

SUBSTATION FUNDAMENTALS

Part 5 Main Components

Module 1

Substation Design, Slobodnik 2025

Part 5 - Main Components Outline



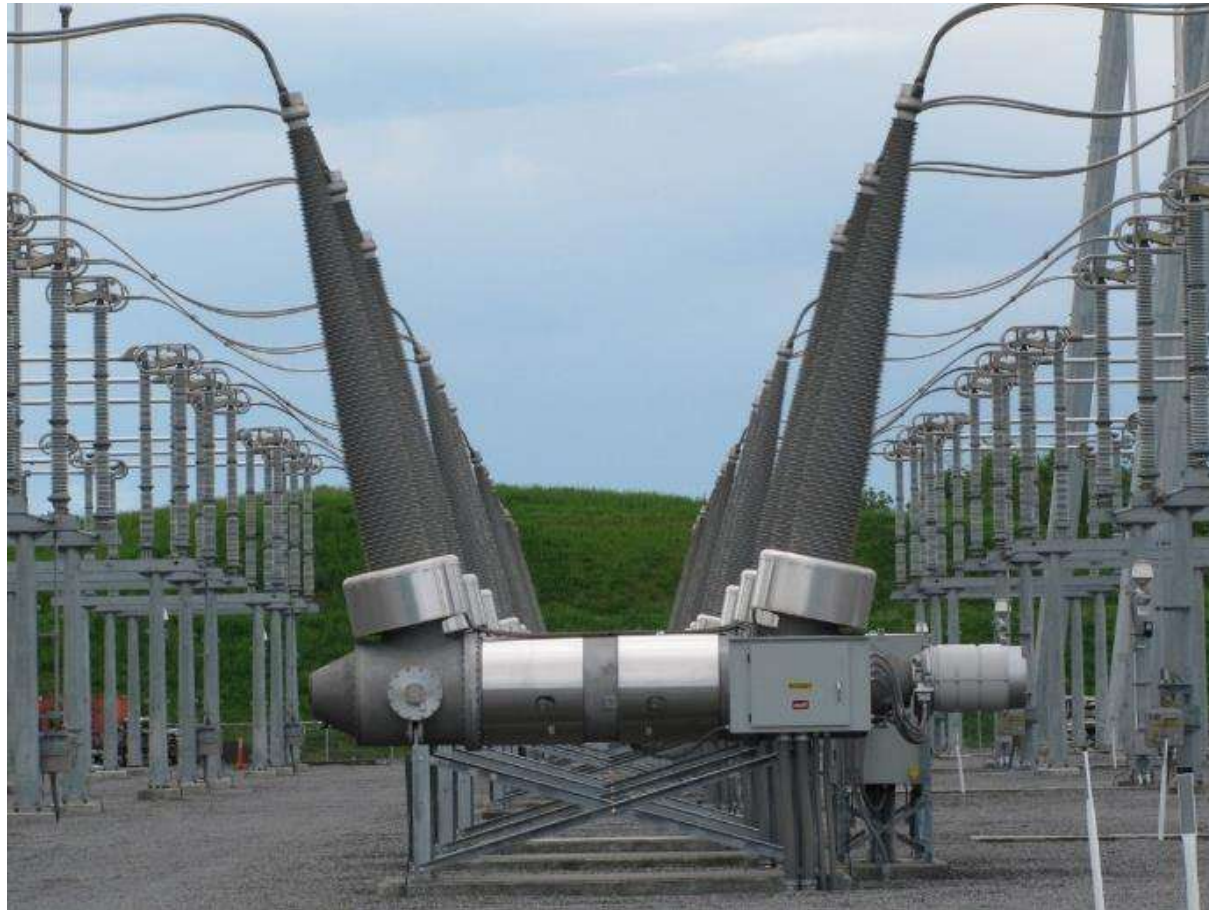
Module 1

1. Transformers
2. Circuit Breakers
3. Disconnectors and Earth Switches
4. Metal Enclosed & Metal Clad Switchgear

Module 2

1. Bushings
2. Instrument Transformers
3. Surge Arresters
4. Miscellaneous Plant (line traps, resistors, corona rings, etc.)
5. Capacitors
6. Reactors
7. FACTS Compensation Equipment

Part 5 - Main Components Module 1



Transformers



General Information

- Function: 1) step-up or step-down voltage;
2) isolation; or 3) phase shifting
- Winding Configurations: two-windings; tertiary winding; auto
- Winding Connections: Δ or Y or grounded Y
- Core Configurations: 1) core form, or 2) shell form
- Insulation Types: 1) liquid-immersed, or 2) dry
- Voltage Regulation: load or no-load winding tap changers
- Cooling: natural & forced convection; air (fan); water (pump)
- Largest, heaviest most expensive substation component
- Not an off-the-shelf commodity
- Must be custom specified, designed and manufactured
- Longest lead time; several months (and up to 2 years for EHV)

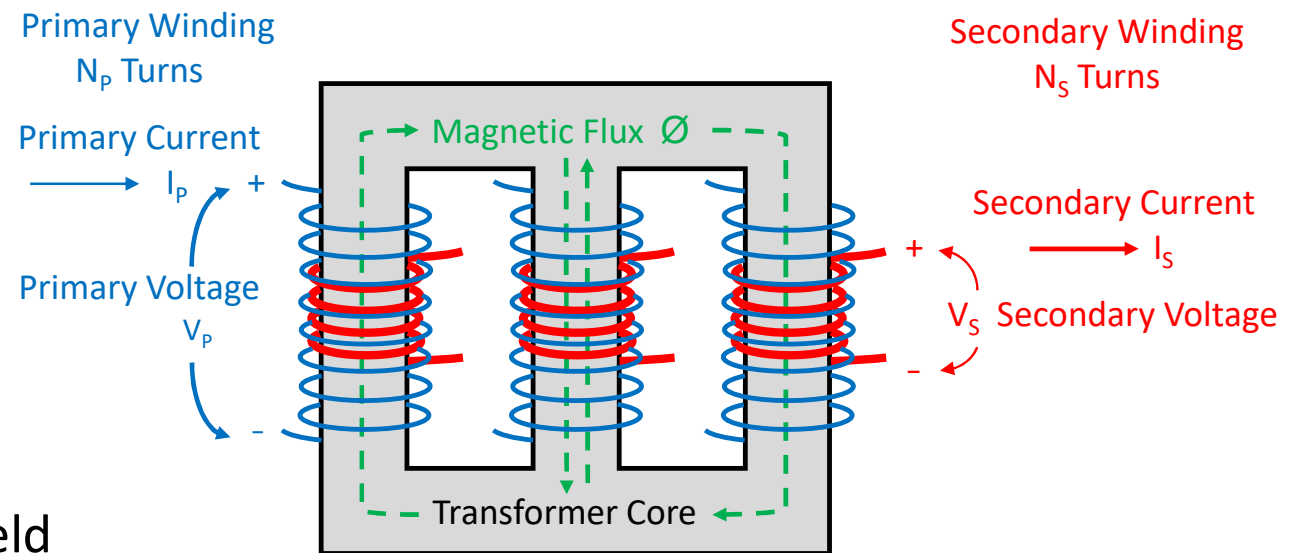


References: IEEE - ANSI C57.12 "Liquid Immersed Power, Distribution & Regulating Transformers Standards"
IEC 60076 "Power Transformer Standard" AS C61 "Australian Transformer Standard"
NEMA Standard TR 1 "Transformers, Step Voltage Regulators and Reactors"

Transformers

Operating Principles

- each phase has two coils that are electrically separate but magnetically linked through the core
- voltage source injects current through primary coil
- alternating current generates alternating electromagnetic field
- mutual inductance between two coils linked by a common magnetic flux generates voltage in secondary coil



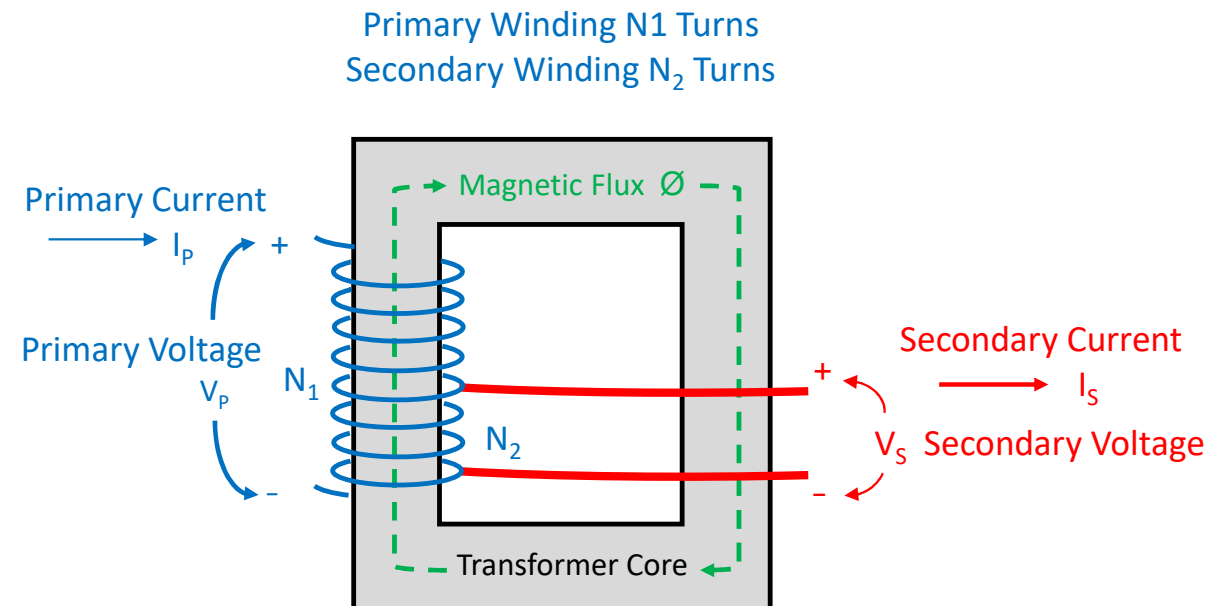
3 phase, 3 legged, core type transformer

$$N_p / N_s = V_p / V_s = I_s / I_p$$

Transformers

Auto Transformer

- a transformer with only one winding per phase acting alone
- portions of the same winding act as both the primary winding and secondary winding of the transformer
- voltage source injects current through the single coil
- taps in that coil at the appropriate point provides the required voltage in secondary circuit



single phase auto transformer

$$K = N_2 / N_1 = V_s / V_p = I_p / I_s$$

Transformers



Thermal Ratings: present a key problem but also opportunities

- A transformer is part of a circuit having a designed rating.
- Expressed in MVA for each stage of cooling (e.g., 12/16/20 MVA)
- Rating depends on manufacturer's core, conductor, insulation and cooling designs.
- Required ratings are specified by planning engineers based on system studies.
- The designer then works to this current level such that it produces either:
 - (1) 98°C hottest spot when the ambient temperature is 20°C (IEC) or
 - (2) 110°C hottest spot when the ambient temperature is 30°C (IEEE) *
- To achieve an adequate service life, while operating, this rated current should not produce a hot spot temperature exceeding the designed maximum.
- **But the ambient is rarely 20 or 30°C - so what happens then?**
- In hotter times/locations the ambient may be above 20/30°C and so applying rated current can lead to temperatures above 98°/110°C and lead to a shorter life.

* Note: specifying the use of thermally upgraded Kraft paper

Transformers



Thermal Ratings (continued)

- **TEMPERATURE** is the dominant factor affecting ageing of winding insulating paper.
- Exceeding hot spot temperatures results in paper embrittlement and degradation.
- If the load current produces a temperature 6°C higher than the rated hottest spot, then life will halve. Equally at 6°C lower, it would double.
- Thus running at full load when the temperatures are high shorten transformer life.
- **So load and ambient temperatures need to be managed by trained engineers:**
 - use of two network transformers in parallel to achieve N-1 shared load (e.g., under normal conditions, even with fans not running they will run at 70°C hotspot should not show paper ageing; if one fails the other can be run taking all the load but with fans on and yet still keep the hotspot below $98/110^{\circ}\text{C}$)
 - use of three seasonal ratings (winter, summer and spring - autumn) with ambients redefined at $10/20/10^{\circ}\text{C}$ and so enabling higher ratings in colder winter months
 - use of intelligence built into a substation can allow dynamic ratings using actual ambients to identify opportunities to overload safely

Transformers

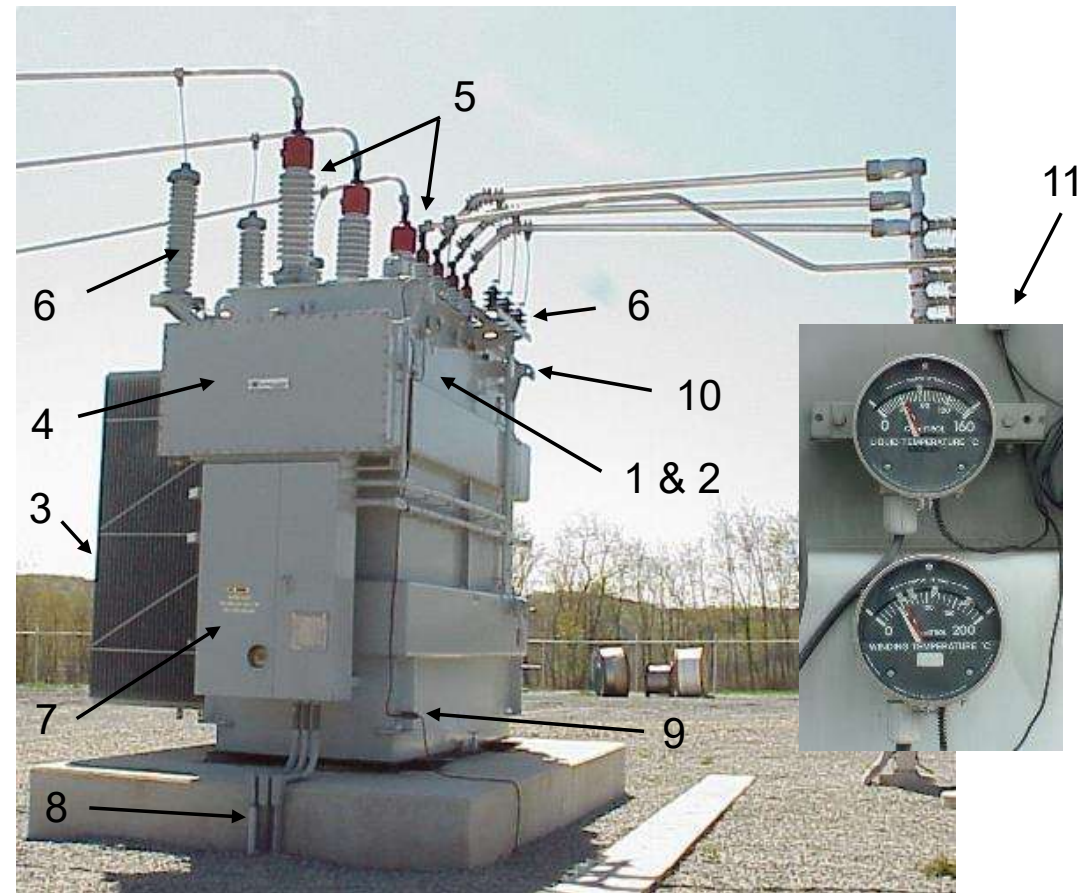
Percent Impedance (% Z) Rating

- Definition: voltage drop at full load due to the winding resistance and leakage reactance expressed as a percentage of the rated voltage.
- It indicates the % of the normal terminal voltage at one side required to circulate full load current under symmetrical short circuit conditions on other side.
 - Example: For a 480 V rated primary, if 9.6 V causes secondary full load current to flow through the shorted secondary, the transformer impedance is $(9.6\text{V}/480\text{V}) \times 100 = 0.02 \times 100 = 2\% Z$
- The impedance of a transformer reflects the resistance of the transformer to the flow of electrical current.
- It has a major effect on system fault levels, and determines the maximum value of current that will flow under fault conditions. $I_{SC} = (I_{FL} / \% Z) \times 100$
 - Low % Z has higher short circuit current and forces requiring bracing to withstand mechanical damage
 - High % Z has lower short circuit forces, but has higher losses and poor regulation and system stability

Transformers

External Components

1. Three Phase Steel Tank
2. Mineral Oil Insulation
3. Cooling Radiators
4. LV Load Tap Changer
5. Bushings
6. Surge Arresters
7. Control Cabinet
8. Control Cables
9. Grounding Bar or Pad, or Earthing Point (two provided)
10. Lifting Lug
11. Gauges

