APPENDIX – 4D

SUBSTATION POWER TRANSFORMERS
APPENDIX 4D

Substation Power Transformers

The substation power transformers transform one nominal level system voltage to another. The power transformers must carry the system power flow under various operating conditions and contingencies. Power transformers are the largest, heaviest, and very costly piece of equipment used in substations. There are two types of power transformers, autotransformer and multiwinding conventional transformers. A three-phase power transformer installation can be a three-phase unit or three single-phase units.

Figure 3-1, 3-2, and 3-3 shows the power transformer, three-phase transformer with tertiary and three-phase Auto-Transformer.

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Figure 3-1: Power Transformer (Shown with Load Tap Changer on Low-Voltage Side)
Figure 3-2: Three-Phase Transformer with Tertiary

Figure 3-3: Three-Phase Auto-Transformer

APPENDIX – 4E

SUBSTATION SF6 GAS CIRCUIT BREAKERS
APPENDIX 4E

Substation SF6 Gas Circuit Breakers

A circuit breaker closes and opens an electric circuit under both load and fault conditions. There are two types of circuit breakers, dead tank and live tank. Dead tank circuit breaker means that the external source and load connections are made through conventional bushings, circuit breaker tank and all accessories are maintained at ground potential. Live tank circuit breaker means that the interrupting mechanism is mounted on an insulating porcelain column and maintained at line potential.

Substation circuit breakers are also classified as three-pole-single-throw and independent pole operation. Three-pole-single-throw circuit breakers utilize one mechanical device to trip all three poles together and independent pole operation circuit breakers utilize one mechanical device per pole to trip individual pole. Figure 3-10, 5-2, and 5-3 shows the power circuit breaker one line, dead tank, and live tank breaker.

Figure 3-10: Circuit Breaker (Shown with Bushing-Type CTs and Reclosing Relay)
Substation air switches are mechanical switching device that are used for changing the connections in a circuit. The switches are required to carry normal load current continuously and short-circuit current for short period of time. Substation air switches are used for circuit breaker isolation, power transformer isolation, electrical equipment bypassing, and bus sectionalizing. Figure 3-5, 3-6, 3-7, and 3-8 shows different type of outdoor air switches.

Figure 3-5: Hook Stick-Operated Disconnecting Switch

Figure 3-6: Three-Phase Gang-Operated Disconnecting Switch with Horn Gaps and Grounding Switch

Figure 3-7: Three-Phase Double Side-Break Disconnecting Switch with Motor Operator
The operating mechanisms are bonded directly to the operator mat/platform with a 4/0 copper ground conductor to ensure that the operating personnel's hands and feet will be maintained at the same potential. Figure 5-22 and 5-23 shows horizontally mounted double break switch with grounding and horizontally mounted double break switch.

Table 4-8 lists the phase spacing of various types of outdoor air switches. The minimum metal-to-metal clearances should be maintained at all times with the switches.
in the open, closed, or anywhere between the open and closed positions.

Table 4-8: Phase Spacing of Outdoor Air Switches

<table>
<thead>
<tr>
<th>Nominal Phase-to-Phase Voltage kV</th>
<th>Maximum Phase-to-Phase Voltage kV</th>
<th>Minimum BIL kV</th>
<th>Minimum Meets-to-Meet for Air Switches (inches)</th>
<th>Vertical Break Disconnect Switches (inches)</th>
<th>Side or Horizontal Break Disconnect Switches (inches)</th>
<th>All Horn Gap Switches (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>8.3</td>
<td>90</td>
<td>0.755 (7)</td>
<td>0.457 (18)</td>
<td>0.702 (30)</td>
<td>0.914 (36)</td>
</tr>
<tr>
<td>14.4</td>
<td>15.5</td>
<td>110</td>
<td>0.805 (12)</td>
<td>0.610 (24)</td>
<td>0.702 (30)</td>
<td>0.914 (36)</td>
</tr>
<tr>
<td>23</td>
<td>25.8</td>
<td>150</td>
<td>0.381 (15)</td>
<td>0.782 (30)</td>
<td>0.914 (36)</td>
<td>1.22 (48)</td>
</tr>
<tr>
<td>34.5</td>
<td>38</td>
<td>200</td>
<td>0.457 (18)</td>
<td>0.914 (36)</td>
<td>1.22 (48)</td>
<td>1.52 (60)</td>
</tr>
<tr>
<td>46</td>
<td>48.3</td>
<td>250</td>
<td>0.533 (21)</td>
<td>1.22 (48)</td>
<td>1.52 (60)</td>
<td>1.83 (72)</td>
</tr>
<tr>
<td>69</td>
<td>72.5</td>
<td>350</td>
<td>0.787 (31)</td>
<td>1.52 (60)</td>
<td>1.83 (72)</td>
<td>2.13 (84)</td>
</tr>
<tr>
<td>115</td>
<td>121</td>
<td>550</td>
<td>1.35 (53)</td>
<td>2.13 (84)</td>
<td>2.74 (108)</td>
<td>3.05 (120)</td>
</tr>
<tr>
<td>138</td>
<td>145</td>
<td>650</td>
<td>1.60 (63)</td>
<td>2.44 (89)</td>
<td>3.35 (132)</td>
<td>3.66 (144)</td>
</tr>
<tr>
<td>161</td>
<td>169</td>
<td>750</td>
<td>1.83 (72)</td>
<td>2.74 (108)</td>
<td>3.96 (158)</td>
<td>4.27 (168)</td>
</tr>
<tr>
<td>230</td>
<td>242</td>
<td>900</td>
<td>2.26 (89)</td>
<td>3.35 (132)</td>
<td>4.67 (192)</td>
<td>4.87 (192)</td>
</tr>
<tr>
<td>230</td>
<td>242</td>
<td>1050</td>
<td>2.67 (105)</td>
<td>3.96 (158)</td>
<td>5.50 (216)</td>
<td>5.50 (216)</td>
</tr>
<tr>
<td>345</td>
<td>362</td>
<td>1300</td>
<td>3.02 (119)</td>
<td>4.43 (174)</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Notes:
1. Values taken from ANSI C37.32 and NEMA SD8.
2. Values listed are for altitudes of 1000 meters (3300 feet) or less. For higher altitudes, the altitude correction factors listed in Table 4-3 should be applied.

