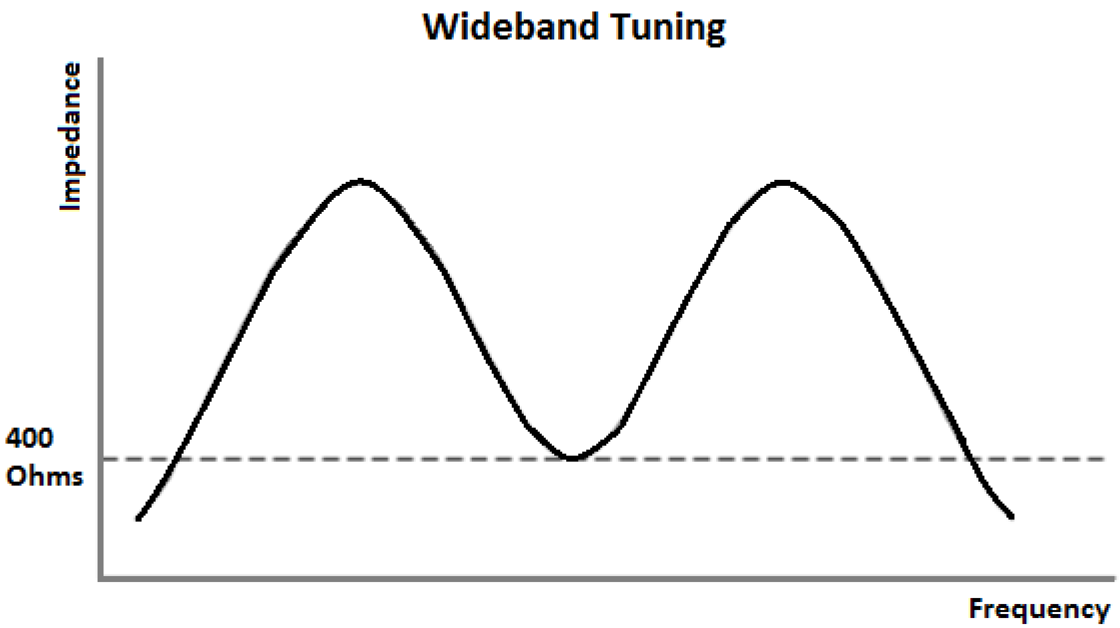


Figure 8

Modulation Types

On/Off modulation is the simplest form of putting information on the carrier wave is only used with directional comparison or phase comparison blocking relaying. As its name implies, the carrier transmitter is normally de-energized. When it is keyed, it simply sends an un-modulated carrier that the receiver interprets as a blocking signal. Voice modulators are usually added so that the transmitter carrier can be modulated and thus provide an extra emergency or voice communication channel. Since a received signal in such a relay scheme does not result in a trip or attempted trip, it is perfectly safe to voice modulate the carrier.

The chief disadvantage of on/off carrier is its quiescent nature. The carrier is off most of the time and, if a component fails during this period, there will be no indication of the failure until the scheme is called on to operate. If it has to block for an external fault at that time, a false trip can occur. Many utilities avoid this situation by applying a carrier checkback scheme. This scheme periodically initiates a characteristic series of carrier bursts from one end of the line. The other end recognizes the test transmission pattern and responds similarly. Receipt of this response at the initiating end verifies the system can transmit and receive data.

Frequency Shift Keying (FSK) is a modulation method that finds widespread use in most relaying, control and data transmission schemes. An un-modulated carrier is sent continuously and is termed the “guard” or “space” signal. When a trip or data signal is desired, the guard or space signal is shifted up or down by a small percentage and the shifted signal is termed the "trip" or "mark" signal. In general, relaying literature uses the trip and guard nomenclature, while mark and space will be found in most data and control literature. Trip and guard signals are separated by very accurate filters on the inputs of the receiver. The advantage of this scheme, particularly for relaying, is the channel monitor capability provided by the continuous transmission. If, at any time, the guard signal disappears without an immediate trip signal, the channel is presumed to have failed and an alarm can be energized. Additional channel security can be obtained by biasing the receiver discriminator to the guard side. A white noise burst, therefore, will produce a small net guard output that can be overcome by a transmitted trip signal even during the burst. This feature makes it possible to drive an FSK carrier signal through an arcing fault on the protected section.

