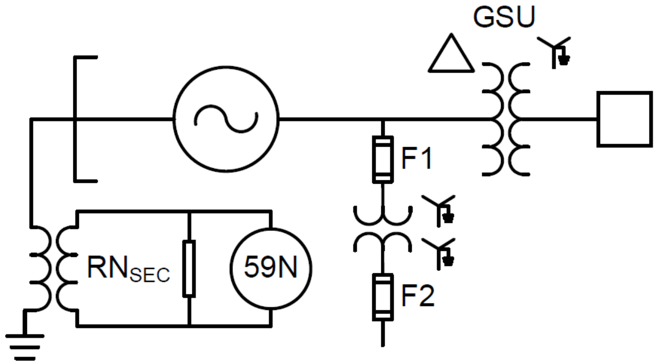
Theory of Voltage Transformer (VT)

Karl M.H. LAI

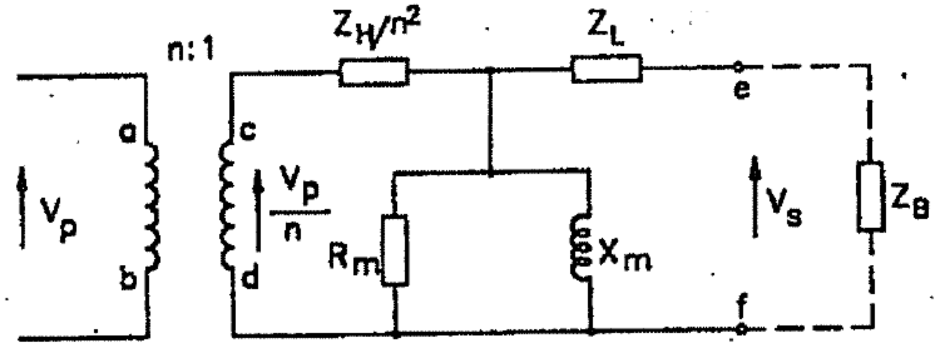
Introduction to Voltage Transformer (VT)

Constant Flux Transformer

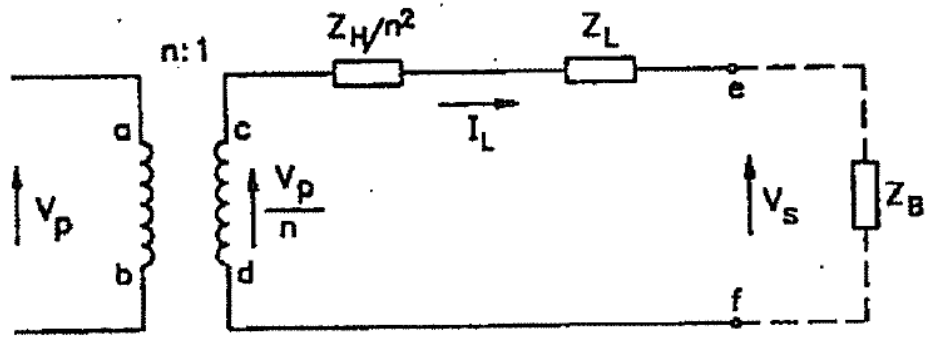
- **Purpose:** VTs are used to isolate relay equipment from high voltage and reduce the voltage to $110V_{L\text{-}L}$.
- **Construction**: The construction of a VT is similar to a power transformer. The rated output is usually a few hundred VA, so heat generation is not a problem. The physical size of a VT is determined by system voltage and insulation requirements.
- **Insulation**: For 11 kV circuits, dry type insulation is used. For high and extra high voltage systems, oil immersed units are common. SF_6 is also used as an insulation medium for high voltage VT, especially in SF6 metal-clad switchgears.
- **Types**: VTs can be three-phase, single-phase for connection between lines, or single-phase connected from line to earth. Three-phase units are common up to 33 kV. Above this voltage, three single phase units connected as a three-phase Star/Star bank are more popular for economic reasons.
- **Protection**: Protection is usually provided by H.R.C. fuses for VTs on the primary side up to 66 kV. Above this voltage, a gas actuated relay may be used.