APPENDIX 4G

Substation Surge Arresters

Substation surge arresters are the protective devices for the substation equipment against system transient overvoltage that may cause flashover and can cause serious damage to the substation equipment. The surge arrester conducts internally and discharges the surge energy to the ground when a transient overvoltage occurs at an arrester location. The surge arrester stops conducting once the overvoltage is reduced and the flow of power returns to normal.

Table 5-58 lists the metal oxide station and intermediate-class arrester characteristics.

<table>
<thead>
<tr>
<th>Station Class</th>
<th>Station Voltage and Arrester Ratings</th>
<th>Surge-Voltage and NMOV Characteristics</th>
<th>High-Cutoff Characteristics</th>
<th>Transmission Line Discharge Collector (Amps)</th>
<th>Pressure Relief (A rms) (Symmetrical)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum Voltage L-G (kVrms)</td>
<td>Minimum NMOV (kA rms)</td>
<td>3.5 μs Iimp (kA rms)</td>
<td>0.2 μs Wave (kA rms)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum Voltage L-G (kVrms)*</td>
<td>Maximum NMOV (kA rms)</td>
<td></td>
<td>Discharge Voltage (MV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.13</td>
<td>4.53</td>
<td>5.0</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>250</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>230</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>220</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>210</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>200</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>190</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>180</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>170</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>160</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>150</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>140</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>130</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>120</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>110</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>100</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>90</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>80</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>70</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>60</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>50</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>40</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>30</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>20</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>10</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.73</td>
<td>0</td>
<td>230-235</td>
<td>10.0 (MAX)</td>
</tr>
</tbody>
</table>

* Voltage range A, ANSI C64.1-1989 [1].

NOTE 1: Equivalent Iimp producing a voltage wave cresting in 0.5 μs. Protective level is maximum DV for a 10 kA impulse current wave on arrester duty cycle rating through 312 kV. 15 kA for duty cycle ratings 368-564 kV, and 20 kA for duty cycle ratings 576-812 kV, per IEEE Std. C62.11-1987 [9].

NOTE 2: Switching surge characteristics based on maximum switching surge classifying current (based on impulse current wave with a time to actual crest of 45 μs to 0 μs) of 500 A on arrester duty cycle ratings 0-100 kV, 1000 A on duty cycle ratings 120-240 kV, and 2000 A on duty cycle ratings above 240 kV, per IEEE Std. C62.11-1987 [9].

NOTE 3: Test values for arresters with porcelain toors have not been standardized.

Table 5-58: Metal Oxide Station and Intermediate-Class Arrester Characteristics

APPENDIX – 4H

SUBSTATION CAPACITOR VOLTAGE TRANSFORMERS (CVT)
APPENDIX 4H

Substation Capacitor Voltage Transformers¹ (CVT)

CVT’s are used for coupling to a power line to provide low voltage(s) for the relay and metering operations. CVT’s are commonly supplied without carrier accessories. CVTs are static equipment and therefore essentially maintenance free. Figure 3-14 and 3-15 shows the one-line of the capacitor voltage transformer. Figure 5-60 shows coupling capacitor, wave trap, tuning unit, and power line carrier transmitter/ receiver.

![Figure 3-14: Coupling Capacitor with Voltage Transformer¹](image)

![Figure 3-15: Coupling Capacitor, Wave Trap, Tuning Unit, and Power Line Carrier Transmitter/ Receiver¹](image)
Figure 5-60: Coupling Capacitor Voltage Transformers With and Without Wave Trap

APPENDIX – 4I

SUBSTATION BATTERY & BATTERY CHARGER
APPENDIX 4I

Substation Battery & Battery Charger\(^1\)

Two of the most important components of a substation dc system are the main battery and charger. These components should be sized correctly. At a minimum, the main battery should be sized to allow normal substation operation for a number of hours. 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. Example 15-1 shows the battery selection method.

<table>
<thead>
<tr>
<th>The model duty cycle could be:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ten 40-watt, 120-volt lamps - 3 hrs. 3.5 amperes</td>
</tr>
<tr>
<td>Relays and panel indicating lamps - 8 hrs. 5.0 amperes</td>
</tr>
<tr>
<td>Communications - 3 hrs. 5.0 amperes</td>
</tr>
<tr>
<td>Three simultaneous Breaker Operations - 1 min. 100.0 amperes</td>
</tr>
</tbody>
</table>

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.