Single Sideband (SSB) is a modulation type that is used extensively in other countries where its multi-channel capability is important because of the lack of a reliable and extensive telephone network such as exists in this country. In those areas, power systems have to provide their own basic voice communications, and the power system itself is an excellent medium. Here, however, SSB carrier has found little use primarily because of its high cost.

Basically, the carrier signal is modulated with voice or data signals, resulting in the transmission of the carrier plus two sidebands containing the carrier plus the modulation frequency and the carrier minus the modulation frequency, which is conventional. Since all the desired information is in each sideband, the carrier and either sideband can be eliminated resulting in a suppressed carrier, single-sideband signal having one-half the bandwidth of a transmission. It is then possible to transmit two voice channels in the bandwidth formerly occupied by one voice channel. Sophisticated equipment is available whereby, with a system of subcarrier frequencies, many channels in multiples of two can be transmitted.

Audio Tone

Audio tone equipment operates in the frequency range from 1000 Hz to about 3000 Hz. Frequency shift keying is the only modulation type available; voice modulation cannot be used. Audio tone is used primarily as a short-distance medium over wire lines. FSK modulation provides ample security, and, in most cases for most telephone applications, reliability is also high. Additional security is available in the form of broadband noise detection and frequency translation detection.

Broadband noise detection is simply a wideband receiver with no corresponding transmitter. If this receiver output exceeds a certain level, a noise alarm is actuated and all channels squelched off. Frequency translation detection utilizes a single unmodulated channel. If the output from this receiver drops, the translation alarm is actuated. This feature is most commonly used with microwave or other multi-channel configurations where a problem in the multiplex equipment can cause frequency shifts.

Audio tone always requires another communication transmission medium to carry the audio (wire line, microwave, optical fiber, power line carrier, or shield wire).

Carrier or Audio Tone on Shield Wire

The chief distinction of this method is the medium rather than the equipment. Transmitters and receivers are the same as those employed in other carrier and audio tone systems. However, in this scheme they are coupled to insulated transmission line shield wires. EHV shield wires are sometimes insulated to reduce losses from induced circulating currents. The usual insulation level is 15 kV, with gaps on the insulators to conduct lightning strokes to ground.

The coupling is usually between two such insulated shield wires through a special coupler containing matching networks, capacitors, protective gaps, and an insulating transformer. This equipment is required to protect the communications equipment from the high energy levels present on such shield wires during lightning strokes.

In general, this method is not used for protective relaying because of the uncertainty of successful communication during lightning strikes. It has found more application for data and voice communications as a low-cost alternative in those cases where the decision to insulate the shield wires had already been made on the basis of inductive loss prevention.

Microwave

Microwave systems have been used extensively on power systems in the past few decades as the requirements for dedicated voice and data communications increase. Because of the high cost of the RF equipment and antenna towers, microwave is generally used where there is a requirement for a large number of channels between two points. Transmission is line of sight only, necessitating intermediate repeater stations for long paths. The cost per channel is relatively low as long as most of the available channels are used and the path length is not excessive.

Microwave systems presently employed use transmission frequencies of 960 MHz and higher, which accounts for the high channel capacity and line-of-sight transmission. There is relative freedom from many forms of interference, but path fading and other forms of distortion can be problems. Most microwave systems require a license from the Federal Communications Commission (FCC) to operate.