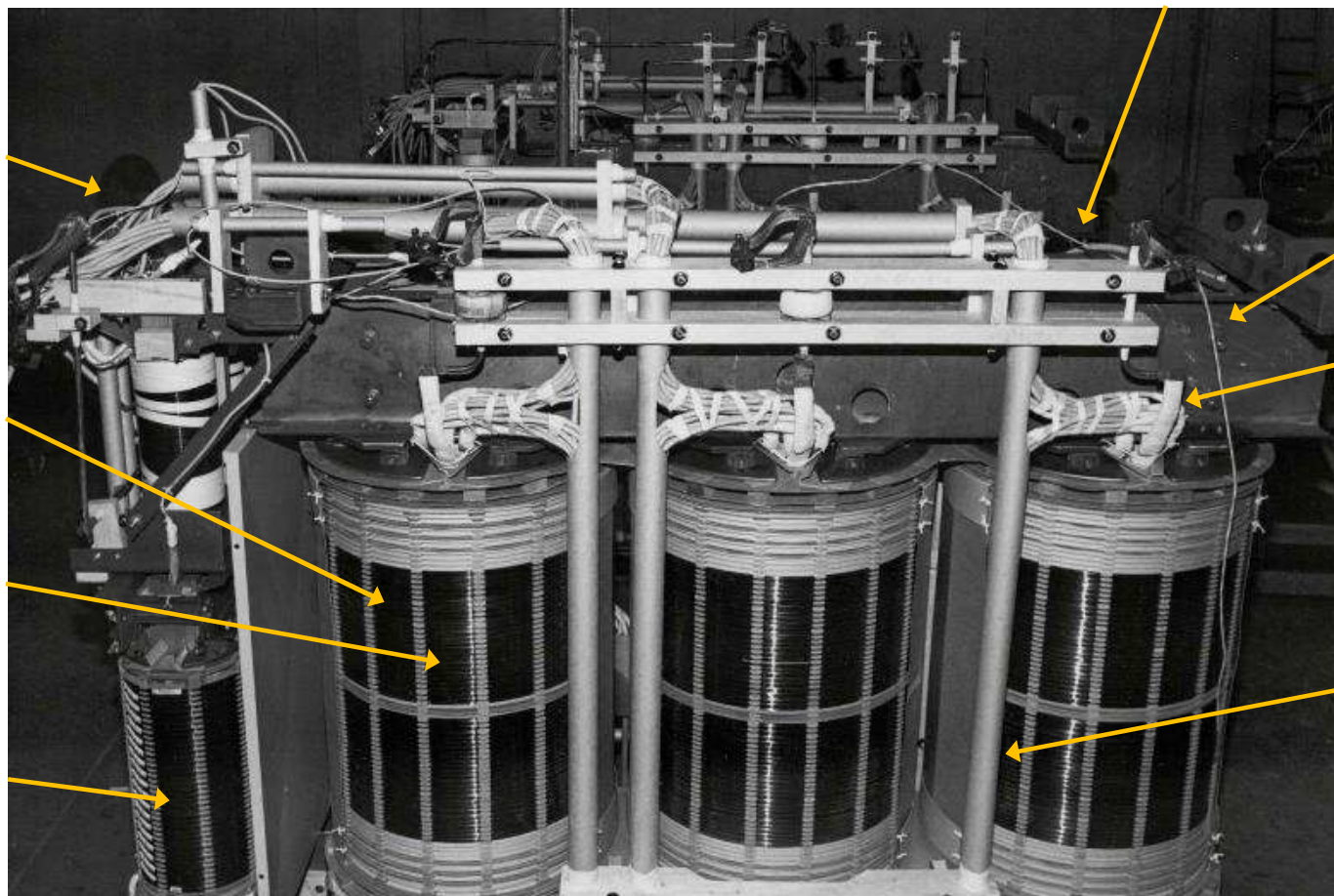


138-13.09 kV, 12/16/20 MVA LTC Transformer

Transformers

Internal Components

High Voltage (HV) No Load Tap Changer (NLTC)
or De-energized Tap Changer (DETC)
at rear of assembly



Low Voltage (LV) Leads to
Load Tap Changer (LTC)
also called On-Load Tap Changer (OLTC)
*Note: the OLTC may be on the
HV side in some regions.*

Copper Windings:
HV Winding concentrically
wound around LV Winding
(best coupling of magnetic fields)

Laminated Silicon Steel Core
(*not visible; surrounded by
LV & HV windings*)

Series Transformer
limits LTC current

Structural
Coil Bracing

LV Leads paper
wrapped

Lead Support
Tubes of cellulose
pressboard

Transformers

Tank Configuration

Three Phase Tank:

- most prevalent; less costly equipment and installation
- restrictive transportation for largest units
- failure results in loss of complete unit; must maintain a fleet of emergency spare units; adds operating cost

Single Phase Tank:

- more costly equipment and installation; also more bus and space required
- more reliable due to isolating failure damage to one unit
- easier and less costly to replace single failed unit
- option to install a 4th unit to connect quickly as a spare in emergency (either moved into place or installed with bus work, switches and controls for quick replacement)



Transformers

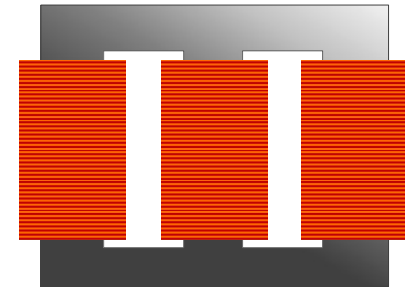
Basic Design Types of Construction

Core Type or Form:

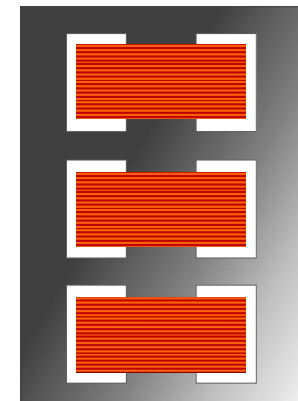
- concentric or cylindrical winding
- windings wound outside and surround the core
- more copper and insulation required; more losses
- lower mechanical strength
- lower output

Shell Type or Form:

- sandwich or disc winding on the central limb
- core surround the windings, which are inside the magnetic circuit (core) that forms a shell around the windings
- less copper and insulation required; less losses
- higher mechanical strength; less prone to damage by through fault
- higher output



3 Phase Core Type

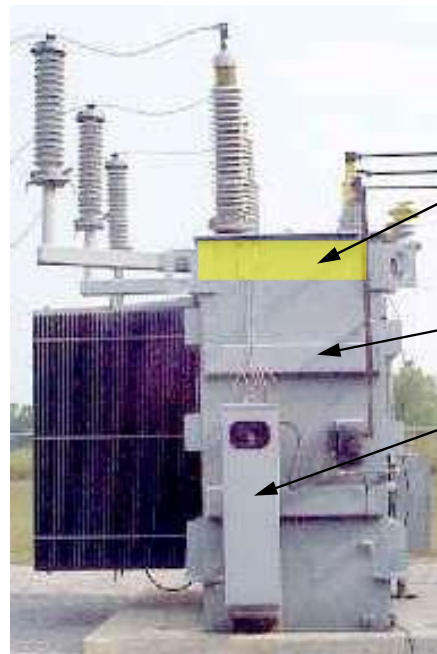


3 Phase Shell Type

Transformers

Oil Preservation Sealing System

- Gas Blanket: top of sealed tank is filled with dry nitrogen (about 10% of tank volume) providing expansion space for changes in oil volume with temperature
- Conservator Tank: separate oil reservoir tank above transformer tank captures the increased oil volume as it expands when temperature increases



N₂ gas space; pressure approx. 0.7 - 1 bar (10-15 psig)

insulating & cooling fluid (refined mineral oil)

Positive Pressure Type: has N₂ supplied from high pressure gas tank with regulator



air in compressible bladder with breather to atmosphere; some have direct contact between oil and air; venting is through moisture drying desiccant

conservator tank or make-up oil reservoir tank

Transformers

Cooling Systems

- Radiators, fans, pumps, coolers (using pumps and fans), water, deflectors; cooling can be in single or multiple stages
- Four Letter Cooling Coding Class

Internal		External	
medium	mechanism	medium	mechanism
1	2	3	4



- **Internal** (inside tank) code letters
 - First letter (Cooling Medium):
 - O = Liquid with flash point ≤ 300 °C
 - L = Liquid with flash point > 300 °C
 - Second letter (Cooling Mechanism):
 - N = Natural convection
 - F = Forced circulation
 - D = Directed flow in main winding
- **External** (outside tank) code letters
 - Third letter (Cooling Medium):
 - A = Air
 - W = Water
 - Fourth letter (Cooling Medium):
 - N = Natural convection
 - F = Forced circulation
- Also dry type transformers are used in certain smaller power applications

Voltage Regulators

Alternate to Load Tap Changers

Voltage Regulator:

- Operation: a liquid-filled autotransformer with multiple winding taps and a built-in load tap changing mechanism to switch taps to raise or lower voltage around a neutral point
- Configuration: single phase; with three bushings (one for the source/input, one for load/output, and one for the neutral)
- Control: microprocessor-based multi-function controller mounted in cabinet on each regulator; derives system reference voltage from internal VT
- Application: at distribution voltages as follows: 1) three phase set used on transformer leads, or 2) one set used on each terminal



Transformers

Standards

- Industry standards provide information for design, manufacturing, testing and operating/loading transformers (*as well as for other major components*)
- Examples below (ANSI/NEMA Standard C57.12) show MVA and insulation criteria
- Also see IEC 60076 “Power transformers”

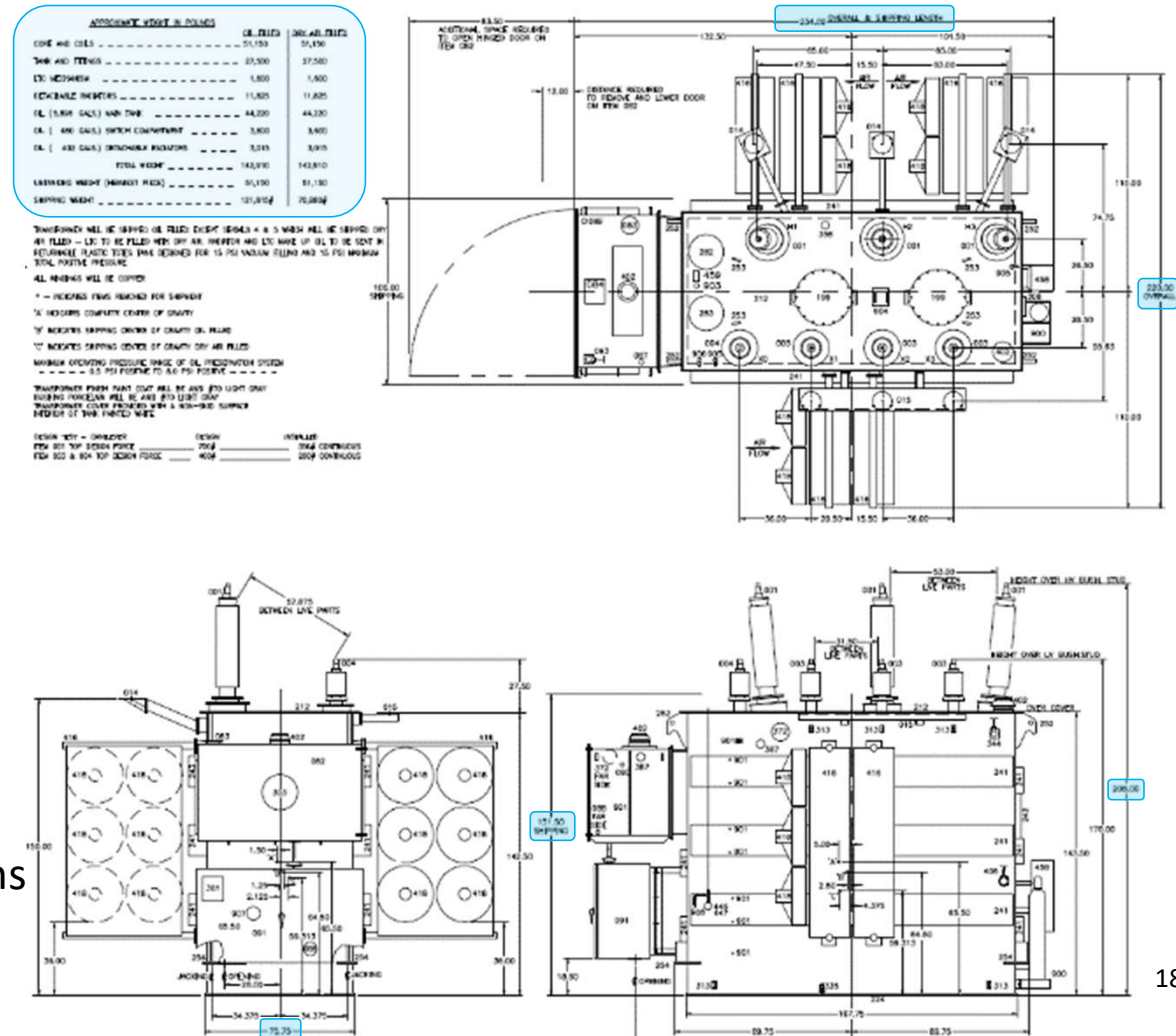
Table 6—Range of Voltage and Kilovolt-Ampere Ratings for Three-Phase Transformers With, or Without, Load Tap Changing 12 000-60 000 kVA						
High voltage Ratings (V)	Low-Voltage Ratings (V)					
	6900,7200,7560,					
	12 470Y/7200,					
	4800,5040,	13 090Y/7560,	12 000,12 600,	34 500,		
	8320Y/4800,	13 200 Y/7620,	13 200,13 800,	34 500GrdY/19 920,		
	8720Y/5040	13 800Y/7970	14 400	24 940GrdY/14 400	36 230GrdY/20 920	
Self-Cooled (OA) Kilovolt-Ampere Ratings (kVA)						
23 000	12 000-15 000	12 000-30 000	—	—	—	
34 500	12 000-15 000	12 000-30 000	12 000-30 000	—	—	
46 000	12 000-15 000	12 000-30 000	12 000-30 000	—	—	
69 000	12 000-15 000	12 000-30 000	12 000-30 000	—	—	
115 000	12 000-15 000	12 000-60 000	12 000-60 000	12 000-60 000	12 000-60 000	
138 000	12 000-15 000	12 000-60 000	12 000-60 000	12 000-60 000	12 000-60 000	

Table 6—Dielectric insulation levels for Class II power transformers ^a						
Nominal system voltage (kV)	Basic lightning impulse insulation level (BIL) (kV crest)	Chopped wave level (kV crest)	Switching impulse level (BSL) (kV crest)	Low frequency test levels		
				Induced-voltage test (phase to ground)		Applied-voltage test level (kV rms)
				One hour level (kV rms)	Enhancement level (kV rms)	
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
15 and below	110	120	—	—	—	34
25	150	165	—	—	—	50
34.5	200	220	—	—	—	70
46	250	275	—	—	—	95
69	250	275	—	—	—	95
	350	385	—	—	—	140
115	350	385	280	105	120	140
	450	495	375	105	120	185
	550	605	460	105	120	230
138	450	495	375	125	145	185
	550	605	460	125	145	230
	650	715	540	125	145	275

Transformers

Design Details

- Transformer manufacturer's **outline** drawing has required design information for the:
 - bushing connectors
 - grounding connectors
 - cable location
 - dimensions for electrical and working clearances
 - foundation design
 - oil containment
- This information is also needed for shipping and handling:
 - road, bridge and tunnel restrictions
 - crane capacity for lifting

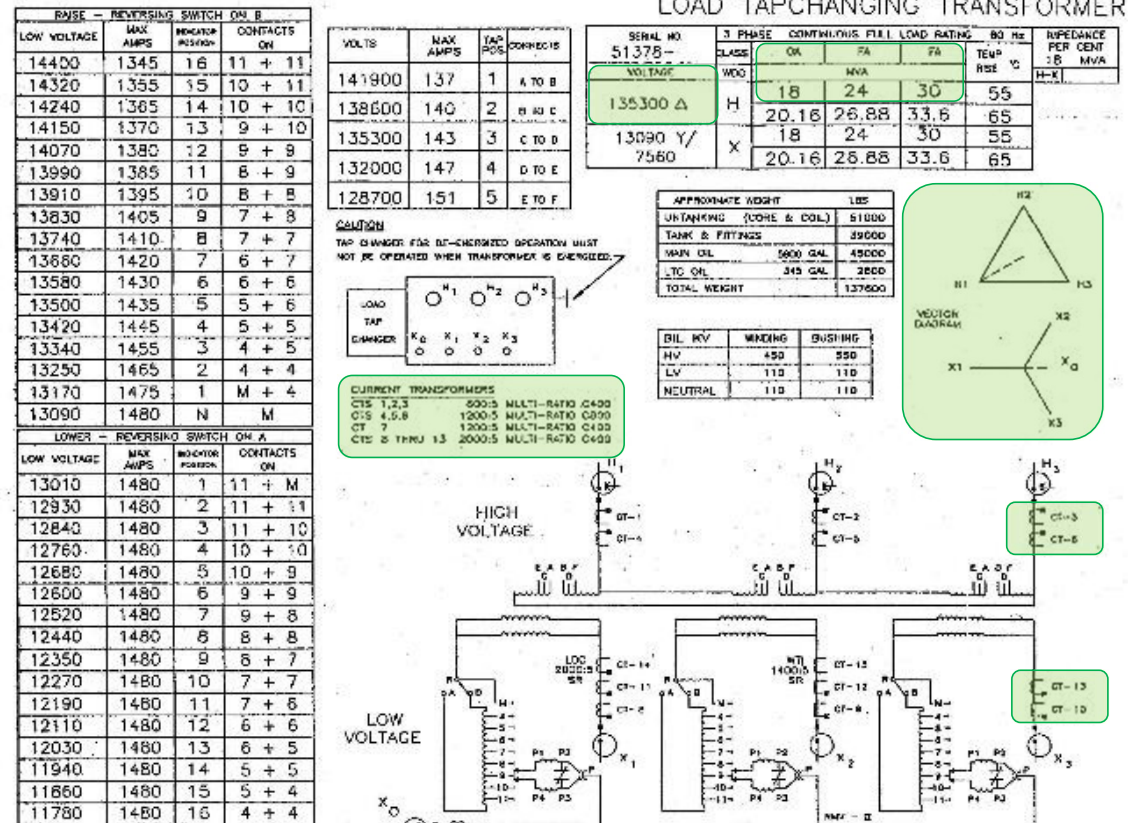


Transformers



Design Details

- Transformer manufacturer's **name plate** or **rating plate** drawing has required design information for the:
 - single line diagram
 - phasing diagram
 - type of winding connections
 - vector diagram
 - standard bushing orientation
 - CT layout (ratio & stacking)
 - voltage regulation steps
 - model and serial numbers for specific unit identification



LIQUID LEVEL 10.5 INCHES BELOW TOP OF MANHOLE FLANGE AT 25°C.
LIQUID LEVEL CHANGES BY .8 INCHES PER 10°C CHANGE IN TEMPERATURE.
OPERATING PRESSURE RANGE OF OIL PRESERVATION SYSTEM 0.5 PSI POSITIVE TO 5.0 PSI POSITIVE.
THIS TRANSFORMER WAS FILLED & PROCESSED IN THE FACTORY WITH NON-PCB DIELECTRIC FLUID IN ACCORDANCE WITH FEDERAL PCB REGULATION 40 CFR CURRENT AT DATE OF MANUFACTURE.