EXAMPLE 15-1: Battery Selection\(^1\)

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, 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 are handled by
the charger within the limits of its capacity. Any excess load is handled by the battery, which is automatically recharged when the intermittent load ceases. The battery carries the entire load when the ac input to the charger fail. Example 15-2 shows the battery charger selection method.

Using the same model as for battery selection, we have:

<table>
<thead>
<tr>
<th></th>
<th>Amperes</th>
<th>Hours</th>
<th>AH</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Lights</td>
<td>3.5</td>
<td>3</td>
<td>10.5</td>
</tr>
<tr>
<td>Communications</td>
<td>5.0</td>
<td>3</td>
<td>15.0</td>
</tr>
<tr>
<td>Breaker operations</td>
<td>100.0</td>
<td>1</td>
<td>1.7</td>
</tr>
<tr>
<td>Panel load</td>
<td>5.0</td>
<td>8</td>
<td>40.0</td>
</tr>
</tbody>
</table>

\[
A = 5 + \frac{1.1 \times 67.2}{8} = 14.24 \text{ Amperes}
\]

The next largest standard size charger should be selected. If the charger is to be operated at altitudes above 1000 meters (3300 feet) and above 40°C (104°F) ambient, check vendor data for correction factors.

**EXAMPLE 15-2: Charger Selection**

APPENDIX – 4J

SUBSTATION GROUNDING
APPENDIX 4J
Substation Grounding

Substation Grounding System

Currents flowing into the grounding grid from surge arrester operations, impulse or switching surge flashover of insulators, and line-to-ground fault currents from the bus or connected transmission lines, all cause potential differences between grounded points in the substation and remote earth. Without a properly designed grounding system, large potential differences can exist between different points within the substation itself. Under normal circumstances, it is the current flow through the ground grid from line-to-ground faults that constitutes the main threat to personnel. Figure 9-5 shows typical current division for a fault on high side of distribution substation.

Figure 9-5: Typical Current Division for a Fault on High Side of Distribution Substation

\[ I_G = 1048 \]
\[ I_G = 742 \]
\[ I_G = 99 \]
An effective grounding system assure such a degree of human safety that a person working or walking in the vicinity of grounded facilities is not exposed to the danger of a critical electric shock. The touch and step voltages produced in a fault condition must be at safe values. A safe value is one that will not produce enough current within a body to cause ventricular fibrillation. Figure 9-28 shows basic shock situations.

Figure 9-28: Basic Shock Situations

An effective grounding system carry and dissipate electric currents into earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service. An effective grounding system provide a low resistance for the protective relays to see and clear ground faults, which improves protective equipment performance particular at minimum fault.
While line-to-ground faults may result in currents of tens of thousands of amperes lasting several seconds, modern relay systems generally reduce the fault duration to a few cycles. During fault current flow, a low ground grid resistance to remote earth is necessarily to provide safety to personnel. It is necessary that the entire grounding system be designed and installed so that under reasonably conceivable circumstances, personnel are not exposed to hazardous potential differences across the body.

IEEE Standard 80, "Guide for Safety in Substation Grounding," is generally recognized as one of the most authoritative guides available. A good grounding system provides a low resistance to remote earth in order to minimize the ground potential rise (GPR). For most transmission and other large substations, the ground resistance is usually about 1 Ω or less.

**Substation Ground Grid Design**

The area of ground grid should cover the entire substation site. The outer ground grid conductors should be placed a minimum of three feet outside of the substation fence parameter to protect persons outside of the fence from possible hazardous touch voltages.

APPENDIX – 4K

SUBSTATION SHIELDING
APPENDIX 4K

Substation Shielding¹

Substation Shielding Design

It is recommended that some form of direct stroke protection be provided since a direct
lightning stroke to an unshielded substation would be very dangerous and damaging.
Direct stroke protection normally consists of shielding the substation equipment by
using lightning masts, overhead shield wires or a combination of these devices. The
types and arrangements of protective schemes used and their effectiveness depend on
the size and configuration of the substation.

Shielding masts can be used for nearly all types of substations to provide protection
against direct lightning strokes. They are particularly useful in large substations and
those of low profile design. Shielding masts can be guyed or self-supporting steel poles
or lattice type towers and are usually made of steel. However, guyed structures within a
substation are discouraged due to interference with equipment access and drive
clearance. In some instances, shielding masts can also be used to provide support for
substation lighting equipment.

Overhead shield wires are often used to provide direct stroke protection. Line pull-off
structures and masts inside the substation support the shield wires. Breakage could
result in outage of and/or damage to equipment since these shield wires is located
above substation buses and equipment. The overhead shield wire systems are
constructed from high quality, high strength materials to minimize possible breakage.
Shield wires should be limited to a maximum design tension of 2000 pounds per
conductor under the appropriate loading conditions as defined in the National Electrical
Safety Code. This tension is based only on wire strength and has to be coordinated
with support structure design. Lower tensions may be required for certain applications,
depending on the capabilities of the support structures. Sag has to be considered to
ensure adequate clearance from energized equipment.