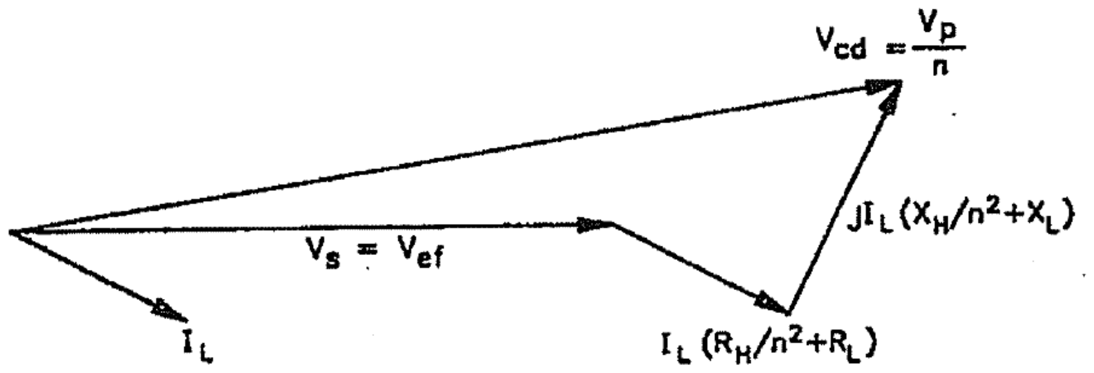
Introduction to Voltage Transformer (VT) – Model and Error



a



b



Errors in VT due to difference in magnitude and phase between V_p / n and V_S.

Error in Magnitude can be calculated from:

$$\varepsilon = \frac{nV_s - V_p}{V_p}$$

Error limits apply at rated frequency at any voltage between 0.8pu and 1.2pu and with rated burdens of between 25% and 100% of rated burden at power factor of 0.8 lagging.

Introduction to Voltage Transformer (VT) - Accuracy Class of VT

- Metering VT Accuracy Requirement:

0.8 to 1.2 x rated voltage
0.25 to 1.0 x rated burden at 0.8 pf

Accuracy class	voltage ratio error (%)	phase displacement (min)
0.1	± 0.1	± 5
0.2	± 0.2	± 10
0.5	± 0.5	± 20
1.0	± 1.0	± 40
3.0	± 3.0	Not specified

- Protection VT Accuracy Requirement:

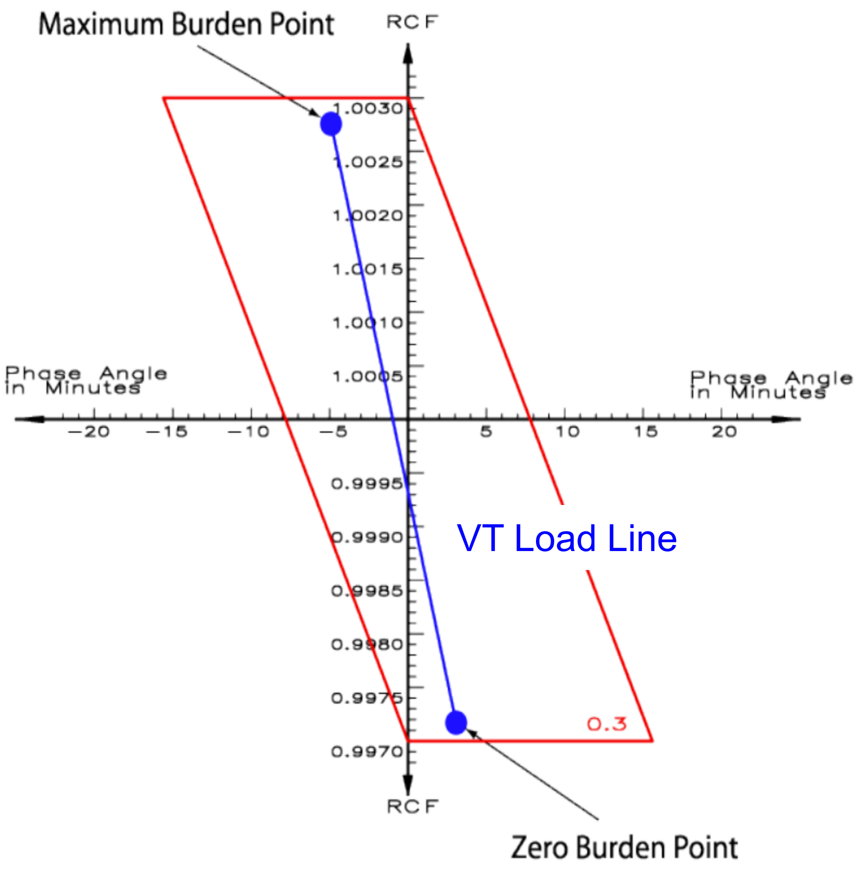
Accuracy class	0.25 to 1.0 x rated burden at 0.8 pf 0.05 to V_f x rated primary voltage voltage ratio error (%)	phase displacement (min)
3P	± 3.0	± 120
6P	± 6.0	± 240