TRANSFORMER FILLED WITH UNHINCHED OIL.
TANK DESIGNED FOR FULL VACUUM FILLING
& 15 PSI MAX. POSITIVE PRESSURE.

Transformers



Specification should include (ratings based on planned load and fault studies):

- Nominal and maximum voltage for primary, secondary, tertiary windings
- Step-down or step-up operation
- BIL/BSL (LIWL/SIWL) of all windings and of all bushings (i.e. internal vs. external ratings)
- MVA capacity and any special loading characteristics (e.g. emergency loading and durations)
- Percent Impedance
- Winding connections (Δ or Y) and grounding provisions
- Regulation: tap changers, types, ranges and steps; load or no-load requirements
- CT requirements ratings, ratios, accuracy, quantities, stacking order
- Loss requirements and evaluating criteria (core or no load or iron loss; copper or load loss; auxiliary losses)
- Cooling class, max. temperature rise, max. ambient temperature, temperature gauges
- Bushings: types, material, color, locations and any elevation de-rating
- Sound level requirements (standard vs. low noise vs. extra low noise)
- Materials: conductors; core steel; tank (sealing, paint, corrosion-resistance, color)
- Environmental conditions: indoor vs. outdoor, altitude, climate, seismic, pollution
- Accessories: arrester brackets, cabinet heater, AC & DC supply voltages, etc.
- Monitoring (dissolved gas, moisture), gauges, alarm, relaying, and instrumentation requirements
- Shipping method (road, rail, barge) and constraints (dimensional and weight); FOB (Freight On Board) destination
- Field work: off-load, assembly, processing, testing and/or commissioning
- Warranty, drawings, instruction books, special tools and spare parts
- Reference applicable industry standards and company specifications and any special custom requirements

Electrical

Physical

Auxiliary

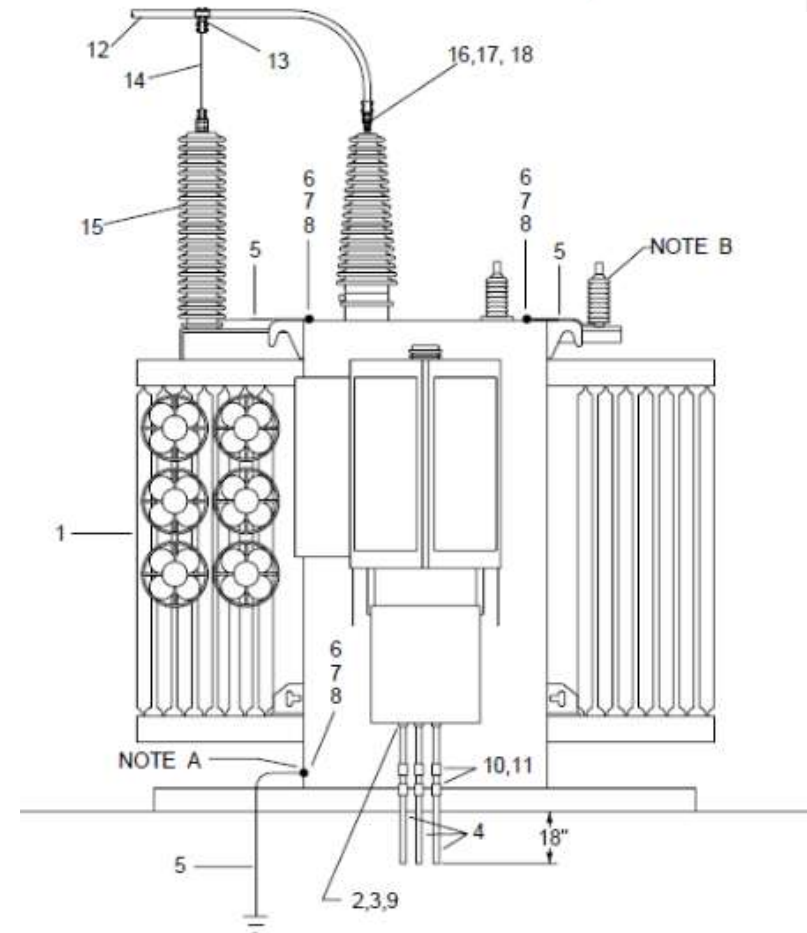
Miscellaneous

Transformers



Final Design

- Use previous details for plan and elevation views, for itemize bill of material, and for all other details (e.g. bus connections, or control cabinet location coordinated with cable layout)
- Good documentation is needed for: bidding, installation, operation, maintenance and designing future related projects
- Finally, as a best-practice, create standard designs in order to benefit from standardization



EXAMPLE
Transformer Standard

Circuit Breakers

General Information

- Main Functions:
 1. to make and carry rated power through a circuit, and to switch and break load under normal conditions
 2. to protect personnel and public from faulted lines or equipment in abnormal situations by clearing the fault
 3. to rapidly clear faults on the network to maintain system security
- Applications: switching and protecting system segments and components (e.g. lines, transformers, capacitors)
- Main Components:
 - Electrical: interrupting assembly, bushings and insulation
 - Mechanical: operating mechanism and linkage
 - Insulating and Interrupting Mediums: SF₆ gas, vacuum and oil
 - Control: devices to operate the breaker (coils, auxiliary contacts, switches)



Initiates Operation

Control



References: IEEE ANSI C37 "Power Switchgear, Circuits & Fuses Standards" collection

IEC 62271-100 "High-Voltage switchgear and controlgear - Alternating-current circuit-breakers"

IEEE C76 "Standard Requirements and Test Code for Outdoor Apparatus Bushing"

Circuit Breakers

Operating Principles

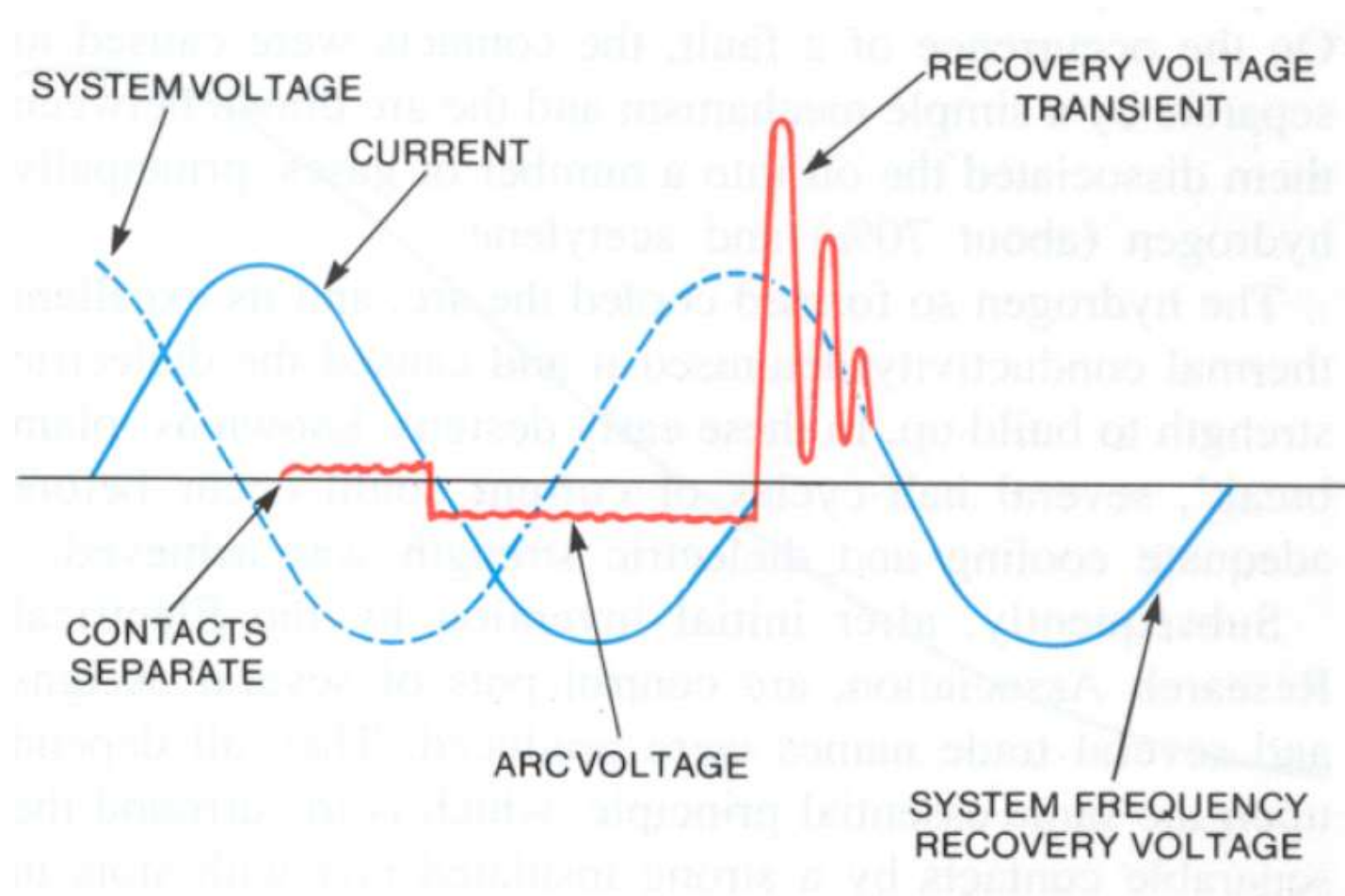
The breaker operates as follows:

- moving and stationary contacts separate to extinguish the arc at current zero
- it commutes arc plasma by removing energy, which is in the form of heat
- it attempts to prevent arc re-ignition (the interrupter must build up dielectric strength faster than the recovery voltage across the gap builds up)
- typical interrupting times: 2 to 8 cycles depending on the age of the breaker

The breaker's ability to interrupt fault current is determined by the:

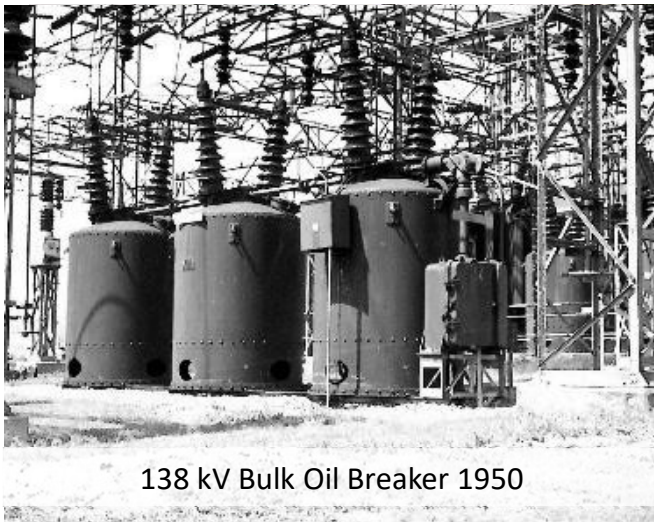
1. Magnitude of the fault current
2. Transient Recovery Voltage (TRV) or the transient voltage that appears across the contacts while interrupting a faulted circuit
3. Rate of Rise of the Recovery Voltage (RRRV) defined as peak TRV divided by the total time from zero voltage to peak voltage; this is the front edge of the TRV across the breaker contacts as it opens after the current goes out

BASIC THEORY OF TRV



Circuit Breakers

Brief evolution of breakers over time



Oil breakers reducing toward optimum sizes.



Oil breakers arriving at minimum size.



EHV breakers using alternates to bulk oil.
Eventually evolving from air blast to SF₆ Gas.

Circuit Breakers

Brief evolution of breakers over time (cont.)



SF₆ gas breakers start to replace oil breakers.
SF₆ gas eventually replace oil technology.



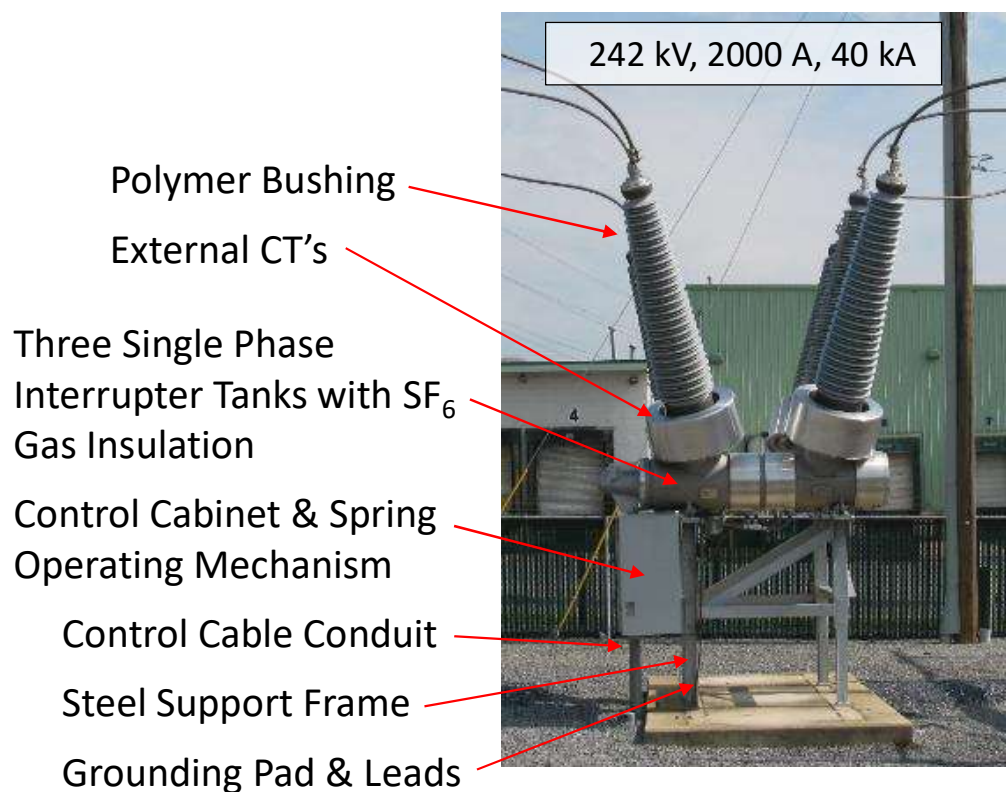
SF₆ gas breakers reach state-of-the-art.
Currently considered the industry norm;
used over a range from LV to EHV levels.