A complete overhead shield wire system should include protection for overhead lines
entering or leaving the substation. In areas not employing transmission line shielding,
substation shield wire systems should be extended at least one-half mile away from the
substation to limit the exposure of the phase conductors to direct strokes near the
substation. Strokes occurring on the lines beyond the shielding will usually be
attenuated enough by the time they reach the substation to be discharged successfully
by the surge arresters without causing equipment damage. The line shield wire
systems should be directly connected to the substation shield wire system and
substation ground grid for adequate protection.

Substation Shielding Design Method

There are fixed angle and rolling sphere to design substation shielding. The fixed angle
substation shielding design method uses vertical angles to determine the number,
position, and height of shielding masts and wires. The shaded areas in Figure 4-17
illustrates the zones of protection for fixed angle shielding method.
The rolling sphere substation shielding design method involves rolling an imaginary sphere over the substation. The sphere rolls up and over lighting masts, shield wires, and other grounded metal objects intended for substation lighting shielding. A piece of equipment is protected from a direct stroke if it remains below the curved surface of the sphere elevated by the shield wires or other devices. Figure 4-18 illustrates the zones of protection for the rolling sphere method.
Figure 4-18: Principle of Rolling Sphere

APPENDIX – 4L

SUBSTATION CONDUIT AND RACEWAY
APPENDIX 4L

Substation Conduit and Raceway

Non-Metallic Conduit

Direct buried nonmetallic conduit for control and power cable including lighting circuits offers the most economical underground system for substations. Non-metallic conduit with a wall thickness suitable for direct earth burial should be selected. Fittings for the conduit, be it plastic, fiber, or cement asbestos, should be procured from the manufacturers of the conduit. This will ensure component compatibility.

Conduit bends should be avoided to limit cable-pulling tension except for equipment risers. Pulling tension should be limited to 1000 lbs. for cables with neoprene, polyethylene or PVC jackets when pulled with a basket grip. Control cables with conductors No. 16 AWG and smaller should be limited to 40 percent of this value or lower if recommended by the manufacturer.

It is good practice to follow the recommendation of the National Electrical Code (NEC) in sizing of individual conduits of the system. This means the total cross sectional area (over insulation) of all conductors in a conduit should not exceed the NEC recommendation of fill for the cross sectional area of the interior of the conduit. The NEC tables indicate 53% fill for conduits with only one cable, 31% for two cables, and 40% for three or more cables.

Cable Trench

In general, cable trenches utilize either no floor or large floor openings to accommodate
conduit entrances and to eliminate floating or frost heaving with consequent misalignment possibility. Cables are placed on a 4 to 6 inch bed of fine sand. The most significant advantages of cable trench use are the labor cost saving, accessibility, and reduced possibility of cable pulling damage. Trenches are becoming the most acceptable cable installation method, particularly in large installations. Figure 10-7 shows pre-cast cable trench.

Figure 10-7: Pre-cast Cable Trench

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APPENDIX – 4M

SUBSTATION RELAYING AND METERING
APPENDIX 4M

Substation Relaying and Metering

Short Circuit

A short circuit or fault is an abnormal connection of relatively low resistance between two or more points of differing potential in a circuit. If one of these points is at ground potential, it is referred to as a "ground fault." If ground potential is not involved, it is referred to as a "phase fault." Phase faults cause excessive currents and low voltages. Ground faults may or may not cause excessive currents or abnormal voltages, depending upon whether the system is normally ungrounded, high- or low-resistance grounded, or effectively grounded.

Excessive Heating

Equipment is designed to deliver full-rated capacity with the temperature maintained below a value that will not be damaging to the equipment. If operating temperature becomes excessive, the life of the equipment (generator, motor, transformer, etc.) will be reduced. Overloading, high ambient temperatures, improper cooling or failure of cooling equipment may cause excessive heating.

Overvoltage

Equipment is designed for nominal operating voltages as stated on its nameplate with a slight allowance (typically between five and ten percent) from this nominal voltage. Abnormal overvoltage may cause: (1) insulation failure; (2) shortening of the equipment life; (3) excessive heating due to greatly increased excitation currents where
electromagnetic devices are used; (4) excessive heating in resistors used in controls; and (5) failure of transistors and other electronic devices.

**Undervoltage**

Continued undervoltage will likely cause overheating of motors, dropping out of contactors, and lead to the failure of electrical equipment.

**Unbalanced Phase Conditions**

On balanced three-phase systems with balanced three-phase loads, a sudden unbalance in the current or the voltages usually indicates an open or a partially shorted phase. On balanced three-phase systems with single-phase loads, the loading on each phase may normally vary, depending upon the magnitude of each single-phase load. However, it is desirable to keep this unbalance to a minimum to maintain balanced voltages for three-phase loads.

**Abnormal Frequency**

Abnormal frequencies can occur when the load does not equal the generation. The frequency may be above or below the system normal frequency.

**Abnormal Pressure**

In electrical equipment, such as transformers, that use liquid as an insulating fluid, high internal pressures can be created during internal faults.

**Abnormal Impedance**

Electrical power equipment has impedance associated with it that either has definite known values or values that may vary within a known range during varying operating conditions.
conditions. These values are normally determined during the manufacture and installation of equipment. Substantial deviations in the impedance of the equipment can indicate a failure of the equipment.