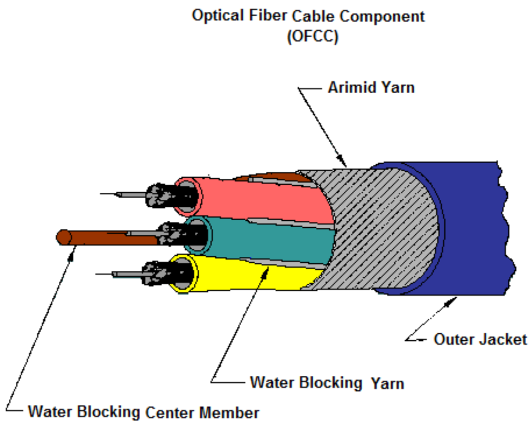
Both analog and digital microwave systems are in use today. Analog microwave systems accept audio input signals that are frequency multiplexed together to form an analog baseband signal that is then used to frequency modulate the higher frequency microwave carrier. Digital signals have to be converted to analog through the use of modems before they can be transmitted on an analog microwave system, which results in an inefficient use of the bandwidth. Analog microwave systems are available in capacities from as few as one to as many as 600 channels. The increasing emphasis on data transmission is driving users toward increasing utilization of digital microwave. The majority of new microwave systems installed today are digital. Unlike analog microwave, digital microwave employs a *digital time-division-multiplexed* (TDM) baseband that is used to digitally modulate the microwave carrier. Analog (voice or audio) information is converted to a data stream using *pulse-code modulation* (PCM) and then fed into the microwave TDM baseband. Data signals ranging from low-speed asynchronous (1200 bits per second) to high-speed synchronous (56 kilobits/second, 1.5 megabits/second, and higher) can be inserted directly onto the TDM baseband without any intermediate modulation as would be required in an analog system. In this way, data is handled much more efficiently than in the analog scheme, and voice is handled equally well. This results in digital microwave systems having a lower per channel cost than analog. Digital microwave systems are available in capacities from as few as one to as many as 2016 channels.

Power utilities typically purchase microwave radios in a monitored *hot-standby* configuration for added reliability. Hot-standby means that each radio contains two transmitters and two receivers, one set for primary and one set for backup, with monitoring and switching circuitry that automatically switches to the backup unit in the event the primary unit fails. For protective relaying on high-voltage transmission lines, it is common to use a microwave system in parallel with power line carrier for maximum security.

MAS are specialized microwave radio systems that are designed specifically for SCADA systems. MAS operate in the 900 to 960 MHz band and can employ analog or digital modulation technology. Each MAS provides a single channel of communications that is shared among four or more remote sites. The radio channel essentially behaves like a party line, so only one site can access the channel at any given time. Therefore, MAS is best suited to SCADA communications where a host computer sequentially polls remote terminal units using a master–slave protocol. This technology is widely used by electric utilities for substation SCADA communications in cases where other non-SCADA voice, data, and relaying applications are not needed. MAS is not suitable for telephone or protective relaying applications.

Optical Fiber

Optical fiber has become the communications technology of choice for most electric utility substation communications. Optical fiber offers the advantages of immunity to electrical sources of interference and noise, and extremely large information-carrying capacity.



Fiber-optic cables are available in a variety of configurations including aerial and underground cables. Two of the most popular types of cable used by electric utilities are optical ground wire (OPGW) and all-dielectric self-supported (ADSS) cables. In the case of OPGW, optical fibers are placed inside a specialized conductor that serves as both a fiber-optic communications facility and a ground wire or shield wire. Since the shield wire is typically installed on the top of the transmission line towers above the energized line, ground clearance problems that often prevent the installation of a communications cable beneath the energized line (i.e., underbuild) are avoided. Also, for newly constructed lines, the incremental costs of a conventional shield wire (a cost that is avoided with OPGW) can be deducted from the costs of the OPGW, increasing the economic feasibility of the OPGW installation. Special suspension and termination hardware is required for the OPGW conductors.

ADSS cable finds its widest application by electric utilities on low-voltage distribution and subtransmission poles (69 kV or less), but can be also used on high-voltage transmission lines where clearances will allow. ADSS cables are self-supported, requiring no supporting messenger. The cables are all-dielectric (containing no metals) so they can be safely installed in the supply space on electric utility poles by properly trained line personnel, and they can be routed directly into an electrical substation from outside the substation ground mat without introducing a ground potential rise hazard. Other cable types that are commonly used include aerial/duct cable (all-dielectric or steel-reinforced) and rodent-resistant cables for direct burial.