- V_f = maximum operating voltage with permissible duration at which a transformer must comply with the relevant thermal requirements for a specified time and with the relevant accuracy requirements (e.g. 1.2 for continuous rating)

Introduction to Voltage Transformer (VT) - Burden

- VT burden refers to total external volt-amp load [VA] at rated secondary voltage within its rated accuracy.
  e.g. VT rated 0.3WXMY will maintain 0.3 accuracy class from 0VA to 75VA ("Y" burden).
- VT accuracy performance changes *linearly* with burden.
- Modern electronic instruments present very low burdens to the VT secondary circuit. Rarely does the burden of a VT circuit exceed 10 VA for modern installations.
- VT manufacturers tend to design VTs to utilize the entire accuracy parallelogram to minimize copper and core steel costs.
- Zero burden point of VTs tends to be near the bottom of the accuracy limits and the maximum burden point tends to be near the top of the accuracy limits.
- Accuracy performance at any other burden can be plotted by moving *linearly and proportionally* between the zero and full burden point.

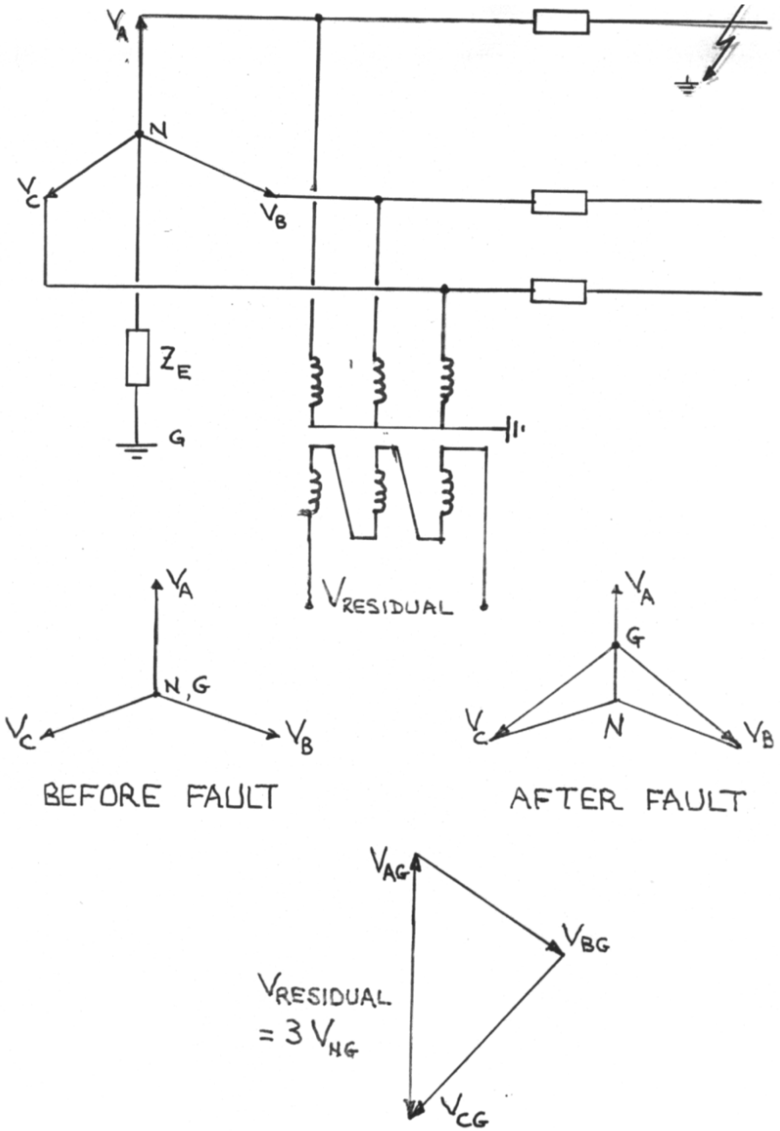
Farben Diagram



Broken Delta of VT

- Zero sequence voltage (neutral voltage shift) is often used for earth fault polarization.
- To measure zero sequence voltage ($3U_0$), a broken delta is used.
- To measure $3U_0$, ϕ_0 must be set up in the VT, requiring an easy return path for the resultant summated flux. Therefore 5-limb VT is often used.
- Primary winding neutral should be earthed, as without an earth, zero sequence exciting current cannot flow.
- Residual voltage = 0 if balance voltage applied, or

  = $3U_0$ of an imbalance system under fault.
- The possible increase of the voltage of un-faulted phases during earth faults (= pole factor) should be considered, and a should be rated to have an appropriate voltage factor.
- Application: 11kV DOCEF protection (e.g. DCD814B)



Why Five-Limb Voltage Transformer?