Out of Step Conditions

Electric power systems in North America operate at a frequency of 60 hertz. All of the generators and rotating equipment on the system rotate at an rpm to maintain the 60 hertz frequency. As such, each machine on the electrical system maintains a relative position, or phase angle, with respect to every other machine on the system. Once a machine exceeds a critical phase angle, it can no longer stay in phase with the system. It is said to have moved out of step with the system. If this condition persists for a long enough period, the machine must be removed from the system and resynchronized to the system.

Excessive System Phase Angles (Synchronism Check)

The closing of a circuit breaker on a system connects the electrical systems on either side of the circuit breaker together. The closing of the breaker will cause any difference of voltage and phase angle across the breaker to be reduced to zero, causing current flow from one system to the other to equalize the system voltages, currents, and phase angles. If the voltage- and phase angle differences across the breaker are too much, excessive currents can flow, resulting in a disturbance to the system, possibly damaging the breaker or adjacent rotating equipment. Typically, the voltage and phase-angle across the breaker is compared to confirm the systems are within proper limits before the breaker is closed.
APPENDIX – 4N

SUBSTATION RELAY SELECTION
APPENDIX 4N

Substation Relay Selection

Instrument transformers provide relays with voltages and currents that are proportional to the voltage and currents on the high voltage primary circuit. Voltage signals are obtained from voltage transformers (VT’s) and current signals from current transformers (CT’s). Microprocessor relays provided status, control and indication functions in addition to protective relaying.

Microprocessor relays provide several advantages over their electromechanical and static relay counterparts. One major advantage is that the microprocessor relay will include more protective functions within a single relay. Consequently, the use of microprocessor relays may result in reduced cost since fewer relays are required. Generally, less relay panel and floor space are needed for these relays so smaller control buildings are needed. These relays typically reduce auxiliary power system requirements. Additionally, the interconnection wiring between devices in a panel is reduced since many of the protective functions are included in one relay enclosure.

In addition to basic relaying microprocessor relays may do fault locating, fault data recording, self testing and metering. Since microprocessor relays tend to have more protective functions available in a relay case, it often allows the substation engineer to provide additional protection he would not have previously considered.

APPENDIX – 4O

SUBSTATION RELAY TYPES
APPENDIX 4O

Substation Relay Types

Overcurrent Relay

The overcurrent relay responds to a magnitude of current above a specified value for a specified time interval. Microprocessor relays convert the current input to the relay into a digital signal. The digital signal can then be compared to the setting values input into the relay. When the current exceeds the setting value, it causes a trip. Complications in applying the relay may occur when the system does not provide adequate differentiation between current values, such as between short lines on a system with high fault current duties.

Distance Relay

The distance relay responds to a combination of both voltage and current. The voltage restrains operation, and the fault current causes operation that has the overall effect of measuring impedance. The relay operates instantaneously (within a few cycles) on a 60 Cycle basis for values of impedance below the set value. When time delay is required for relay coordination, the microprocessor relay utilizes an internal time delay function to control the tripping functions of the relay.

Since the relay responds directly to the value of impedance represented by the fault current and voltage applied to the relay, it will discriminate more correctly between the locations of faults since its impedance also may represent the electrical power system. The distance relay may be used more successfully on an electric power system when the magnitudes of fault current do not provide adequate location differentiation to be
able to accurately trip specific breakers and isolate a fault.

**Differential Relay**

The differential relay is a current operated relay that responds to the difference between two or more currents above a set value. The relay works on the basis of the differential principal that what goes into the device must come out. If the current does not add to zero, the “error” (fault) current flows to cause the relay to operate and trip the protected device.

The differential relay is used to provide high-speed protection from internal faults to equipment such as transformers, generators, and buses. Relays are designed to permit differences in the input currents due to current transformer mismatch, and due to applications where the input currents come from different system voltages, such as transformers.

Differential relays are often used with a lockout relay to trip all power sources to the device and prevent the device from being automatically or remotely re-energized. The relays are very sensitive. The operation of the device usually means major problems with the protected device and the likely failure in the success of re-energizing the equipment.

**Undervoltage & Overvoltage Relay**

The undervoltage and overvoltage relays respond to a magnitude of voltage below or above a specified value. Microprocessor relays convert the voltage input to the relay into a digital signal. The digital signal can then be compared to the setting values input
into the relay. With the microprocessor relay, various voltage/time curves or multiple time delay settings can be input to set the relay operation.

**Power Relay**

A power relay responds to the product of the magnitude of voltage, current, and the cosine of the phase angle between the voltage and current, and is set to operate above a specified value. The relay is inherently directional in that the normally open contacts close for power flow in one direction above a set value but remain open for power flow of any amount in the opposite direction.

**Directional Overcurrent Relay**

A directional overcurrent relay is a relay that operates only for excessive current flow in a given direction. Microprocessor relays often provide a choice as to the polarizing method that can be used for determining the direction of fault.

**Pressure Relay**

The pressure relay responds to sudden changes in fluid or gas pressure. It basically consists of a pressure sensitive element and a bypass orifice, located between the equipment to which the relay is connected, and a chamber that is part of the relay. During slow pressure changes the bypass orifice maintains the pressure in the chamber to the same value as in the equipment. During sudden pressure changes, the orifice is not capable of maintaining the pressure in the chamber at the same value as in the equipment, and the pressure sensitive element mechanically operates a set of contacts.