Fiber-optic transmission systems are primarily digital, utilizing TDM technology as is also used with digital microwave. Optical transceivers are available in capacities ranging from as few as one channel to many thousands. Fiber-optic transmission equipment from some manufacturers has been designed specifically for substation applications, supporting voice, data, and protective relaying functions. These specialized substation multiplexers are typically available at capacities of DS1 (1.544 megabits per second or up to 24 voice channels), SONET OC-1 (51.84 megabits per second or up to 672 voice channels), and SONET OC-3 (155.520 megabits per second or up to 2016 voice channels). These systems include advanced features such as embedded network surveillance, control, and management software, and fault-tolerant rings.

Another specialized application for optical fiber in substation communications is GPR isolation of metallic wire communications circuits. Because GPR can occur in electrical substations during short circuits on the electrical power system, metallic facilities such as telephone lines that enter the substation from outside the ground grid has to be electrically isolated from the substation ground influence. Since optical fibers do not conduct electricity, fiber-optic entrance links can be used to electrically isolate these metallic circuits in lieu of the more insulating transformers and mutual drainage reactors that have been traditionally used for this purpose. Special fiber-optic isolators are commercially available for this purpose.

Wire Lines

Wire lines leased from the telephone company are used in many cases for routine voice and data traffic. Wire lines entering substations for the purpose of communications, control, and protective relaying require special attention for high-voltage protection. These circuits may be used in the event of a power system fault; therefore, operation during these periods is crucial to personnel safety, equipment damage protection, and service reliability. The use of high-voltage protection aims to minimize the impact of GPR and induced voltages. Varying methods of protection are being used today. The most common equipment used in wire-line protection ranges from carbon blocks, spark gaps, and gas-filled and solid-state protectors to the more advanced relays, filters, neutralizing transformers and reactors, isolating transformers, and the more recent use of optical couplers.

IEEE Std. 487-1992, “Protection Theory and Philosophy”, covers the different design and philosophical approaches the telecommunications protection engineer and the power protective relaying engineer may take in protecting telecommunications equipment. Information on many factors is needed to properly design a protection scheme. A few of these conditions are:

- Total available single-phase-to-ground fault current and its distribution, maximum GPR (rms), X/R ratio, fault-produced longitudinal induction, lightning exposure
- Power station ground grid impedance to remote earth and grid area
- The extent of the GPR zone of influence
- Whether the transmission parameters and service performance objectives are compatible with the available or proposed facilities
- Anticipated future changes in any of the above data
- Whether lightning protection is required

Utilizing IEEE Std. 487-1992 is highly recommended for properly designing a protection system scheme. The system designs and protection concepts contained in this standard have been mutually agreed to by the power and telephone industries. Wire lines entering substation premises have to have special protection against induced currents and rise in station ground potential.

Voice and Data Channels circuits may use carbon blocks or similar devices that will remove the circuit from service when they operate. Voice traffic in most areas can be handled over wire lines since occasional interruptions can be tolerated in voice and data transmission. Relaying can be performed over wire lines only if the responsible telephone company can be relied on to provide circuits that are adequately protected against the effects of nearby power system disturbances.

Relaying Channels circuits have to remain in service during and after a power system fault. For audio tone circuits, fiber-optic isolators, high-voltage insulating transformers, gas tubes with mutual drainage reactors, and possibly neutralizing transformers may be required. Pilot-wire circuits require neutralizing transformers whenever DC monitoring is used.

Satellite Communications

Very small aperture terminals (VSATs) have been widely and successfully used for SCADA master station-to-RTU communications. VSAT networks optimized for SCADA are offered by network providers that sell the fixed transceiver equipment to the end user and then lease satellite airtime (space segment) on a monthly basis. Monthly charges are based on the amount of data that is actually transmitted by each VSAT. SCADA VSATs are most commonly used by electric utilities and pipeline companies that have to communicate with RTUs over very large areas where leased telephone line and private communication network costs are prohibitive.

Since the VSAT space segment is leased, and therefore entails recurring monthly costs, VSATs are generally regarded as an alternative to leased telephone lines. VSATs do offer certain advantages over leased lines, insofar as they are not prone to outage resulting from wind, ice, or lightning. Since VSATs are wireless, they do not require high-voltage isolation as do leased telephone lines entering substations. VSATs can experience path outages during extremely heavy rainfall. VSATs also suffer outages around the spring and fall equinoxes, although these times are predictable and total equinox outage time is generally only 1 to 2 hours per year.