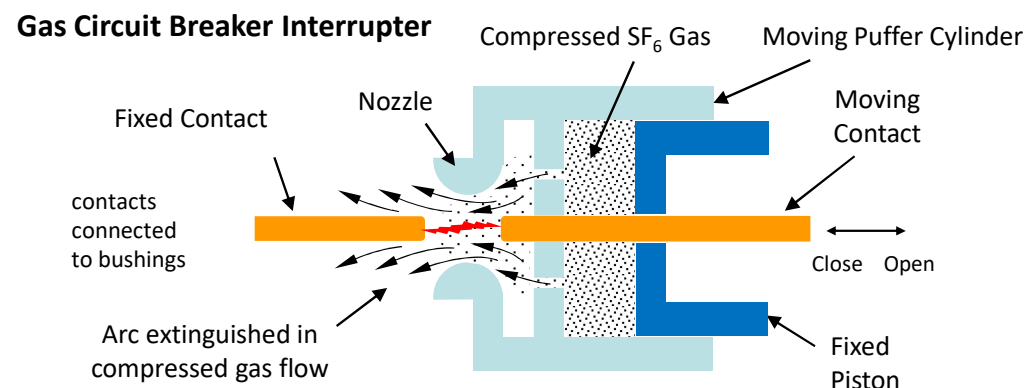
EHV SF₆ gas breakers replacing old air blast technology (background).
Environmental concerns mainly drove the changes along with desire for lower maintenance and the need for manufacturers to supply required ratings.
New environmental concerns with SF₆ as a greenhouse gas are prompting alternate gases. *(Note: topic covered in Part 11 **Trends in Substations.**)*

Circuit Breakers

Gas Circuit Breaker External Components



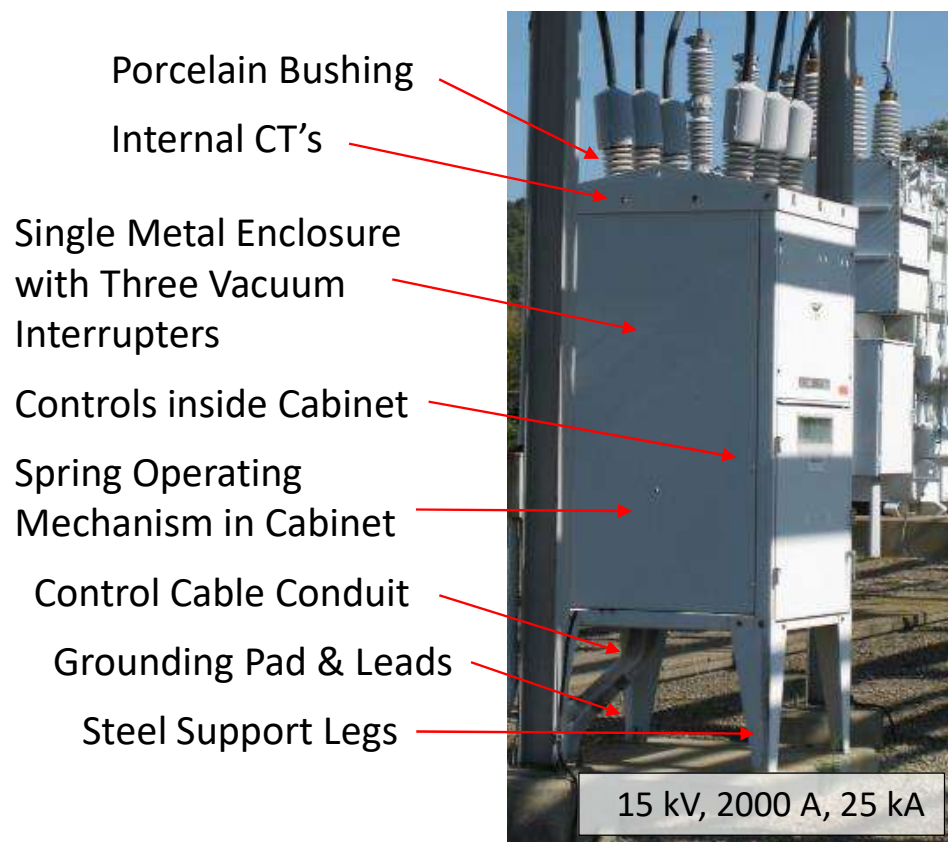
Internal Components



- high contact separation speed (5-10 m/s) ensures dielectric recovery across gap; medium gap (15-20 cm)
 - Single Puffer Technology: moving contact/cylinder develops pressure (50-90 psig or 350-620 kpa) to cool and extinguish arc and replenish dielectric media
 - higher duty breakers have multiple interrupters
 - tank heater needed in cold climate prevents liquefaction
 - environmental concerns: handling gas, leaks, toxic by-products from arcing, and greenhouse gas
- (alternate gas covered in Part 11 Trends in Substations)

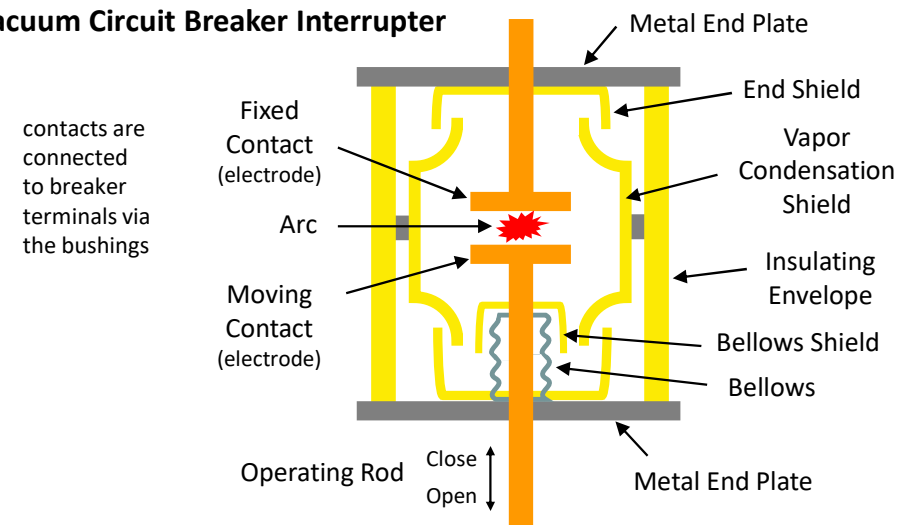
Circuit Breakers

Vacuum Circuit Breaker External Components



Internal Components

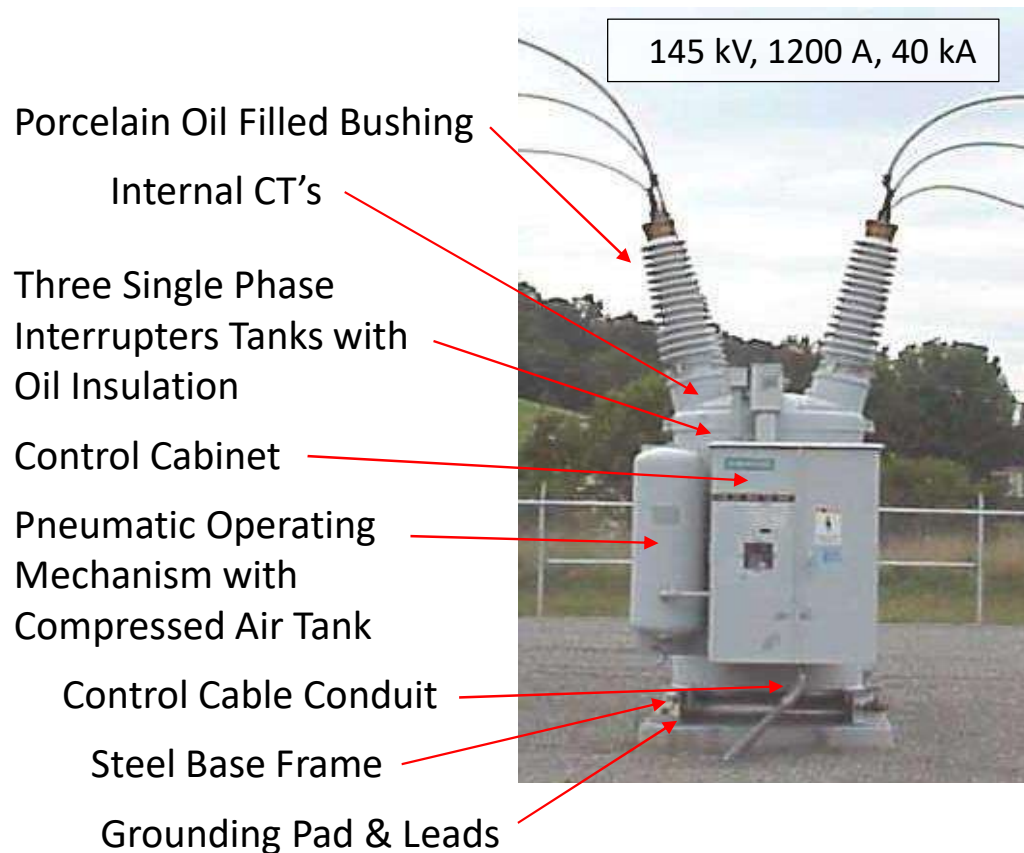
Vacuum Circuit Breaker Interrupter



- arc interruption occurs in vacuum
- ratings: 15 kV to 145 kV
- vacuum bottles in series for higher voltage
- contacts move small distance $2 \text{ cm} \pm (0.75'' \pm)$
- **Caution: high voltage across a small gap can generate x-ray radiation**

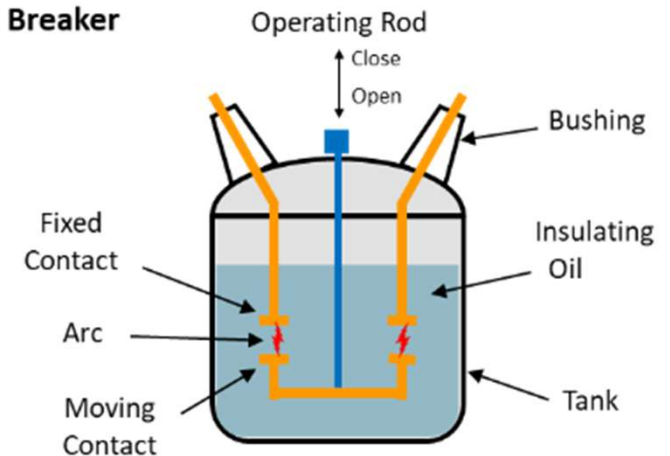
Circuit Breakers

Oil Circuit Breaker External Components



Internal Components

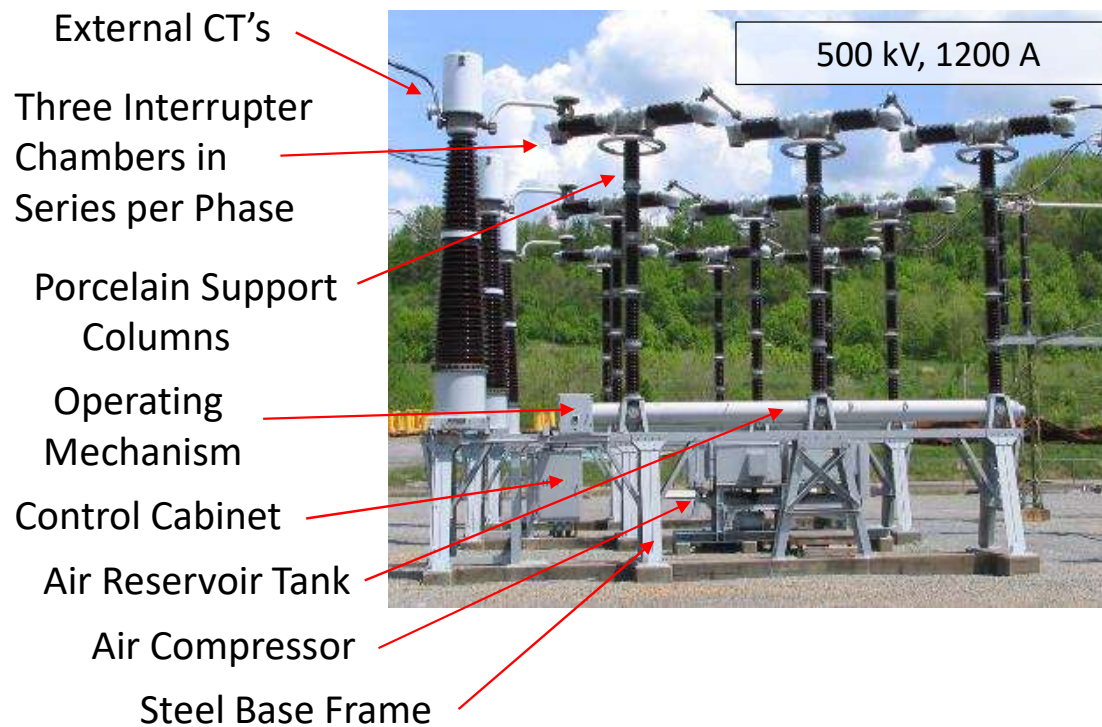
Oil Circuit Breaker



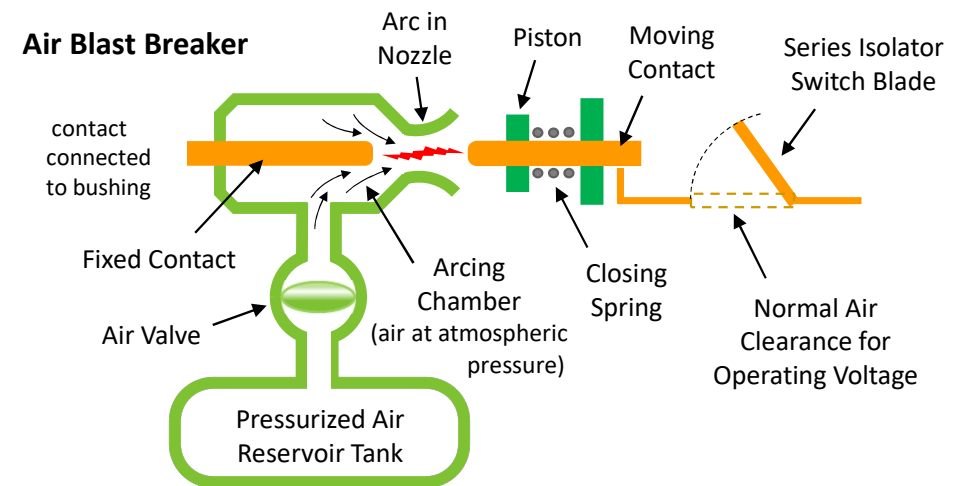
- many legacy oil breakers are still in use today
- oil cools and extinguishes arc to fully establish the dielectric in open gap
- oil flow also disperses the arc by-products
- two interrupters per phase connected by a lift rod that moves the contacts
- larger significant gap distance than gas breakers
- environmental concerns: leaks to waterways, and drinking supplies

Circuit Breakers

Air Blast Breaker External Components



Internal Components



- also a legacy breakers with a few still in use today
- compressed air is the arc interrupting medium
- stored pressurized air is released thru a nozzle
- high-velocity air jet commute the arc into arc splitter chutes which lengthens and extinguishes it
- contacts rapidly move into a small sealed chamber
- very high noise level when operating as high pressure air exhausts to the atmosphere

Circuit Breakers

Dead Tank vs. Live Tank Design

1. Dead Tank: interrupter enclosure tank is at ground potential supported on stand
2. Live Tank: interrupter enclosure tank is at line potential supported on insulators

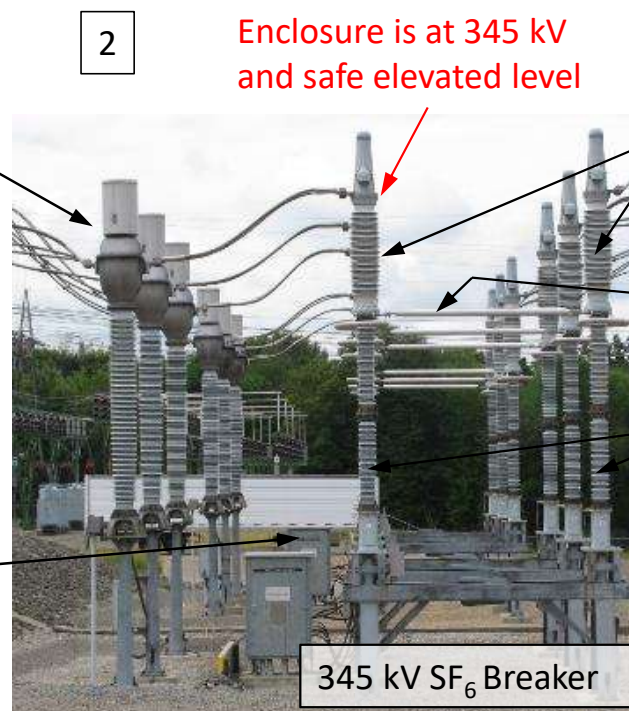


Dead tank breakers use bushing slip-over CT's

Enclosure is at 0 V and ground level

Interrupter in tank supported on steel rack

Mechanism is at low level for both systems



Enclosure is at 345 kV and safe elevated level

Two interrupters in series to give higher interrupting capacity

Connecting bus

Interrupters supported on porcelain insulators; makes higher center of gravity subject to seismic stress

North American/IEEE markets tend to favor dead tank designs while Europe/IEC markets prefer live tank.

Circuit Breakers

Operating Mechanisms: stores energy to open and close breaker.

Protective relay activates solenoid tripping a latch mechanism to release the energy through a rod.

Duty cycle of open-close sequence (e.g. O-C-O-15 seconds-C-O where O=Open and C=Close).



High maintenance due to potential air leaks.



High maintenance due to potential fluid leaks.



Preferred due to simpler, low maintenance design

Circuit Breakers

Basic Design Process

- Project Plan: define device requirements
- Industry Standards: ratings and capabilities for application, design, manufacture and maintenance
- Utilities Specification: for procurement
- Manufacturer Drawings: nameplate, physical outline, controls schematics
- Design Details: checklists, plan and elevation views, bill of material
- Standardization: standard designs for repetitive, economic use



NOTE: consider special capabilities required (e.g., Synchronous Close Breaker with controlled switching when voltage across the breaker contacts is zero to minimize/eliminate switching transients by energizing a capacitor.



Circuit Breakers

Specification should include:

- Nominal and maximum system voltage
- BIL/BSL (LIWL/SIWL) requirements
- Continuous current
- Short circuit interrupting current (for system fault duty); the X/R ratio (for asymmetry fault current)
- Special load characteristics: capacitor, transformer, reactor or long transmission line switching
- CT requirements: ratings, ratios, accuracy, quantities, stacking order
- Clearances: phase spacing and height requirements; pole configuration
- Bushings: types, material, color, creepage, any high elevation de-rating
- Environmental conditions: indoor vs. outdoor, altitude, climate, seismic, pollution
- Materials: conductors (copper or aluminum); tank (steel or aluminum); support stand finish (paint, color)
- Operating mechanism: pneumatic, hydraulic, spring
- AC / DC supply voltages: for control, motors, auxiliaries
- Accessories: bushing, grading capacitors, closing resistors, cabinet heater, tank heaters, synchronized closing, etc.
- Monitoring, relaying, gauges, and instrumentation requirements
- Shipping method (road, rail or barge); constraints (dimensional and weight); FOB (Freight or Free On Board) destination
- Field work: assembly, gas supplied, testing and/or commissioning
- Warranty, drawings, instruction books, special tools and spare parts
- Reference applicable industry standards and company specifications and any special custom requirements

Voltage

Current

Physical

Auxiliary

Miscellaneous

Required ratings based on planned load and fault currents per system studies.