**Auxiliary Relay**

Auxiliary Relays perform such functions as time delay, counting, and providing
additional contacts upon receiving a signal from the initiating relay. These relays are necessary to provide the broad variety of schemes required by a power system.

APPENDIX – 4P

SUBSTATION SITE GRADING
APPENDIX 4P

Substation Site Grading

Site should be designed to meet the state and local storm water requirements. The goal will be to balance the cut and fill quantities and minimize the amount of borrowed fill to be delivered to the site or excess cut to be removed from the site. The substation should be surfaced with 4 to 6 inches of crushed rock. There are generally three basic profiles for substation yards. Figure 6-1 shows the section of flat yard grading.

![Figure 6-1: Flat Yard](image1)

Figure 6-2 shows the section of sloped yard grading on moderately sloped site.

![Figure 6-2: Sloped Yard on Moderately Sloped Site](image2)

Figure 6-3 shows the section of stepped yard grading.

![Figure 6-3: Stepped Yard](image3)
APPENDIX – 4Q

SUBSTATION FOUNDATION
APPENDIX 4Q

Substation Foundation

The foundations shall be designed using the base reactions from the structure supplier’s calculations and the subsurface conditions from the geotechnical report. The foundations will be sized such that the soil is not overstressed and the foundations deflection is less than 1 inch and rotation is less than 0.5 degrees. Figure 8-4 and 8-7 show drilled shaft and spread footing foundation elevation.

Figure 8-4: Drilled Shaft Elevation

Figure 8-7: Spread Footing Elevation

APPENDIX – 4R

SUBSTATION STRUCTURES
APPENDIX 4R

Substation Structures

Substation structures are designed for environmental and dynamic conditions they will likely experience throughout their service lives. Additional design requirements include client specific loads and clearances that are required for maintenance and construction purposes.

Substation Conceptual Design

Considering each substation structure and the electrical equipment it supports as a system. Substation steel is designed to conform to the requirements of the National Electrical Manufacturers Association (NEMA SG6) for outdoor substations.

Substation Line Support Structures

Line support structures may be multiple bays or single bays as directed by the electrical arrangement. In addition to conductors and shield wires these structures typically support shield masts, switches, wave traps or other equipment.

Substation Lightning Masts

The Substation lighting masts are in addition to the masts that sit atop the yard deadend structures to protect the substation equipment from direct lightning strikes. The shield wire mast structures are designed for the same loading conditions as the line support structures.

Substation Equipment Support Structures

The equipment support structures at the substations consisting of Switch Stands, Bus Supports, CVT Supports, Surge Arresters, etc. and are not standard structures. Each
structure type is a unique design based on the physical arrangement and loading conditions at each yard.

APPENDIX – 4S

SUBSTATION CONTROL BUILDING
APPENDIX 4S

Substation Control Building

The manufacturer can design and fabricate the required building components when given the building size, wind, snow, and ice loads, and any special requirements such as additional roof loads for suspended cable trays and other equipment. Figure 16-1 and 16-2 show pre-fabricated metal and masonry block control building.

Figure 16-1: Pre-Engineered Metal Control Building

Figure 16-2: Typical Masonry Block Control Building

APPENDIX – 4T

SUBSTATION CONTROL BUILDING LAYOUT
APPENDIX 4T

Substation Control Building Layout

Controls and Relay Panels

Most relaying, metering, and control equipment is mounted on fabricated control and relay panels installed within the control building. A variety of panel types are available to suit individual requirements. The relaying, metering, and control equipment can all be mounted on one panel, allocating a separate panel for each circuit. Figure 16-4 and 16-5 shows typical relay/control panel layout, microprocessor, electromechanical relays, mimic bus, and 19-inch rack-mount relay/communications equipment.

Panels are located in an arrangement that conforms as closely as possible to the actual equipment and circuit layout in the substation yard to facilitate operation. Mimic buses

Figure 16-4: Typical Relay/Control Panel Layout, microprocessor, electromechanical relays, and mimic bus.

Figure 16-5: 19-Inch Rack-Mount Relay/Communications Equipment
can be used on the control panels to assist in circuit location and operation. The mimic buses identify the bus and circuit arrangements. Meters should be positioned at eye level and switches at a convenient operating level. Recording meters needs to be located for ease of viewing and chart replacement. Relays are located beginning at the tops of the relay panels and working downward. Nameplates are mounted for all devices.

Panels include small sections perpendicular to the main section at each end for installation of terminal and fuse blocks, or small auxiliary devices. Cable connections from the equipment in the substation yard are made directly to terminal blocks mounted on the panels.

**DC Equipment**

Substation dc equipment located in the control building normally consists of the battery, battery charger, monitoring and control devices and distribution panel board. The batteries located in a separate room. The battery chargers, monitoring and control devices, and distribution panel boards are located in the control and relay room to facilitate cable routing and equipment maintenance.

The battery room should be separated from the control room with a full height, non-fire rated wall. The battery area needs to adequately ventilate by a powered ventilation system to limit accumulation of hydrogen gas as well as pull climate-controlled air through battery room for heating and cooling. A neutralizing agent for rinsing eyes and skin should be provided in the battery area in addition to eye protection and protective
clothing. Figure 15-3 shows typical DC auxiliary system.