- Magnetic Flux Density can be calculated as

mmf

$$\phi = \oint B(r,t) \cdot dA = \frac{Ni}{\Re}$$

reluctance

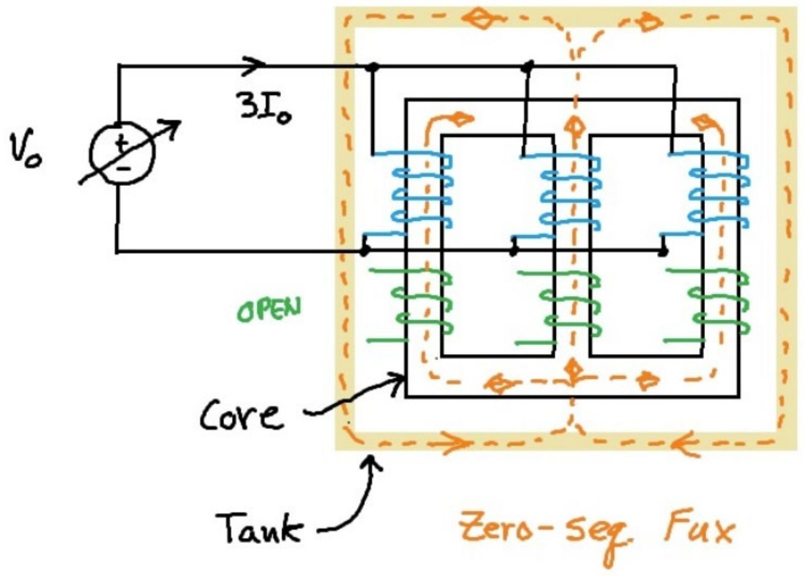
- Current flowing through coils produces flux according to the reluctance path.
- Induced Voltage is obtained with Variable Magnetic Field according to Faraday's Law:

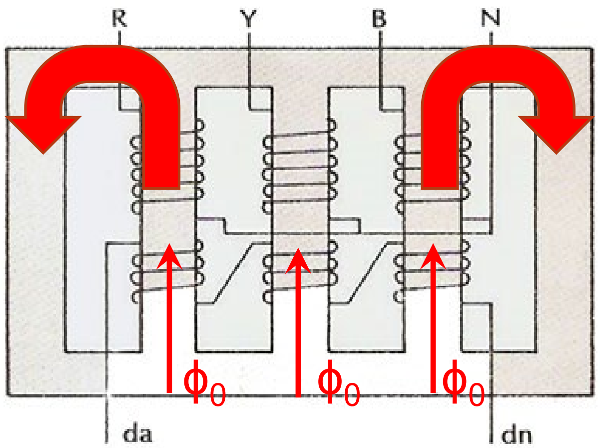
$$\varepsilon = N\frac{d\phi}{dt} = L\frac{di}{dt}$$

- Combining the two equations, magnetizing inductance can be found as:

$$L_m = \frac{N^2}{\Re}$$

- An easy magnetic path (for zero-sequence flux) means a small zero sequence reluctance, hence producing a large magnetizing inductance for large voltage output across terminal.
- The only concerns for saturation is in transient condition. At steady state, the input flux balance the output flux. Net flux at steady state does not drive the core to saturation.