Other requirements based on design, construction, operating and maintenance needs.

Circuit Reclosers



General Information

- Reclosers are similar to breakers in construction and application, but with lighter duty switching and protection capabilities than breakers, and are generally lower cost (typical reclosers are 14.4 to 34.5 kV and 12.5 or 16 kA)
- They are constructed to different standards than breakers
- Reclosers are self-controlled devices with integral control devices (breakers use relays on control panels in control buildings)
- Reclosers are designed with predetermined control capabilities or schemes (breakers permit wider range of permissible values for tripping, delays & reclosing)
- Recloser utilizes an integral closing solenoid mechanism for energy to operate (breakers have external operating mechanisms and linkage)
- Typically used on distribution circuit terminals in substations and are pole mounted for application out on distribution lines as single or three phase devices



Circuit Reclosers

Design Information

The substation design will follow the steps similar to those for breakers:

- required ratings
- selected type or device
- industry standards
- manufacturers drawings
- design drawing & details
- design checklist
- specification

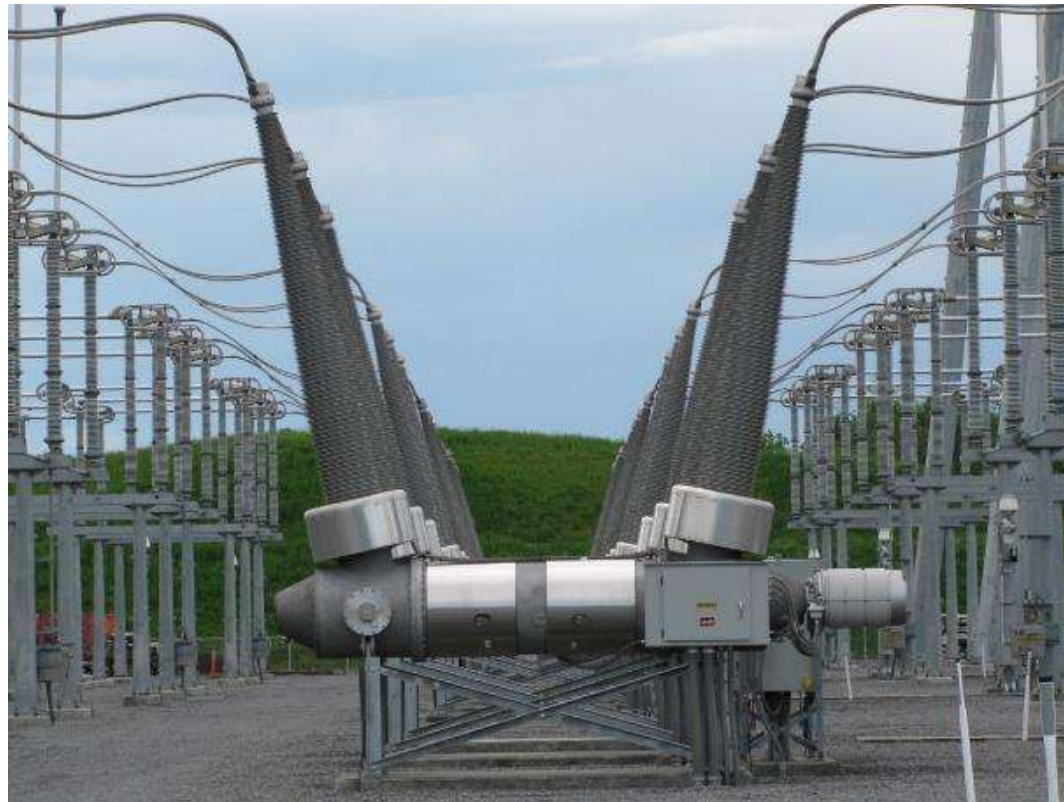
Typical installations



Can be set to operate for
single phase fault clearing

... all of which should be geared toward **standardization**

First Set of Questions

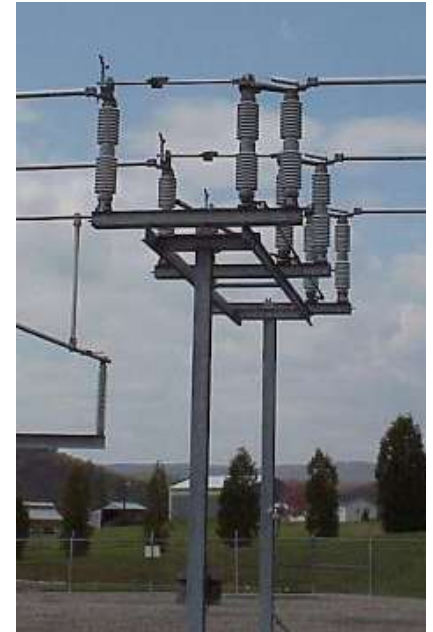


Disconnect, Isolator or Disconnect Switch



General Information

- Definition:
 - Disconnect, Isolator or Disconnect Switch are regional names used for the same mechanical device capable of switching circuits under **negligible** current flow conditions only
 - No-Load Isolator is another term used for a disconnect
 - Off-Circuit Isolator is a term used for a disconnect capable of switching **dead** (non-energized) circuits only
- NOTE: they are not to be confused with the following special purpose switches which will be addressed on other slides:
 - Circuit Interrupter Switch
 - Earthing Switch

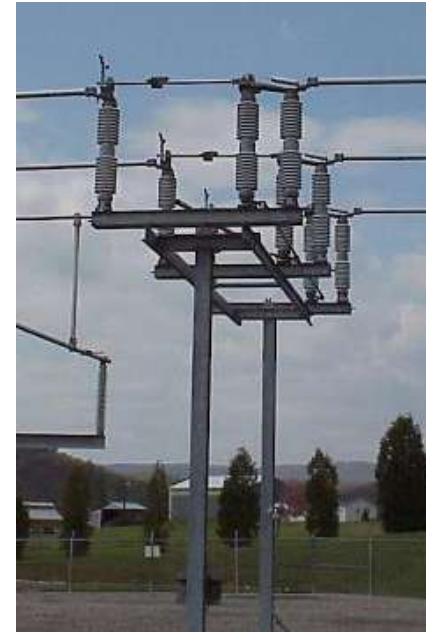


Disconnect, Isolator or Disconnect Switch



General Information (continued)

- Capabilities:
 - When “Closed”, must carry rated normal current continuously and abnormal short-term current flow for a specified time.
 - When “Open”, must provide a visible air gap with isolation distance for rated voltage withstand for safe maintenance by personnel.
 - And to “open” and “close” a circuit under negligible current conditions or when there is no significant voltage change across the terminals of each of its poles.
 - They have very limited current switching capability and are not intended for frequent use or breaking load current; thus must be used in combination with a short circuit interruptions device.

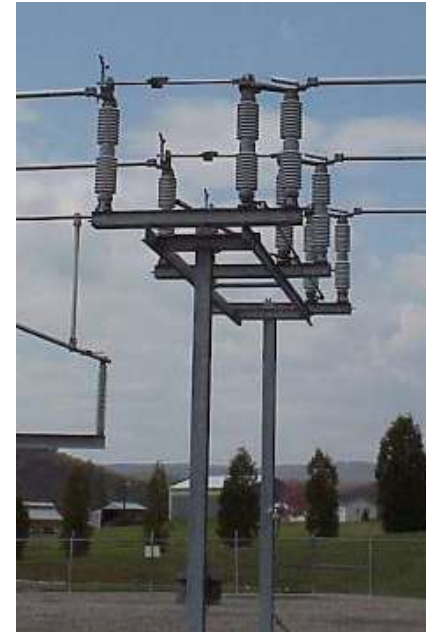


Disconnect, Isolator or Disconnect Switch



General Information (continued)

- Functions:
 - connects and disconnects designated parts of a circuit
 - provides a safe visible air gap opening in a circuit
 - usually not used to interrupt or connect energized circuits
- Typical switch applications:
 - disconnect and isolate breakers, transformers, lines and bus sections for safe inspection or maintenance
 - by-pass a breaker or meter for maintenance
- Operating Types: manual or motorized
- Configurations: 1) single pole or 2) three pole group operated
- Mounting: horizontal; vertical; upright; underhung; inverted; angled

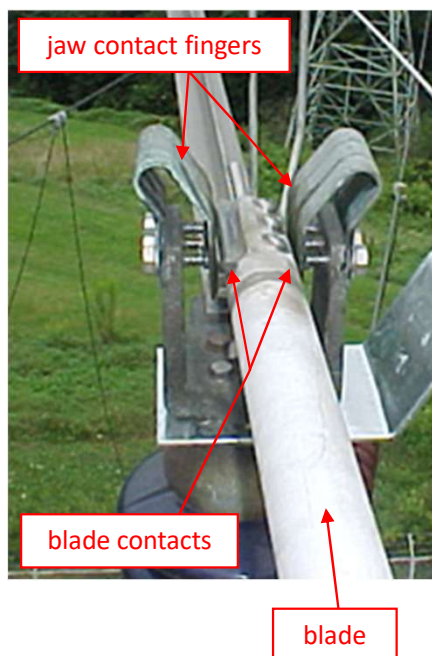


References: IEEE ANSI C37 "Power Switchgear, Circuits & Fuses Standards" collection
IEC 62271-103 "High-voltage switchgear and control gear"

Disconnectors

Operating Principles

- Current is transferred through durable plated contacts on blade to the switch jaw
- Single pole operation: only one pole of three operates at a time
- Three pole operation: all three poles operate simultaneously



Single Pole Operated Switch



Three Pole Operated Switch

Disconnectors

Types of Switches

Hook Stick Disconnect Switch

- single phase or pole unit
- each phase operated independently (not ganged via mechanical linkage)
- manually operated using a hot-stick tool
- no load or fault interrupting capability
- used only for isolating equipment and providing visible opening with an air gap
- typical ratings:
 - 7.5 kV to 69 kV nominal
 - 600 A to 4000 A continuous



15 kV 600 A Recloser Disconnects three single pole switches

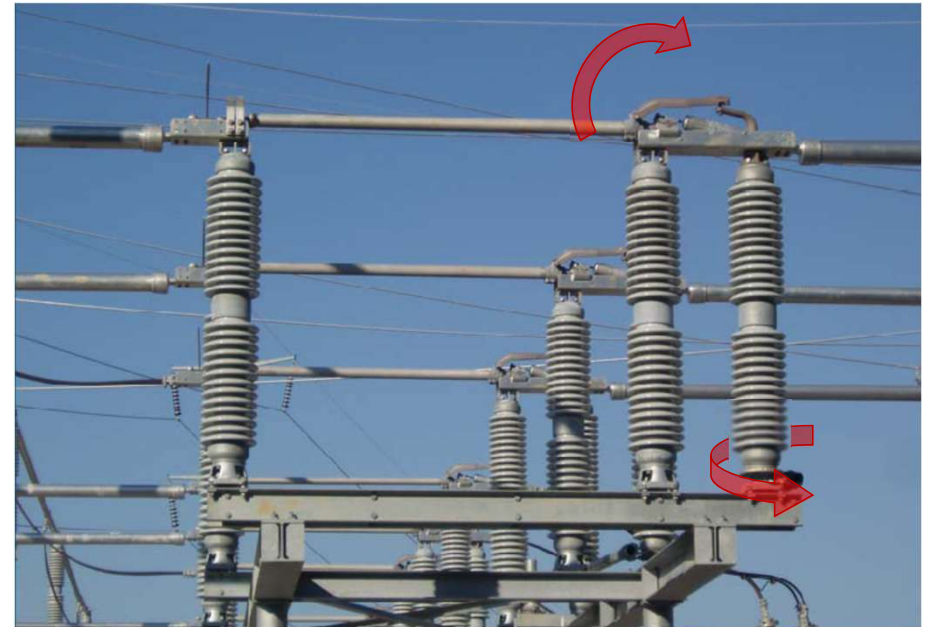
Operated by inserting a hot- or hook-stick tool in ring on blade and manually pulled open. Essential to provide adequate, safe space for hook-stick operator to reach and pull the blade.

Disconnectors

Types of Switches (cont.)

Group Operated Disconnect Switch

- three phase group or ganged operated (all phases linked and operate together)
- no load interrupting capability
- no fault interrupting capability
- used only for isolating equipment and providing a visible opening via an air gap
- typical ratings:
 - 7.5 kV to 800 kV nominal
 - 600 A to 4000 A continuous
- Note: good safety practice is to orient the switch so that the blade is de-energized in the open position, if possible



138 kV 1200 A Vertical Break Switch
upright mounted on double galvanized steel channels

Operating mechanism rotates linking rods to rotate insulator which turns pivot arm pulling blade upward around its hinge point (assisted by a counterbalance).

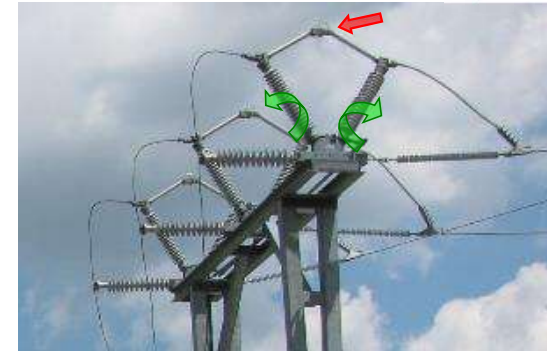
Disconnectors

Types of Switches (cont.)

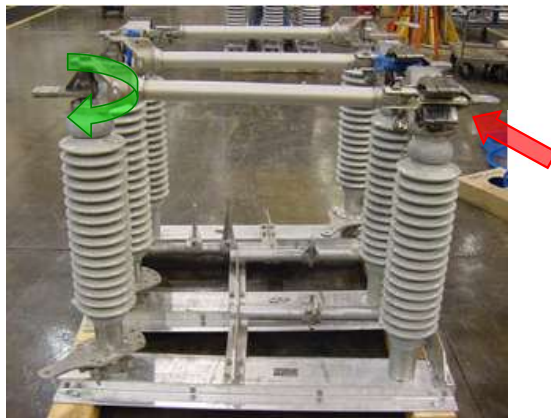
Group Operated Disconnect Switch

Various Operating and Mounting Configurations

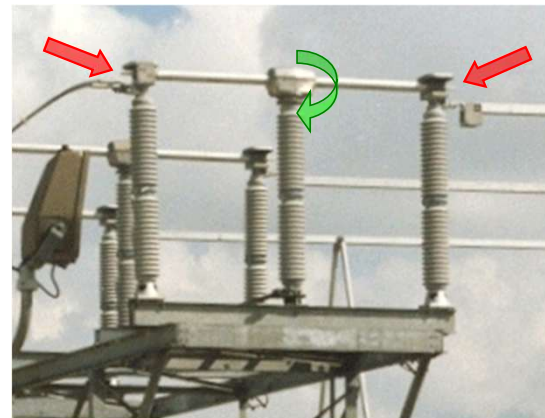
 = Insulator & Blade Rotation
 = Contact Break Point



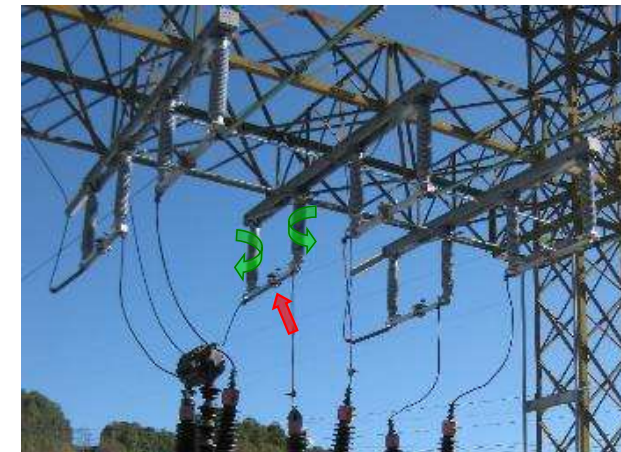
Center break, V-mounted



Side-break
(on shipping pallet)



Double side-break
or double end-break



Double inverted disconnectors:
center break, underhung mounted

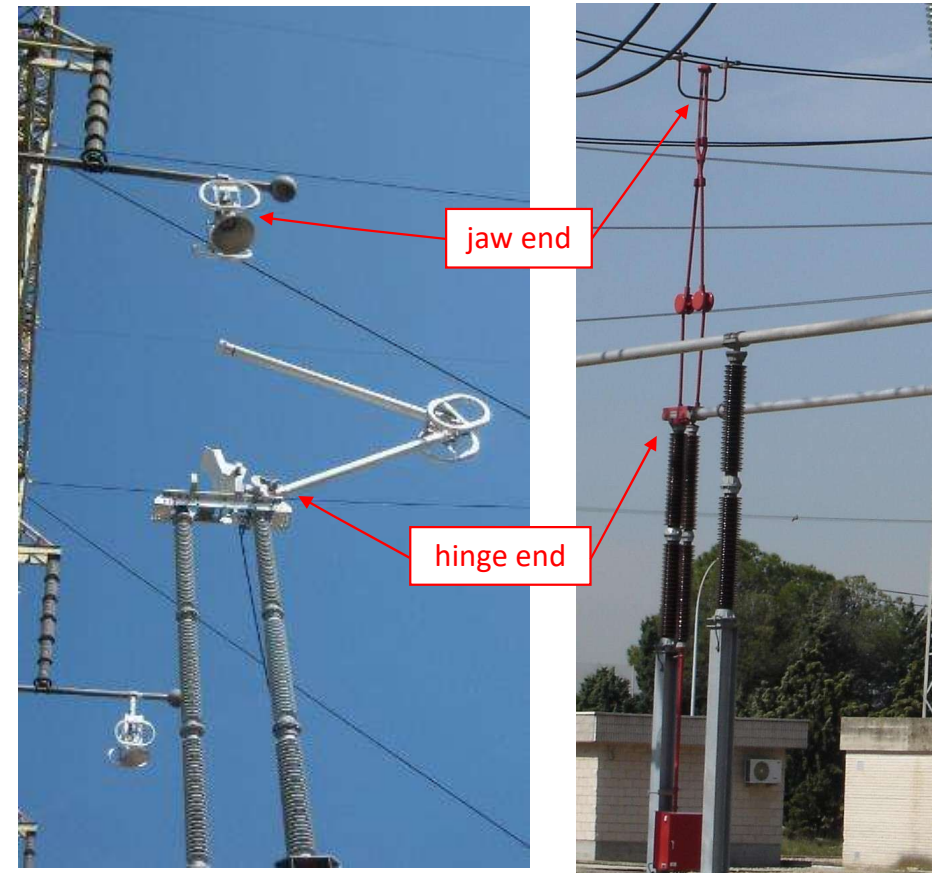
Disconnectors

Types of Switches (cont.) Other Operating Configurations

Semi-Pantograph (*left*): switch with a “knee” or “elbow” type joint in the blade; can be configured with either a vertical or horizontal gap or reach

Full-Pantograph (*right*): switch with a “scissor-like” framework of jointed rods in the blade; for vertical gap

- Note that these examples are EHV switches; so due to wide phase spacing, each pole unit must have its own support structure with motor operator
- This is another example of a switch using single pole operation.