![Figure 15-3: Typical DC Auxiliary System](image)

**Figure 15-3: Typical DC Auxiliary System**

**AC Equipment**

A low voltage AC system is provided for lighting, outlets, heating, ventilating, air conditioning (HVAC) equipment, and miscellaneous control functions. Outlets are located throughout the control building to provide adequate accessibility.

An AC distribution panel board located inside the control building is used to supply the indoor lights, convenience outlets, HVAC equipment, and other devices. Multiple separate sources are provided for the ac system service for greater reliability. These sources are fed through a manual or automatic transfer switch, so that ac system power can be restored if one source fails. Figure 15-2 shows typical AC auxiliary system.
Cable Trays

Cable trays used for overhead routing of cables to and between control and relay panels. Expanded ladder type trays can be used to provide the best facilities for conductors entering and leaving the trays. An advantage of cable trays is the ability to lay rather than pull in the conductors. Cable trays are selected and installed in accordance with the National Electrical Code and National Electrical Manufacturers Association (NEMA) Standards.

Control Building HVAC System

Heating, ventilating and air-conditioning (HVAC) systems are required to maintain the functions and accuracy of electrical equipment installed in the control building. Electric heat pumps can be used at the substation control buildings for both heating and cooling.
The heat pumps are equipped with economizers, which allow the units to use outside air for cooling rather than air-conditioning during mild outside air temperatures, thereby incurring significant energy savings. A louver should be used to relieve air introduced to the space during economizer mode. This prevents over-pressurization of the space.

APPENDIX – 4U

SUBSTATION COMMUNICATION
APPENDIX 4U

Substation Communication

A commercial telephone can be installed in the control building for external communications. System telephones or voice channels over carrier systems may be used for systems communications. Substation supervisory control and data acquisition systems (SCADA) can be installed for remote control and monitoring of substation equipment. Figure 17-1 and 17-5 show typical substation carrier system and microwave.

Figure 17-1: Typical Carrier System

Figure 17-5: 6 GHz Microwave Terminal Mounted on Substation Box Structure
Figure 17-7 and 17-8 show OPGW splice on deadend structure in substation, fiber-optic multiplexers and fiber-optic patch panel.

<table>
<thead>
<tr>
<th>Substation Bus Configurations Cost</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 4-1

Substation Bus Configurations Cost

<table>
<thead>
<tr>
<th>Bus Configuration</th>
<th>Cost Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Bus</td>
<td>100%</td>
</tr>
<tr>
<td>Sectionalized Bus</td>
<td>122%</td>
</tr>
<tr>
<td>Main and Transfer Bus</td>
<td>143%</td>
</tr>
<tr>
<td>Ring Bus</td>
<td>114%</td>
</tr>
<tr>
<td>Break-And-A-Half</td>
<td>158%</td>
</tr>
<tr>
<td>Double Breaker-Double Bus</td>
<td>214%</td>
</tr>
</tbody>
</table>

Table 4-1: Cost comparison between the bus configurations\(^1\)

---

<table>
<thead>
<tr>
<th>Table 4-2: Substation Clearances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
## Table 4-2
### Substation Clearances

<table>
<thead>
<tr>
<th>Nominal Phase-to-Phase Voltage (kV)</th>
<th>Maximum Phase-to-Phase Voltage (kV)</th>
<th>BIL (kV)</th>
<th>Minimum Metal-to-Metal for Rigid Conductors (meters) (Inches)</th>
<th>Centerline-to-Centerline Phase Spacing for Rigid Buses (meters) (Inches)</th>
<th>Minimum to Grounded Parts for Rigid Conductors (meters) (Inches)</th>
<th>Minimum Between Bare Overhead Conductors (feet) (3)</th>
<th>Minimum Between Bare Overhead Conductors and Roadways Inside Substation Enclosure (meters) (feet) (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>8.3</td>
<td>95</td>
<td>0.178 (7)</td>
<td>0.457 (18)</td>
<td>0.152 (6)</td>
<td>2.44 (8)</td>
<td>6.10 (20)</td>
</tr>
<tr>
<td>14.4</td>
<td>15.5</td>
<td>110</td>
<td>0.305 (12)</td>
<td>0.610 (24)</td>
<td>0.178 (7)</td>
<td>2.74 (9)</td>
<td>6.40 (21)</td>
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<tr>
<td>23</td>
<td>25.8</td>
<td>150</td>
<td>0.361 (15)</td>
<td>0.762 (30)</td>
<td>0.254 (10)</td>
<td>3.05 (10)</td>
<td>6.71 (22)</td>
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<td>34.5</td>
<td>38</td>
<td>200</td>
<td>0.457 (18)</td>
<td>0.914 (35)</td>
<td>0.330 (13)</td>
<td>3.05 (10)</td>
<td>6.71 (22)</td>
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<td>46</td>
<td>48.3</td>
<td>250</td>
<td>0.533 (21)</td>
<td>1.22 (48)</td>
<td>0.432 (17)</td>
<td>3.05 (10)</td>
<td>6.71 (22)</td>
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<tr>
<td>69</td>
<td>72.5</td>
<td>350</td>
<td>0.767 (31)</td>
<td>1.52 (60)</td>
<td>0.635 (25)</td>
<td>3.35 (11)</td>
<td>7.01 (23)</td>
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<td>115</td>
<td>121</td>
<td>550</td>
<td>1.35 (53)</td>
<td>2.13 (84)</td>
<td>1.07 (42)</td>
<td>3.66 (12)</td>
<td>7.62 (25)</td>
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<tr>
<td>136</td>
<td>145</td>
<td>650</td>
<td>1.60 (63)</td>
<td>2.44 (95)</td>
<td>1.27 (50)</td>
<td>3.96 (13)</td>
<td>7.62 (25)</td>
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<tr>
<td>161</td>
<td>169</td>
<td>750</td>
<td>1.83 (72)</td>
<td>2.74 (108)</td>
<td>1.47 (58)</td>
<td>4.27 (14)</td>
<td>7.92 (26)</td>
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<tr>
<td>230</td>
<td>242</td>
<td>900</td>
<td>2.26 (89)</td>
<td>3.35 (132)</td>
<td>1.80 (71)</td>
<td>4.57 (15)</td>
<td>8.23 (27)</td>
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<tr>
<td>230</td>
<td>242</td>
<td>1050</td>
<td>2.67 (105)</td>
<td>3.96 (156)</td>
<td>2.11 (83)</td>
<td>4.88 (16)</td>
<td>8.53 (28)</td>
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<tr>
<td>345</td>
<td>362</td>
<td>1050</td>
<td>2.67 (105)</td>
<td>3.96 (156)</td>
<td>2.13 (84)</td>
<td>4.88 (16)</td>
<td>8.53 (28)</td>
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<tr>
<td>345</td>
<td>362</td>
<td>1300</td>
<td>3.02 (119)</td>
<td>4.43 (174)</td>
<td>2.64 (104)</td>
<td>5.49 (18)</td>
<td>9.14 (30)</td>
</tr>
</tbody>
</table>