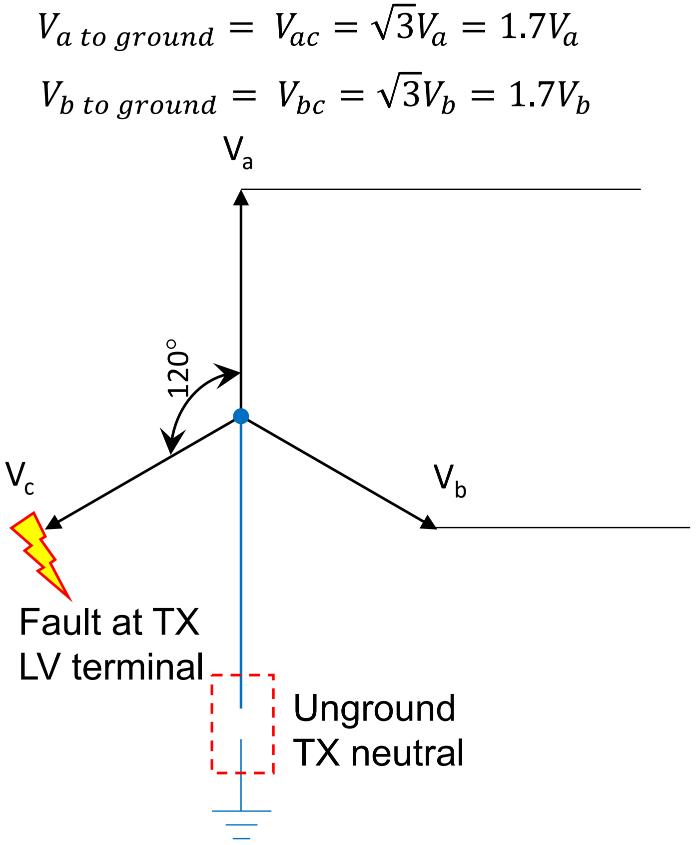
5-limb type

Voltage Factor

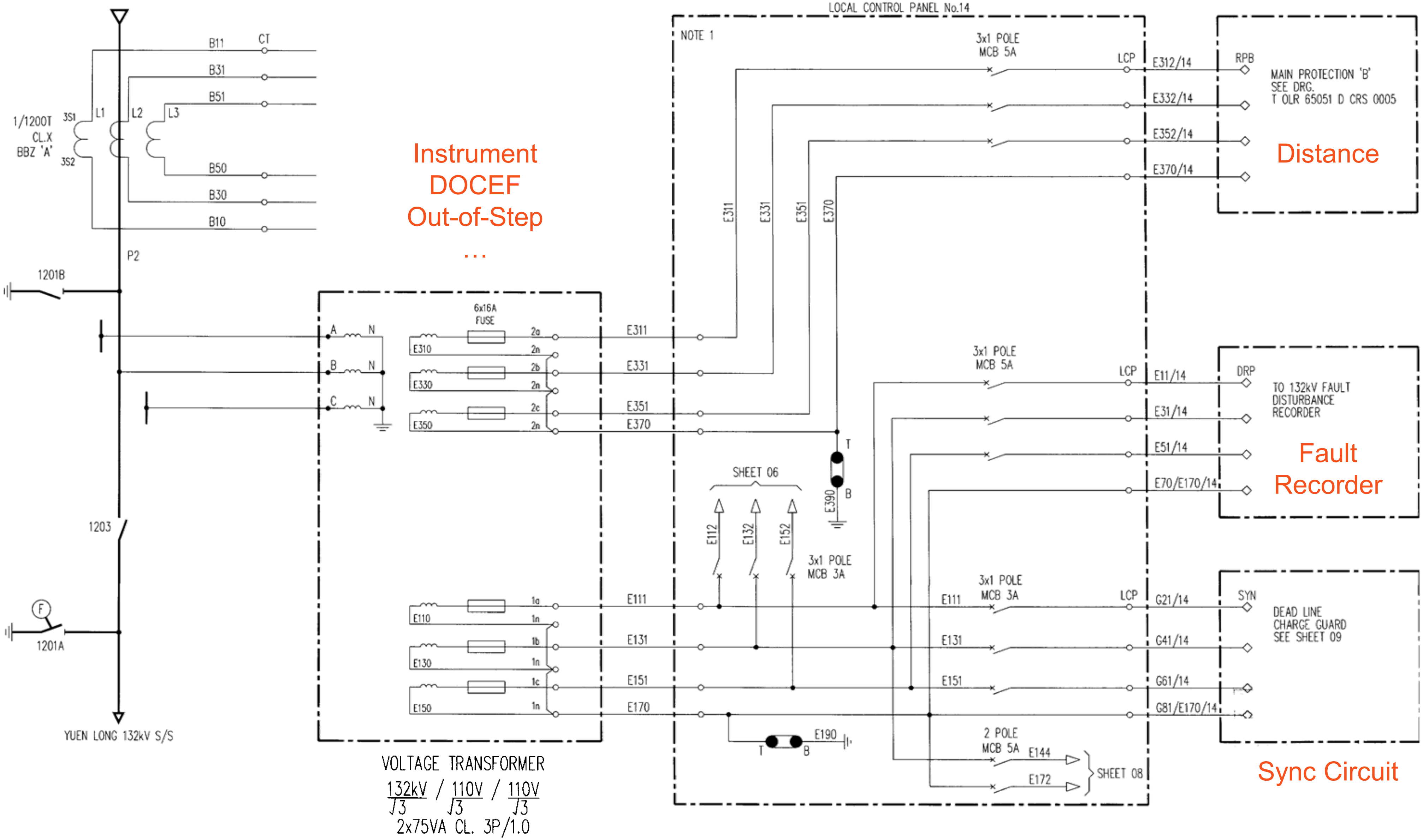
Referring to **IEC60044**,

- Voltage Factor (Vf) is determined by the maximum operating voltage, connection of VT primary winding and system earthing conditions.