Disconnectors

Types of Switches (cont.) Other Specialty Configurations



N.O. switch
to reserve bus

N.C. switch
to main bus

Tandem hook-stick switch: back-to-back switches for transferring load from one source to another (e.g. from 12 kV main bus through bottom switch to 12 kV reserve bus through top switch)

By-pass
switch in
N.C. position

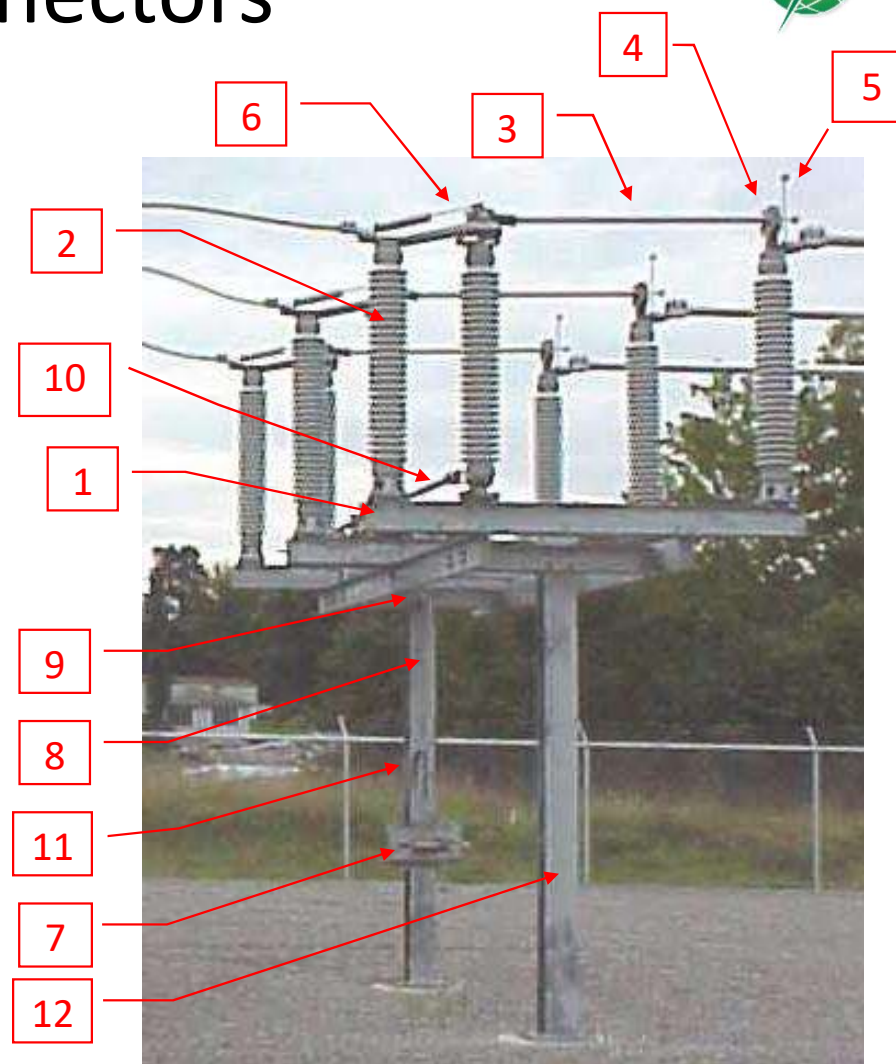


By-pass hook-stick switch: used here closed to connect 12 kV voltage regulators to transformer leads, which can then be opened to by-pass regulators for maintenance while keeping transformer in-service

Disconnectors

Components

1. Switch base
2. Insulators
3. Blade
4. Jaw end with contact fingers
5. Arcing horns
6. Hinge end (blade pivot point) with counter-balance
7. Operating mechanism (manual)
8. Vertical operator pipe
9. Outboard or offset bearing
10. Inter-pole linkage or rods
11. Operator rod grounding strap
12. Structure



Disconnectors



Ratings

- vary depending on type, voltage, current and fault duty, also ...
- consider insulator strength for type of mounting (vert. or horizontal), and
- environmental conditions (icing, contamination,...) in which it must operate

Source: CIGRE TB No. 740
Contemporary design of low cost substations in developing countries

Device type Voltage level [kV]	 Center Break	 Double Side Break	 Pantograph	 Vertical Break	 Knee Type	 V- Type	 Side Break	 Semi-Pantograph
≤ 1200	-	≤ 5000 A ≤ 50 kA	-	-	-	-	-	-
≤ 800				≤ 5000 A ≤ 50 kA	≤ 3150 A ≤ 63 kA			≤ 3150 A ≤ 40 kA
≤ 550 (525)	≤ 4000 A ≤ 63 kA	≤ 5000 A ≤ 63 kA	≤ 4000 A ≤ 63 kA	≤ 4000 A ≤ 63 kA	≤ 4000 A ≤ 63 kA			≤ 4000 A ≤ 63 kA
≤ 420 (363)			≤ 4000 A ≤ 80 kA	≤ 4000 A ≤ 80 kA	≤ 4000 A ≤ 63 kA			≤ 5000 ≤ 63
≤ 300		≤ 3150 A ≤ 40 kA	≤ 4000 A ≤ 63 kA	≤ 3150 A ≤ 63 kA	-			-
≤ 245 (252)		≤ 4000 A ≤ 50 kA			≤ 4000 A ≤ 50 kA			≤ 4000 A ≤ 50 kA
≤ 170		≤ 4000 A ≤ 63 kA	≤ 3150 A ≤ 50 kA	≤ 3150 A ≤ 50 kA	≤ 2500 A ≤ 40 kA	≤ 2000 A ≤ 40 kA		≤ 3150 A ≤ 40 kA
≤ 145								
≤ 123 (126)								
≤ 72.5		≤ 2000 A ≤ 50 kA	≤ 4000 A ≤ 50 kA	-	≤ 5000 A ≤ 50 kA	-		-
≤ 48	≤ 2500 A ≤ 50 kA		-					

Disconnectors

Types of Operating Mechanisms

- Provide torsional force to vertical operating pipe and then to the inter-phase pipes; except for the pump type which provided linear reciprocating up-down motion
- Provisions to pad lock prevent malicious operation

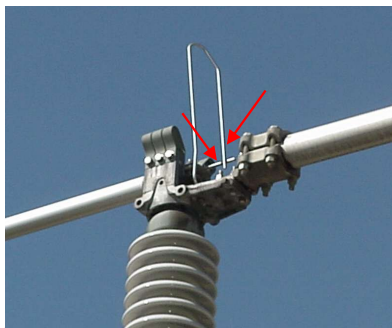


Disconnectors

Switch Accessories

Provide additional functions for disconnectors as required for specific applications

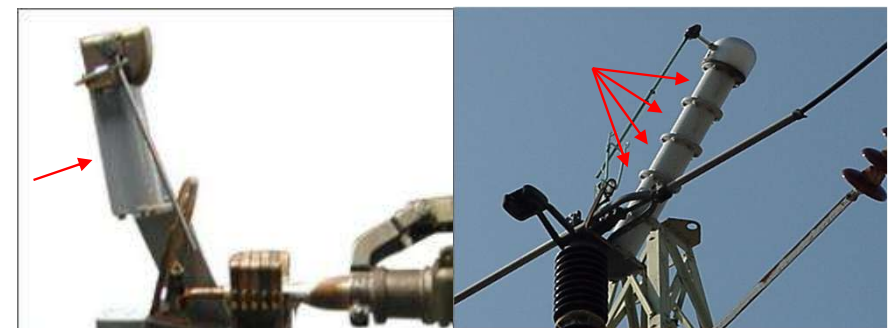
- Arcing Horn: inexpensive contacts to keep the arc off of expensive main contacts
- High Velocity Interrupter: quick whipping action allows switch to break the arc of the capacitive charging current on a line up to a specific line length
- Load Break Device: vacuum interrupter(s) tripped via linkage on the opening blade



Arcing Horn
(approx. 2 to 10 A)



High Velocity Interrupter or Quick Break Device
(approx. 15 to 20 A) *Note: not used to break load*



Load Break Devices: single & multiple interrupters
(interruption capacity depends on device rating)

Disconnectors

Switch Accessories (cont.)

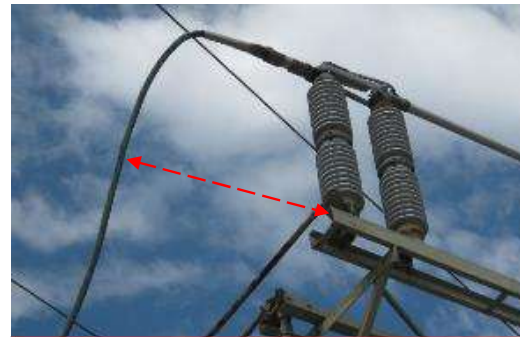
- Auxiliary Switch: provide open/close status for remote monitoring; mounted on operating pipe inside or outside the mechanism cabinet
- Interlocks: uses interlocking keys to prevent switching errors (e.g. disconnector must be open to release a key to unlock its earth switch operator to close it)
- Wire Guides & Outriggers: relieve strain on terminal pads; maintain safe clearance
- Contact Hood/Cover (*not shown*): prevents the contacts from accumulating ice



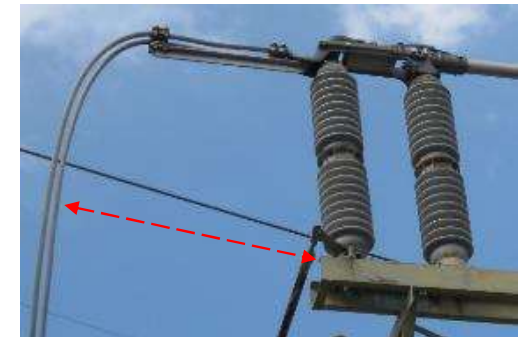
Auxiliary Switches



Interlocks



Wire Guide



Outrigger

Disconnectors



Basic Design Process

- Project Plan: define device requirements
- Industry Standards: ratings and capabilities for application, design, manufacture and maintenance
- Utilities Specification: for procurement
- Manufacturer Drawings: nameplate, physical outline, controls schematics
- Design Details: checklists, plan and elevation views, bill of material
- Standardization: standard designs for repetitive, economic use



Disconnectors

Specification

- Voltages: nominal and maximum system voltage; BIL/BSL (LIWL/SIWL) requirements
- Currents: 1) continuous; 2) peak withstand (short circuit fault duty); 3) short time (3 second)
- Load break devices: load interrupting device, quick break (as required)
- Special load characteristics: loop switching [busbar transfer rating], dropping line charging current, transformer magnetizing, capacitor charging; terminal pad pull-off tension
- Switch Type (vertical break, side break, center break, etc.)
- Orientation: vertical, inverted or upright mounting and structure detail drawings
- Operating mechanism: hook-stick or gang-operation; swing arm, worm gear (gear ratio), or motor
- Dimensions and Clearances: phase spacing and mounting height requirements; provide support structure drawings
- Insulator: provisions (by buyer or seller), types, material, strength, color, creepage
- Materials: conductors (copper or aluminum); base (paint, galvanizing)
- Environmental conditions: altitude, climate, wind, ice, seismic, pollution
- AC / DC circuit voltages: for control, motor torque rating, auxiliaries
- Accessories: wire guides/out-riggers and length, cabinet heater, auxiliary switches, monitoring, etc.
- Shipping method and constraints (dimensional & weight; road restrictions), FOB (Freight On Board) destination
- Field work: assembly, testing and/or commissioning
- Warranty, drawings, instruction books, and spare parts
- Reference applicable industry standards and company specifications, or special custom requirements

Electrical

Physical

Auxiliary

Miscellaneous

Required ratings based on planned load and fault current according to system studies.

Other requirements based on design, construction, operating and maintenance needs.

Earthing or Grounding Switch



General Information

- Definition: Earthing Switch or Grounding Switch (US) is a special switch intended to connect phase conductors to earth for safety purposes
- Capability:
 - Withstand for a specified duration currents under abnormal conditions such as those of short-circuit
 - can have a short circuit making capacity either to act as a “fault thrower” switch at the end of a long distribution feeder, or to provide for inadvertent operation of a live circuit to earth

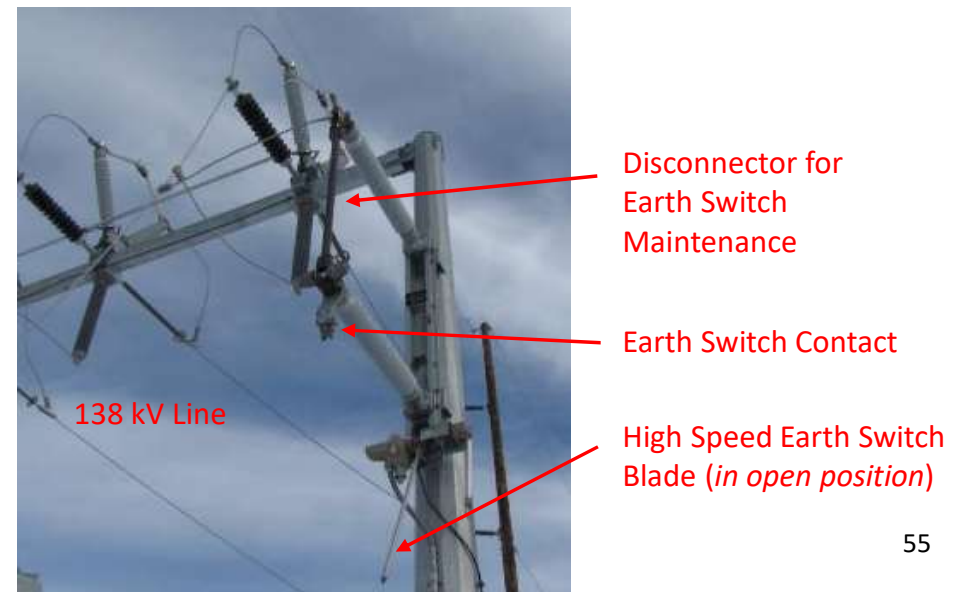
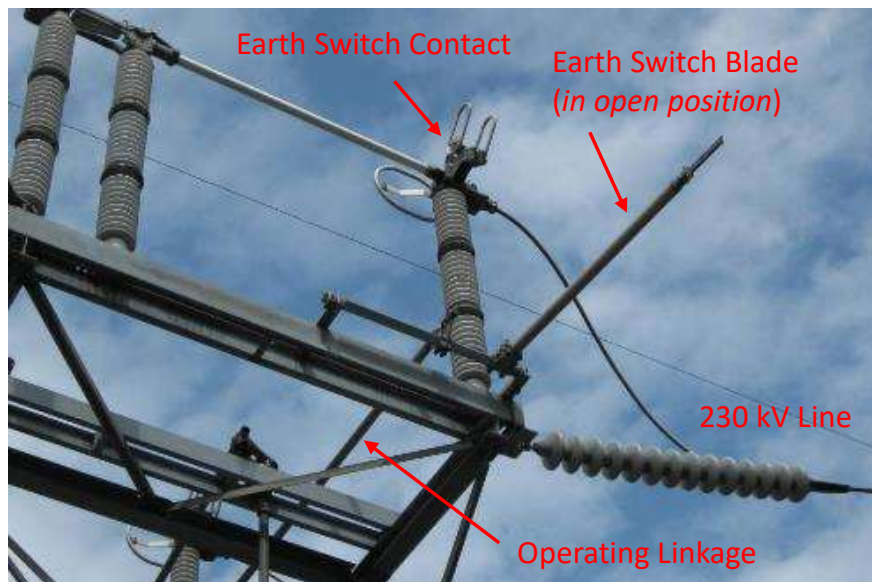