VSAT network vendors also offer advanced network management services that are not available for leased telephone lines. Since all signals pass through the vendor’s hub facility, the vendor can carefully monitor channel performance and make maintenance adjustments when necessary.

Each message transmission between a master station and an RTU has to make two round trips to the geostationary satellite via the vendor’s hub. Since each round trip requires at least 0.239 seconds to complete, the space segment delay for a single message is approximately 0.5 seconds. For this reason, inefficient SCADA master station-to-RTU communication protocols can result in the introduction of considerable communications delays.

VSATs should only be employed for data applications such as SCADA, and where relatively long time delays can be tolerated. VSATs are not considered suitable for voice or protective relaying applications.

Substation Communications Acronyms

Table 4 has some of the commonly used telecommunications acronyms.

Table 4
Telecommunication Acronyms

Term	Description
All-Dielectric Self-Supporting (ADSS)	ADSS cables are self-supported, requiring no support messenger. The cables are all dielectric (containing no metals), so they can be safely installed in the supply space on electric utility poles.
Asynchronous Transfer Mode (ATM)	A communications transmission and switching standard for carrying broadband signals at speeds of up to 2.2 gigabits per second. Combines techniques of time division multiplexing and packet switching.
Basic Impulse Insulation Level (BIL)	A rating level to determine how insulating materials react to impulse voltages. As BIL increases, so does the amount of insulation required to protect the equipment.
DS1	Digital Signal Level 1; the designation given to a digital hierarchy of circuits or channels operating at 1.544 Mbps; commonly referred to as T1.
EHV	Extra high voltage; usually ranges from 345 kV to 765 kV.
Federal Communications Commission (FCC)	A board of commissioners appointed by the President who have the power to regulate non-federal communications systems.
Frequency Shift Keying (FSK)	Modulation type used in short-distance wire-line communications.
Ground Potential Rise (GPR)	A phenomenon that occurs when there is a high-voltage difference between a grounded communications site and a distant site connected by wire-line communication circuits that has the potential to damage communication equipment.
Intelligent Electronic Devices (IEDs)	Electronic equipment that provides monitoring and controlling capabilities.

kHz	Kilohertz; one thousand cycles per second.
Line Tuner Unit (LTU)	A tuning network used to match the transmitter output impedance with the impedance seen at the coupling capacitor input.
MHz	Megahertz; one million cycles per second.
Multiple/Address System (MAS)	Radio system using master–slave protocol to communicate to a minimum of four remote computers.
OC-1	SONET optical carrier 1, operating at data rate of 51.84 Mbps.
OC-3	SONET optical carrier 3, operating at data rate of 155.52 Mbps.
Optical Ground Wire (OPGW)	Optical fibers (numbering typically from 6 to 48 fibers) placed inside a specialized conductor that serves as both a fiber-optic communications facility and a ground wire or shield wire.
Pulse Code Modulation (PCM)	A scheme of transmitting data by digitizing and then using pulse codes to transmit the digitized data.
Remote Terminal Unit (RTU)	An electronic device used to control and monitor Input/Output points, within an overall system and to communicate the derived data to a master station or other “host” unit.
SCADA	Supervisory Control and Data Acquisition; used by utilities and other process-oriented operations to collect data from machinery that may be spread over a very large geographic area. A basic SCADA system consists of two types of devices master and remote. The master resides at a centrally manned location while the remotes are generally placed at unmanned locations. Communication between master and a number of remotes can be via telephone-like circuit, radio channels, or fiber-optic communications media.
SONET	Synchronous Optical Network; standard for optical transport formulated by the Exchange Carrier Standards Association (ESCA) for ANSI; essentially a standard for

Time-Division Multiplexing (TDM)	A method of transmitting several signals on a single line on a time-sharing basis.

Summary

This course has covered the design and application of AC and DC auxiliary systems used to support the operation of an electrical substation. In addition, the use of automation in substations was reviewed as well as the use of communications technology in substations.

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