Voltage factor V_f	Time rating	Primary winding connection/system earthing conditions
1.2	continuous	Between lines in any network Between transformer star point and earth in any network
1.2 **1.5**	continuous 30 sec	Between line and earth in an **effectively earthed** network
1.2 **1.9 = 1.7 + 0.2**	continuous 30 sec	Between line and earth in a **non-effectively earthed neutral system** with automatic earth fault tripping
1.2 **1.9 (= 1.7 + 0.2)**	continuous 8 hours	Between line and earth in an **isolated neutral system** without automatic earth fault tripping, or in a resonant earthed system without automatic earth fault tripping

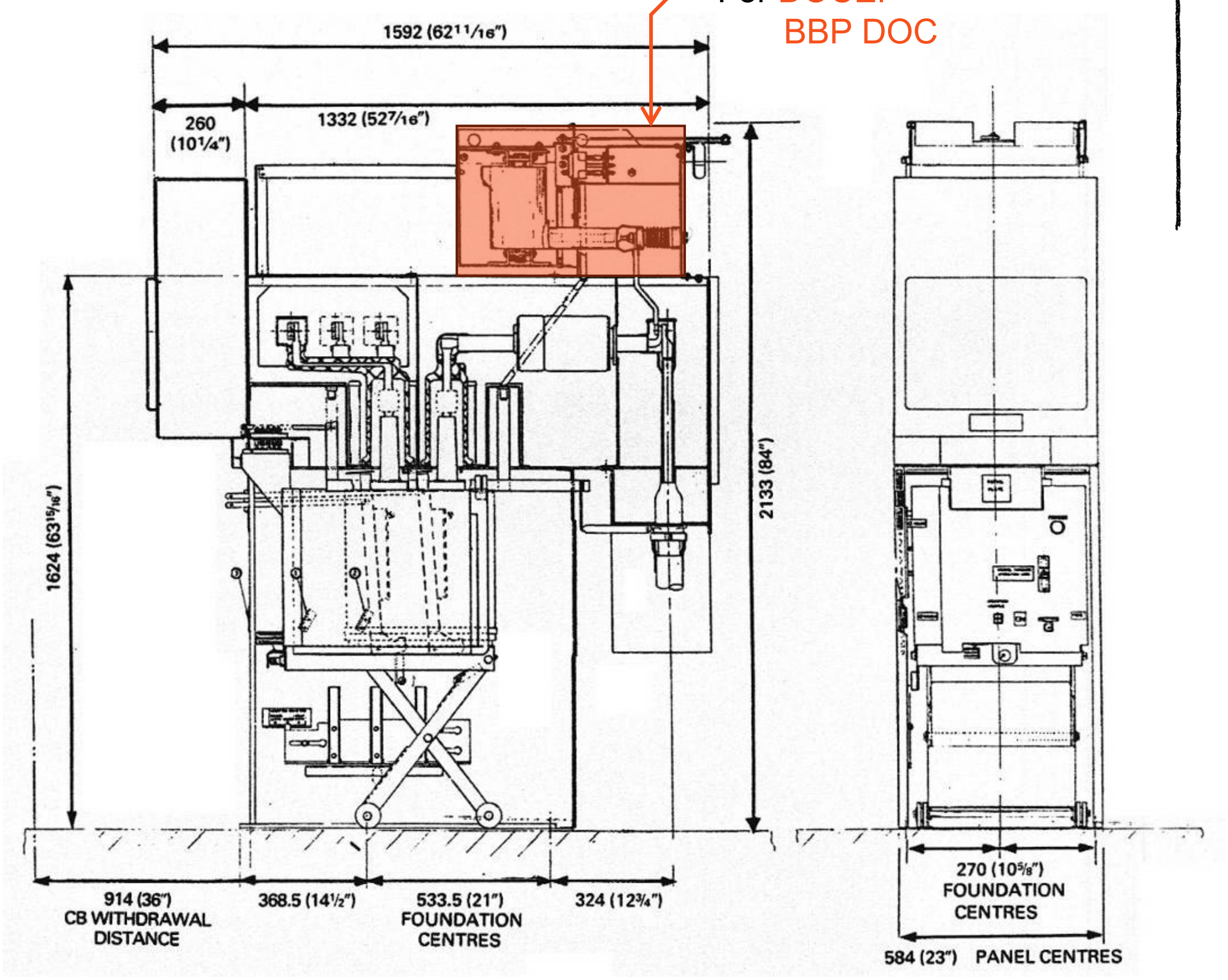


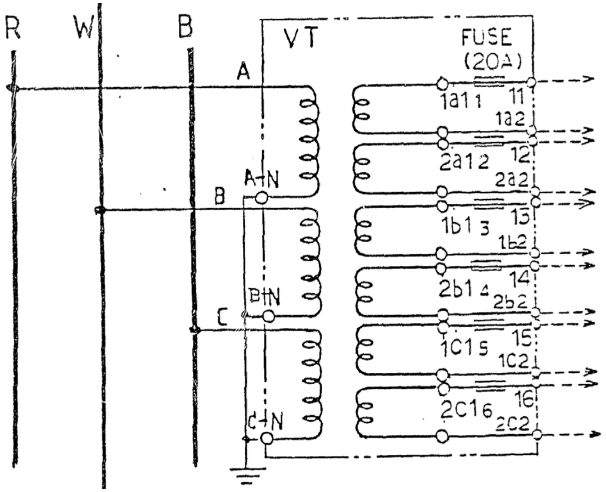
Applications of VT – Protection and Control