Earthing or Grounding Switch
in the “open” position

Earthing or Grounding Switch



- Used to earth a de-energized circuit/line on an opened disconnector for safety of workers during line maintenance (*shown on left*)
- High speed earthing switch (also called fast earthing switch or fault throwing switch) creates a phase-to-ground fault as part of a transformer protection scheme which triggers remote relays and breakers to trip the line (*shown on right*); and for protection against secondary arc (re-ignition) on breakers associated with transmission line reactors



Circuit Interrupter Switch

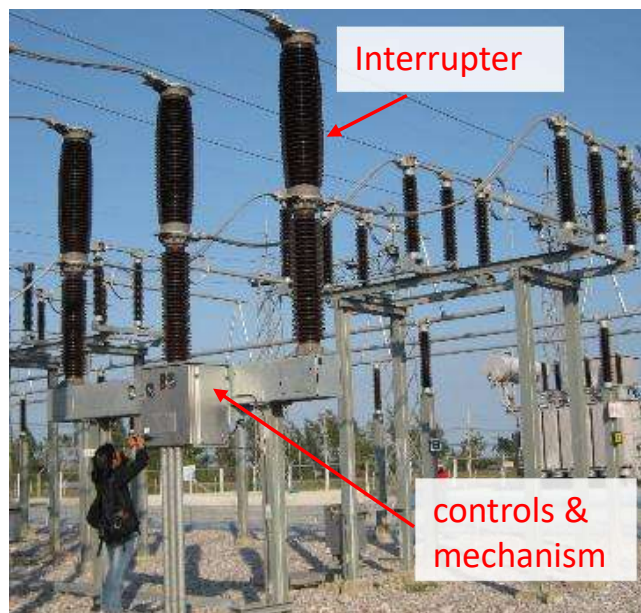


Background Information

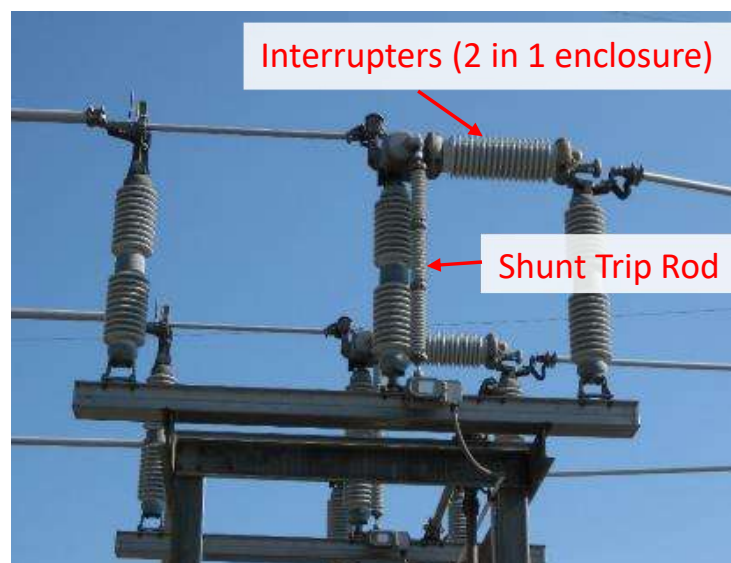
- **Switchgear** is electrical equipment used to control, protect, interrupt, switch and isolate the flow of electrical power in normal and emergency conditions
- Main components of switchgear are circuit breakers, disconnectors and fuses
- Some special purpose related devices economically applied in substation can be:
 - Circuit Interrupter or Load Break Switch: used to make, carry and break load currents in normal circuit conditions with some limited amount of overload, magnetic, capacitive, or short-term, short circuit current (i.e. transformer exciting current or line charging current); but no fault interruption
 - Circuit Switcher: a product similar as above, but uses SF₆ interrupters to interrupt load and protect against transient overvoltages, overloads and limited fault current; but cannot provide reclosing
 - Hybrid Devices: combined switchgear items reducing the space requirements
- Advantages: these devices can be easy to install and to maintain
- Disadvantages: misapplication of device; integral CT's are not provided

Circuit Interrupter Switch

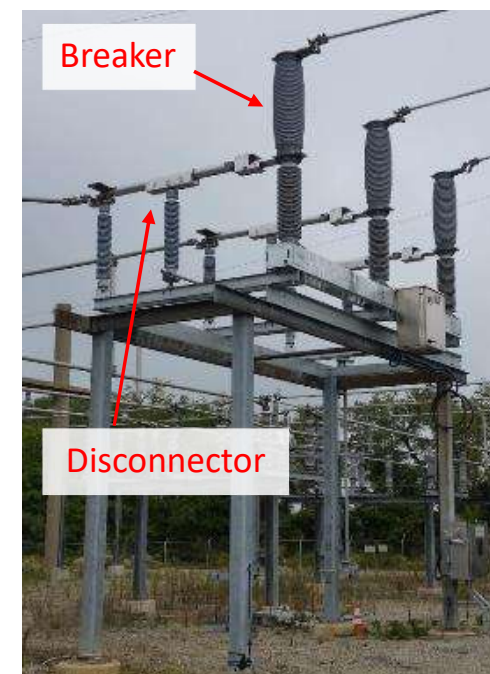
Typical installations



115 kV Circuit Interrupter with Disconnector (for visible opening)



145 kV 1200 A Circuit Switcher
(two SF₆ interrupters in series opened via solenoid operated high speed shunt trip device)



Hybrid Disconnecting Circuit Breaker
(combines the functions of a 138 kV breaker and disconnector in one unit)

- All devices must fit the application duty and be operated within nameplate ratings
- Manufacturers push initiations (e.g. disconnecting breaker) as reducing costs and saving space
- Utilities see some disadvantages from design/operational perspectives (e.g. fitting in CTs)

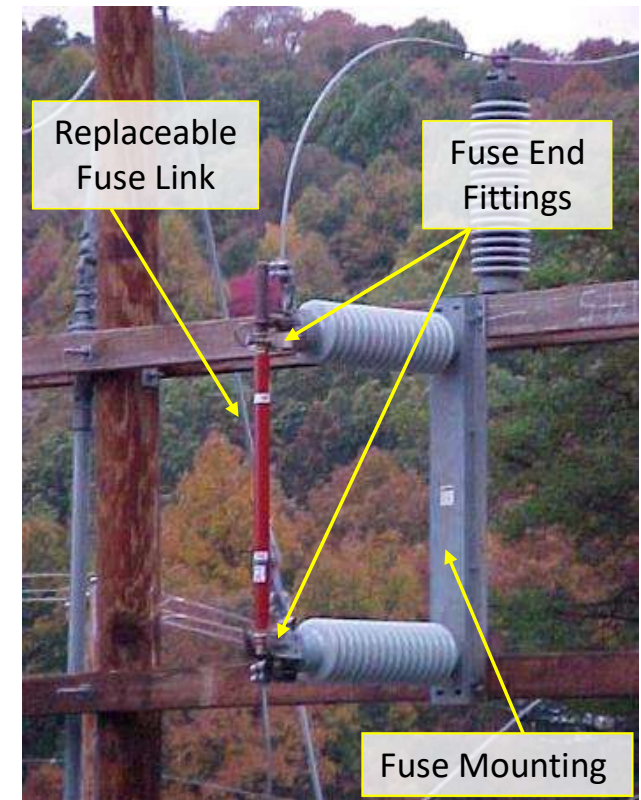
Power Fuse

Economical protection when applicable

- Operation: interrupts flow of electrical current when it is overloaded by melting a replaceable element
- Application: protect downstream equipment from fault current damage (e.g. distribution station transformers)
- Construction: galvanized steel base with insulators
- Ratings: typical voltages 12 to 69 kV; links with various interrupting current and speed (slow, standard, fast) ratings; mountings based on available fault current
- Precaution: expulsion type fuse generates gas that expands blowing out bottom of the tube to extinguish the arc; consider orientation of mounting during design; also do not stand under fuses in substations

Reference: IEC series 60282 "High-voltage fuses"

IEEE C37.40, 41, 42, 44, 46, 47 (various standard for HV fuses)



69 kV Mounting, 200 A Continuous, 8.75 kA Interrupting, available Fusible Links 3 to 200 A

Metal Clad & Metal Enclosed Switchgear



General Information

- **Metal Enclosed Switchgear:** a switchgear assembly enclosed in sheet metal containing buses, interrupter switches, power fuses, breakers and possibly control/auxiliary devices accessed by doors or removable covers.
 - not compartmentalized; unsegregated; a fault could spread to adjacent parts
 - typically use fixed pattern (fixed mounted) components that are permanently mounted and cannot be removed for maintenance or replacement without significant effort
 - usually manually operated
 - simpler construction
 - more compact; smaller footprint
 - less expensive



Metal Clad & Metal Enclosed Switchgear



General Information

- **Metal Clad Switchgear:** a switchgear assembly enclosed in sheet metal containing buses, interrupter switches, power fuses, breakers with control and auxiliary devices having the main internal components are individually compartmentalized in sheet metal cubicles or cells accessed by doors plus safety shutters/barriers that segregate the HV parts.
 - compartments provide additional insulation and safety measures (e.g., use of insulated bus and connections)
 - drawout breakers (plug-in) are easily removable for maintenance or replacement
 - electrically operated with protective relays
 - more robust for higher fault currents
 - more costly



Example: 15 kV 3000 A bus outdoor walk-in sheltered aisle with 12 single high breaker cubicles in a single row and UG feeder exits

Metal Clad & Metal Enclosed Switchgear



General Information

- Types:
 - indoor or outdoor
 - with or without a walk-in sheltered/protected aisle
 - single or double high (stacked switchgear) in cubicles
 - single or double row line-ups of cubicles
- Ratings: voltages up to 38 kV and ampacity up to 3000 A
- Specification/Ratings: voltage; BIL; current; fault duty; auxiliary devices; high altitude; seismic; etc.
- Design Considerations: bushings; bus configuration; control relays; underground cable locations; foundation type; arc flash protection
- Construction Considerations: front and rear access/working space; shipping in single, or multiple pieces to be joined in field



Example: 15 kV 3000 A bus outdoor walk-in sheltered aisle with 12 single high breaker cubicles in a single row and UG feeder exits

References: IEEE C37.20.2 "IEEE Standard for Metal Clad Switchgear"

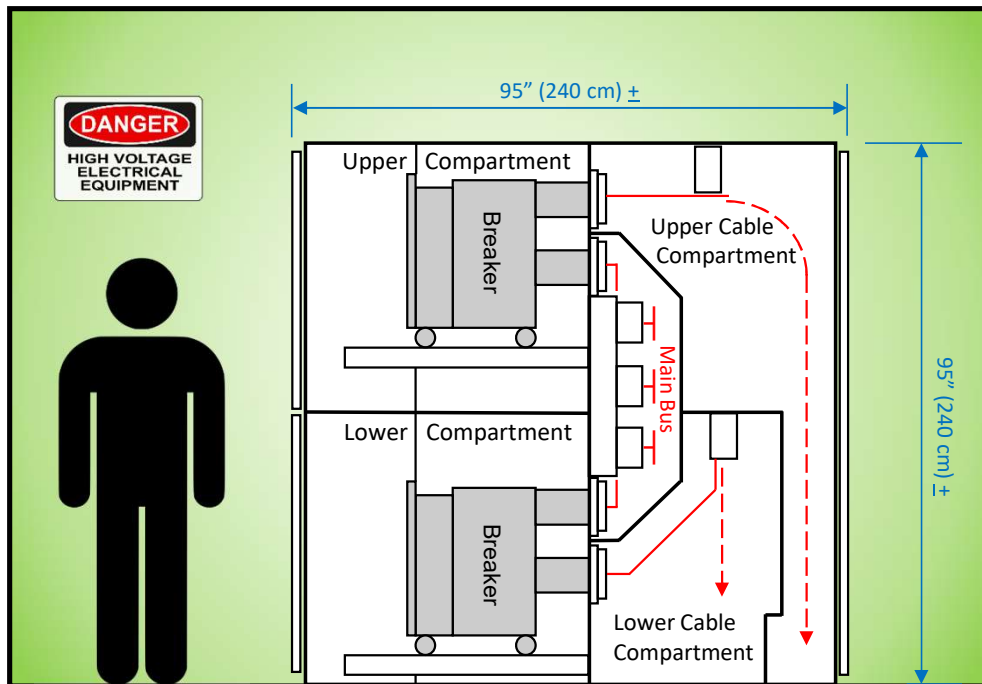
IEC 62271-200 "High-voltage switchgear and controlgear - Part 200: AC metal-enclosed switchgear and controlgear"

Metal Clad & Metal Enclosed Switchgear

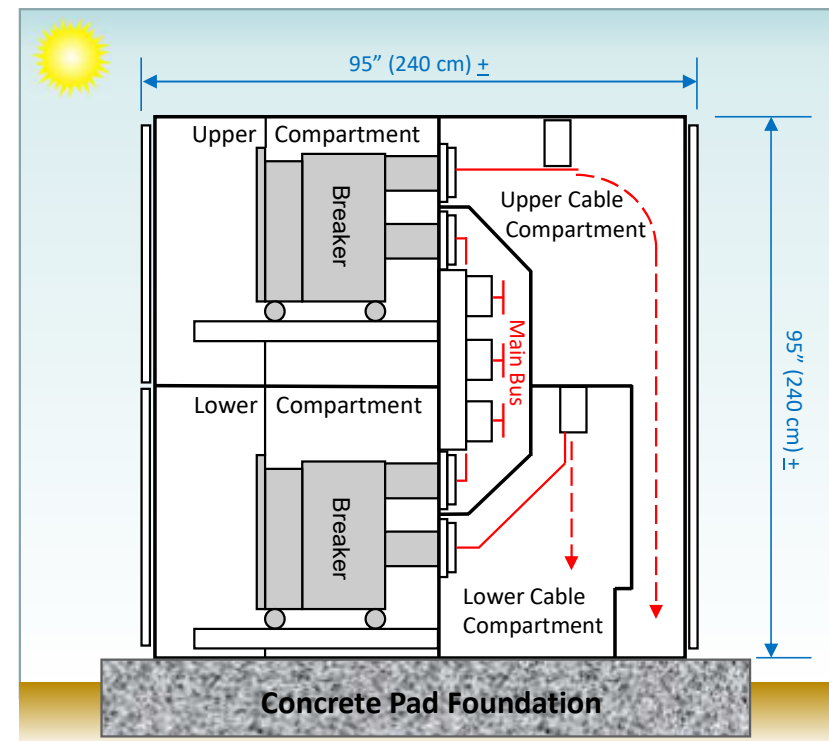


Typical Installation Arrangements

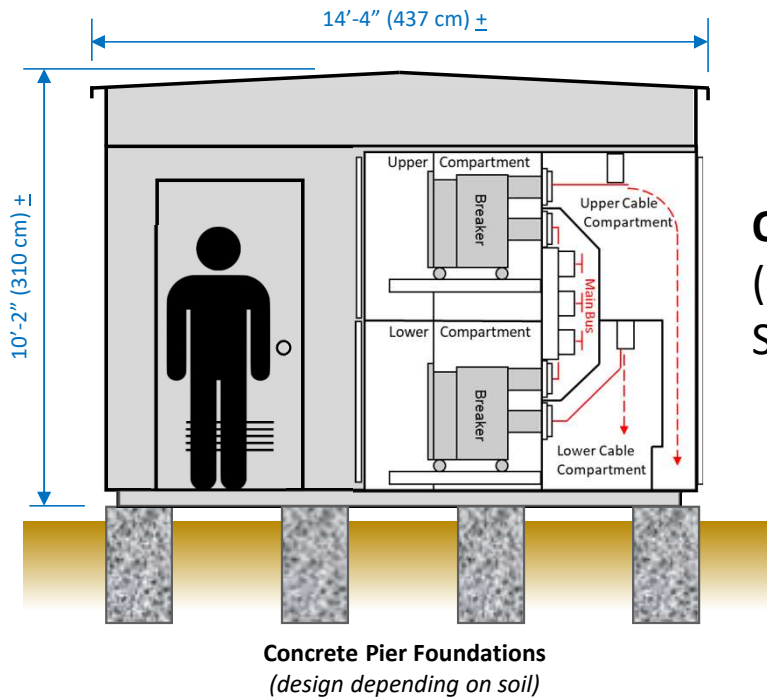
Indoor Type (e.g., inside power station or GIS building)
Single Row Line-Up with Double Breaker Cubicles



Outdoor Type (in distribution or industrial substation)
Single Row Line-Up with Double Breaker Cubicles
(also called Two-High Breaker Cubicles)

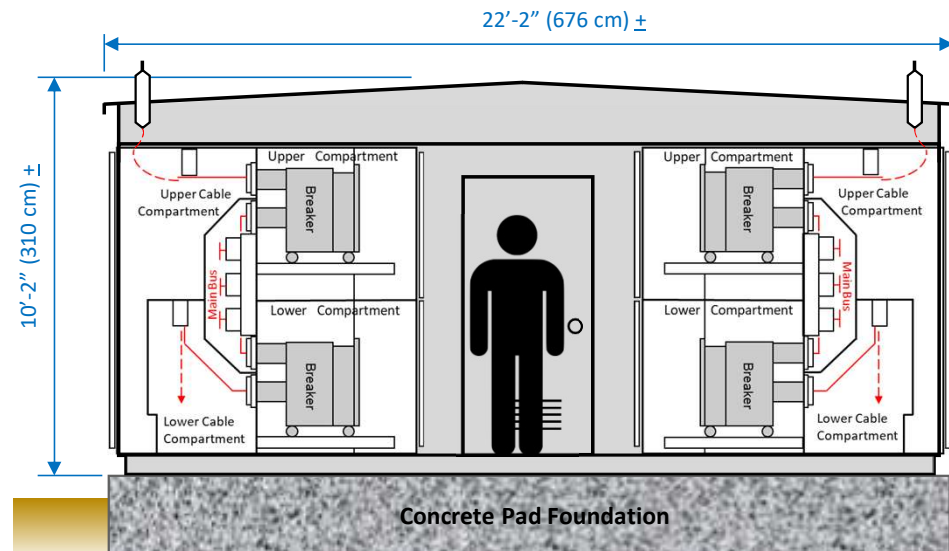


Typical Installation Arrangements (cont.)