Notes:

1. Values listed are for altitudes of 1000 meters (3300 feet) or less. For higher altitudes, the altitude correction factors listed in Table 4-3 should be applied.
2. This is the minimum clearance from the top of structure, equipment, or apparatus foundation to energized conductors.
3. In no cases should the clearance from the top of a foundation to the bottom of equipment bushings or insulators of energized equipment or apparatus be less than 2.44 meters (8 feet).
4. This dimension indicates the clearance required for truck traffic under the overhead line while maintaining ground clearance.

---

TABLE 4-3

Substation Insulators
### TABLE 4-3

Substation Insulators

<table>
<thead>
<tr>
<th>Nominal System Voltage (kV)</th>
<th>Apparatus Insulator BIL (Impulse Withstand) (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>95</td>
</tr>
<tr>
<td>14.4</td>
<td>110</td>
</tr>
<tr>
<td>23</td>
<td>150</td>
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<tr>
<td>345</td>
<td>1050</td>
</tr>
<tr>
<td>345</td>
<td>1300</td>
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</tbody>
</table>

Table 4-3: Insulator BIL Ratings for Nominal System Voltages

| Regulatory Permits |
### TABLE 5-1

**Regulatory Permits**

<table>
<thead>
<tr>
<th>Regulation/Permit</th>
<th>Agency</th>
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<tbody>
<tr>
<td><strong>Federal</strong></td>
<td></td>
</tr>
<tr>
<td>Section 404 Wetland Permit</td>
<td>U.S. Army Corps of Engineers (USACE)</td>
</tr>
<tr>
<td>Endangered Species Act</td>
<td>U.S. Fish and Wildlife Service (USFWS)</td>
</tr>
<tr>
<td>FAA Notifications</td>
<td>Federal Aviation Administration (FAA)</td>
</tr>
<tr>
<td><strong>State</strong></td>
<td></td>
</tr>
<tr>
<td>Environmental Assessment Review</td>
<td>Pollution Control Agency (PCA)</td>
</tr>
<tr>
<td>Section 401 Water Quality Certification</td>
<td>Pollution Control Agency (PCA)</td>
</tr>
<tr>
<td>Public Water Work Permit</td>
<td>Department of Natural Resources (DNR)</td>
</tr>
<tr>
<td>Wetland Conservation Act</td>
<td>Local Natural Resource Conservation Service (NRCS)</td>
</tr>
<tr>
<td>NPDES Storm Water Permit</td>
<td>Pollution Control Agency (PCA)</td>
</tr>
<tr>
<td>Conservation Reserve Program</td>
<td>Local Natural Resource Conservation Service (NRCS)</td>
</tr>
<tr>
<td>Endangered Species Act</td>
<td>Department of Natural Resources (DNR)</td>
</tr>
<tr>
<td>National Historic Preservation Act</td>
<td>State Historic Society (SHS) / State Historic Preservation Officer (SHPO)</td>
</tr>
<tr>
<td>License to Cross Public Waters</td>
<td>Department of Natural Resources (DNR)</td>
</tr>
<tr>
<td>Utility Permit</td>
<td>Department of Transportation (DOT)</td>
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<tr>
<td>Wildlife Diversity Program</td>
<td>Game and Fish Protection (GFP)</td>
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<td><strong>Local</strong></td>
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<tr>
<td>Road Crossing Permits</td>
<td>County</td>
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<tr>
<td>Building Permits</td>
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<td>Driveway/Access Permits</td>
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<tr>
<td>Drainage Ditch/Tile</td>
<td>County</td>
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Table 5-1: Regulatory Permits

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