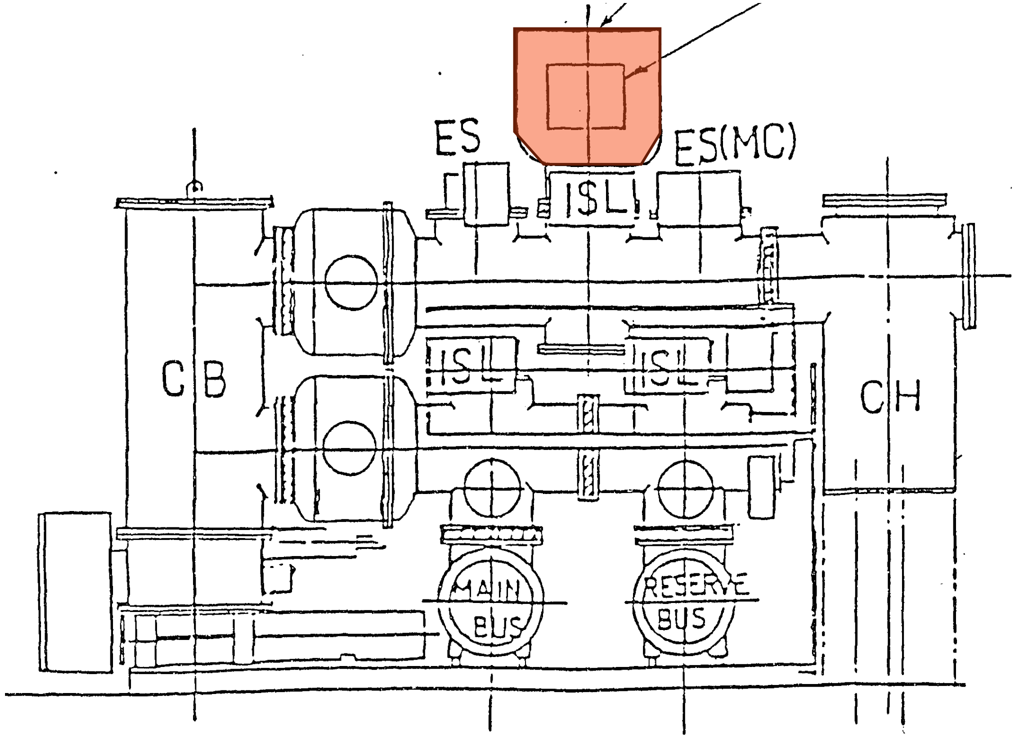
Applications of VT

VT at Tx Panel (11kV)
For DOCEF
BBP DOC



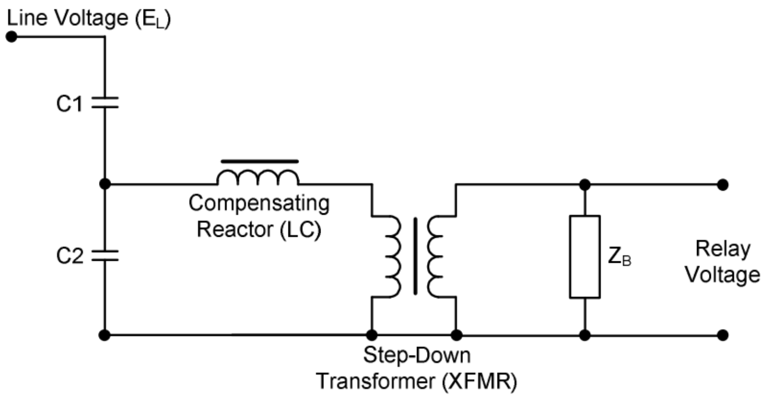


VT at Fdr Panel (132kV)
For DIST

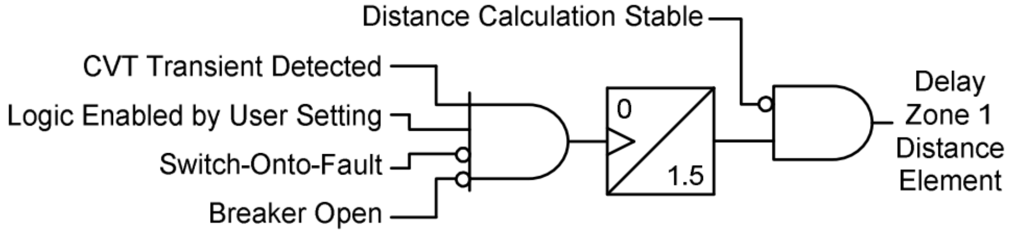


Capacitive Voltage Transformer - Introduction

- Capacitive Voltage Transformer (CVT) employs capacitance voltage divider concept.
- With inductor to form LRC resonant circuit at rated frequency (50Hz) to be pure resistive.
- Transient responses are less satisfactory due to transient oscillation with harmonics and inrush voltage during fault condition
- CVT transients are **larger** for zero-voltage point on wave faults, low CVT capacitance, AFSCs, high SIRs, low transformer ratios, high excitation current, and inductive and larger burdens (in VA).
- CVT transients are **lower** for peak-voltage point on wave faults, higher CVT capacitance, PFSCs, low SIRs, higher transformer ratios, low excitation current, and resistive and low burdens (in VA)