Outdoor Walk-In with Sheltered Aisle or Protected Aisle Type
(e.g., in a distribution, industrial or commercial substation)
Single Row Line-Up with Double Breaker Cubicles

Outdoor Walk-In with Common Sheltered Aisle or Protected Aisle Type
(e.g., for a larger distribution substation)
Double Row Line-Up with Double Breaker Cubicles



Metal Clad Switchgear (example)



Internal Components

Protection & Control LV Compartment:

- front door serves as control panel with relay, switches, terminals and wiring



Circuit Breaker HV Compartment:

- drawout vacuum breaker with shutters covering HV components when breaker is removed



Example: Walk-in Type 15 kV 2000 A Bus with 1200A Breaker Cubicles

Note: HV equipment is physically separated from the LV devices.

Metal Clad Switchgear (example)



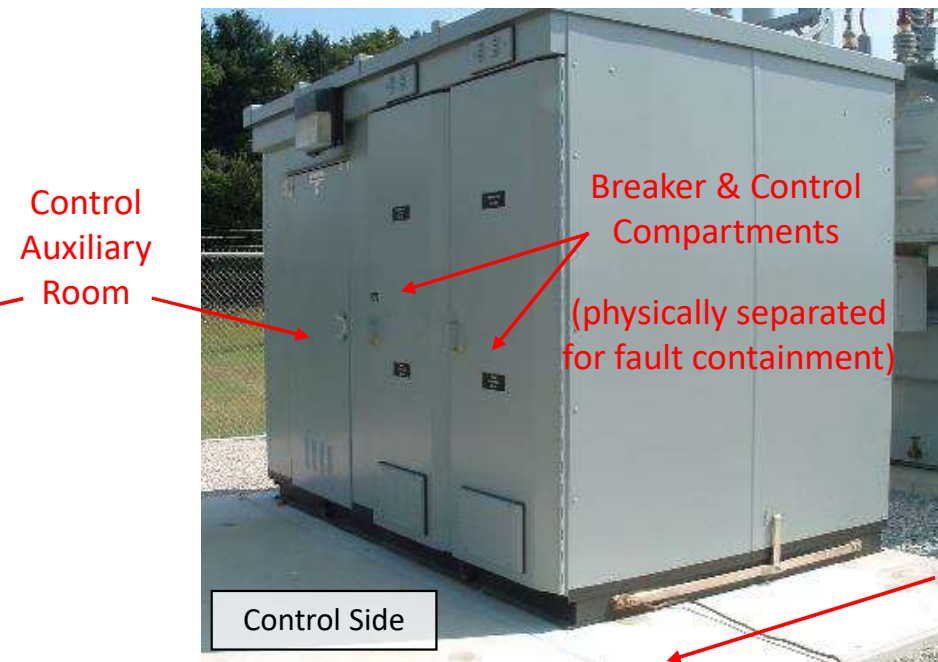
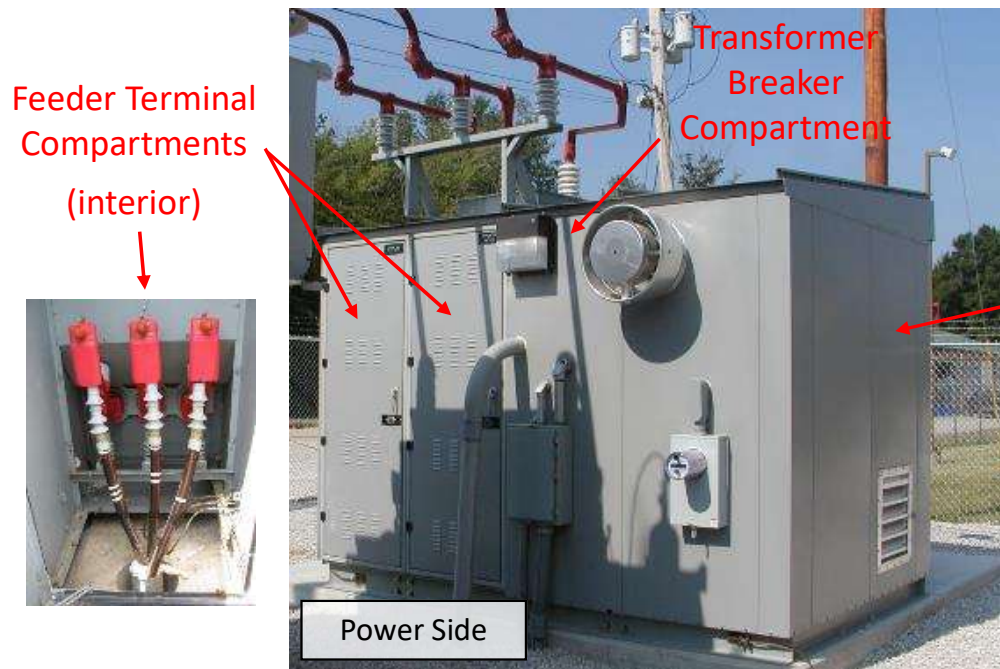
External Components

Power Entry/Exit HV Compartments:

- bushings for transformer leads, and access doors to UG cable terminations

Protection LV & Breaker HV Compartments:

- relays, wiring, plus draw-out vacuum interrupter breakers



Concrete Working Pad

Example: Non-walk-in w/o sheltered access 15 kV 2000 A Bus with Breaker Cubicles for 1 Transformer and 2 UG Feeders including small control room

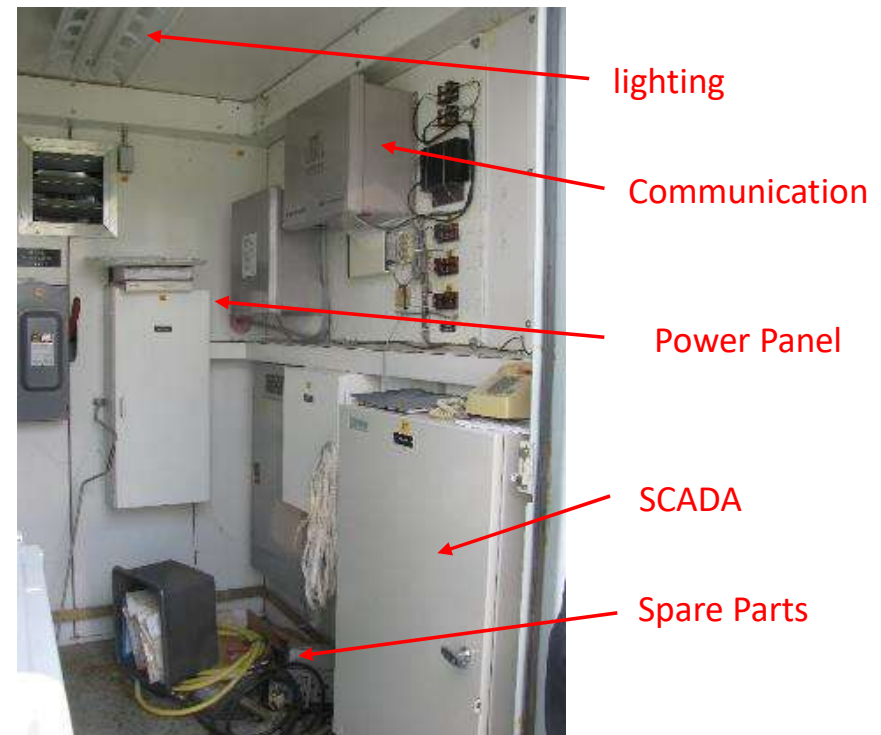
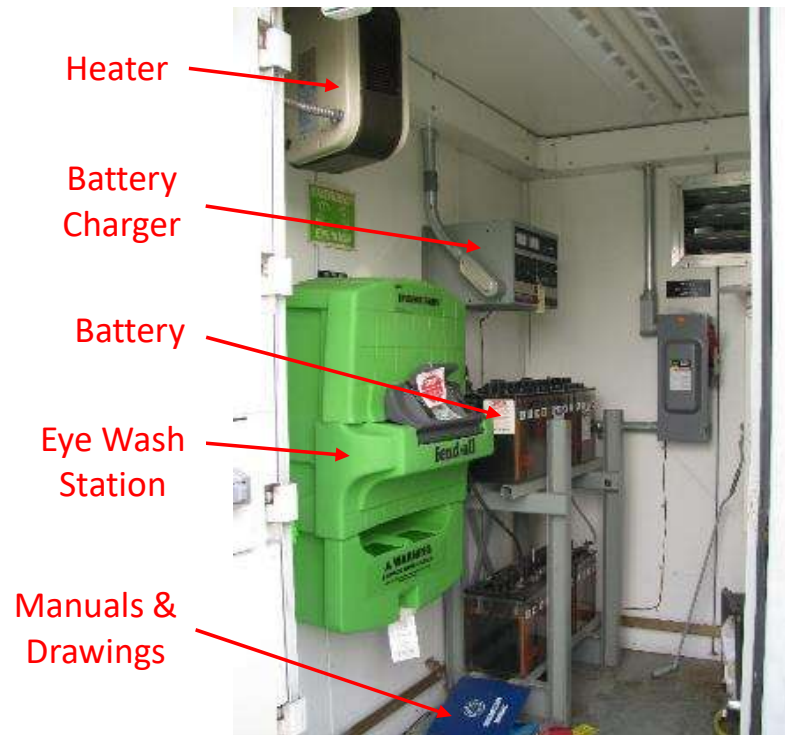
Metal Clad Switchgear (example)



Internal Control Room Components

Integral Control Compartment (for switchgear on previous slide):

- controls, relaying, SCADA, communication, AC/DC power, battery, HVAC, lighting



Example: Small integral control room for the 15 kV 2000 A Bus with Breaker Cubicles from the previous slide

Metal Clad & Metal Enclosed Switchgear



Arc Flash Resistant Safety Features

Optional features available to mitigate arc flash:

- remote racking device for breaker removal at safe distance for maintenance
- mechanical interlocks for proper operating sequence
- glass portals to visually inspect condition of HV compartment before opening
- integral baffles and vents to safely direct arc blast away from personnel



Reference: IEEE 1584 "Guide for Performing Arc-Flash Hazard Calculations"

Metal Clad & Metal Enclosed Switchgear



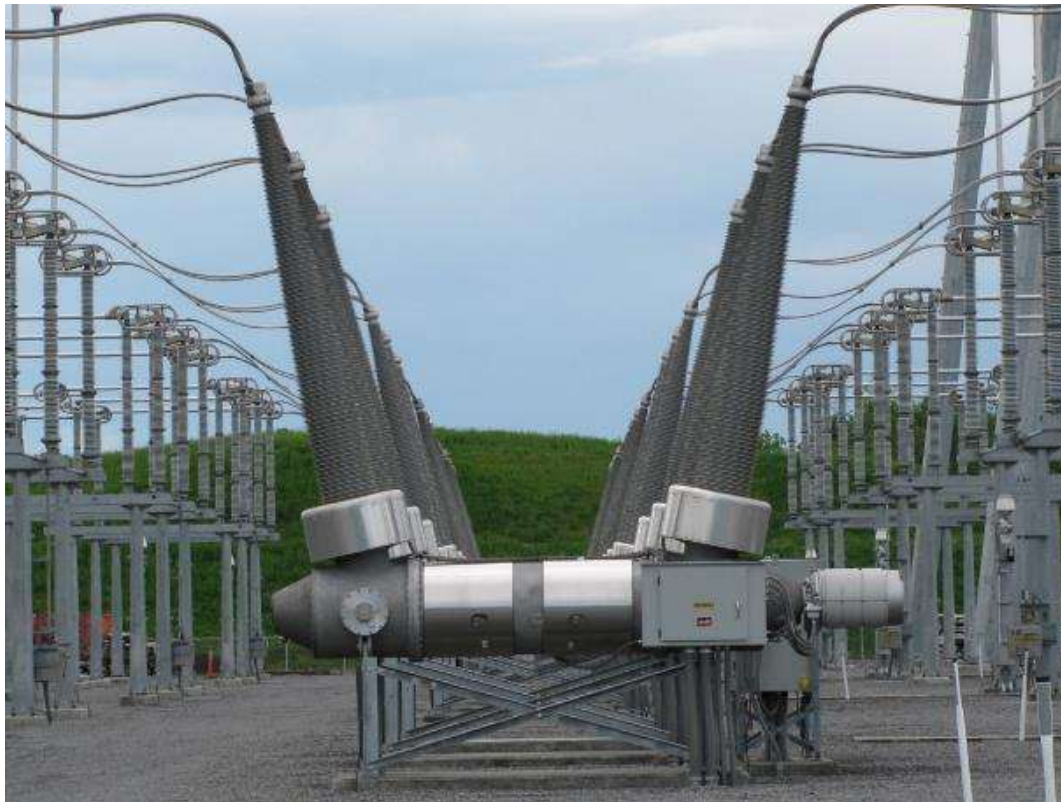
Design Considerations:

- custom design and fabrication by a manufacturer to a customer's specifications
- designer needs a good single line and phasing diagrams and a detailed specification
- need for detailed operator interface layout specification
- thorough review/approval of vendor's design is essential to get correct equipment
- verify component/system compliance to specs during Factory Acceptance Tests
- integrating this into the substation design is similar to other major equipment

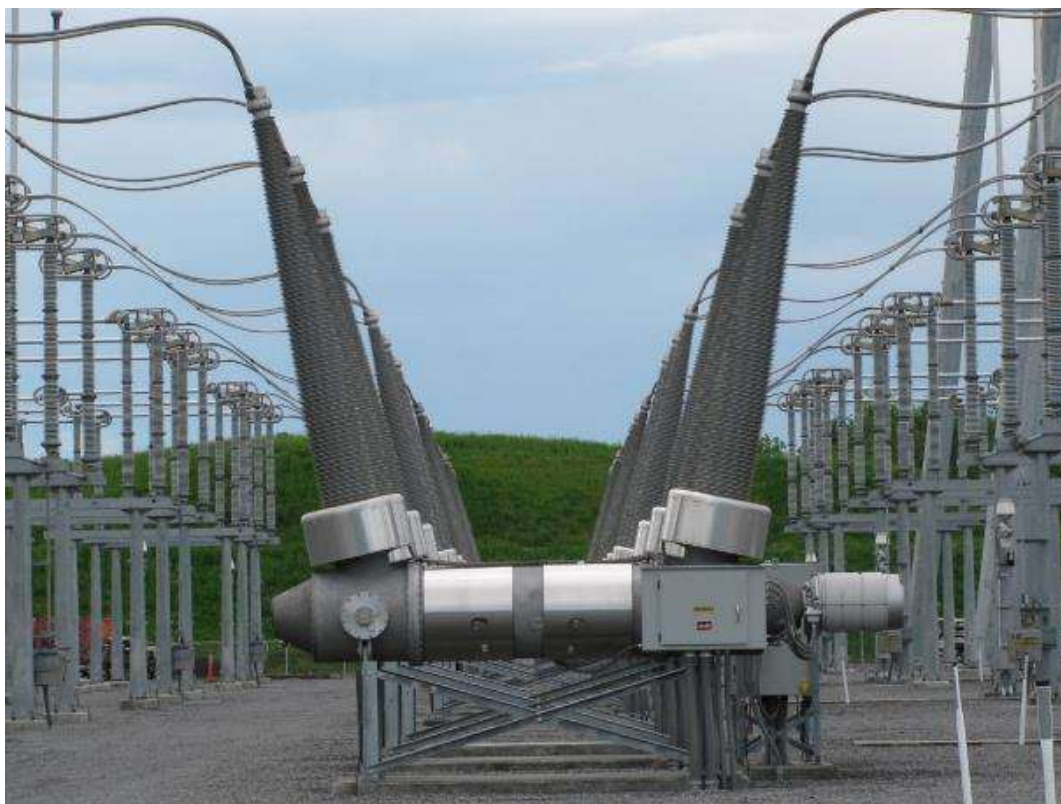


Example: 38 kV 1200 A bus walk-in sheltered aisle with single high breaker/control cubicles in a single row with all control room equipment

Second Set of Questions



Questions ?



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