- For older relays, CVT caused distance overreach include disabling Zone 1, time-delaying Zone 1, or restricting Zone 1 reach per the guidelines based on burden, SIR, and ferro-resonance suppression design.



CVT Transient Logic



Capacitive Voltage Transformer – Equivalent Model

The output voltage is represented by

$$V_O = \frac{KV_pR_{eq}}{R_{eq} + j\left(\omega L - \frac{1}{\omega C}\right)}$$

where R_{eq} is the equivalent resistance reflected to primary circuit.

At resonance,

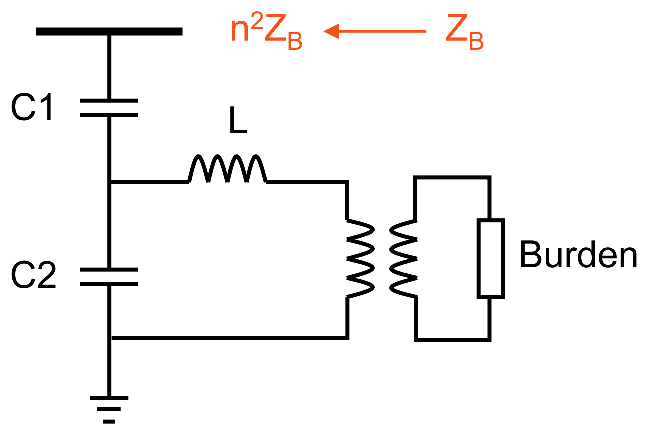
$$\omega_0 L = \frac{1}{\omega_0 C}$$

$$V_O = \frac{KV_p}{1 + j\frac{1}{\omega_0 C R_{eq}}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)}$$

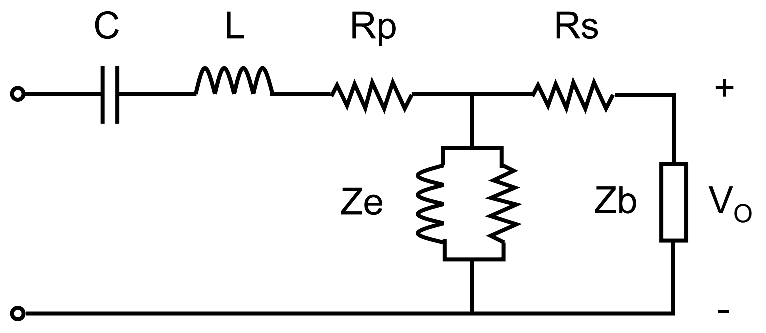
Hence

$$\frac{V_O}{KV_p} = \frac{1}{1 + jD}$$

$$D = \frac{1}{\omega_0 C R_{eq}}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) = \frac{\delta}{\omega_0 C R_{eq}}$$



Equivalent Circuit

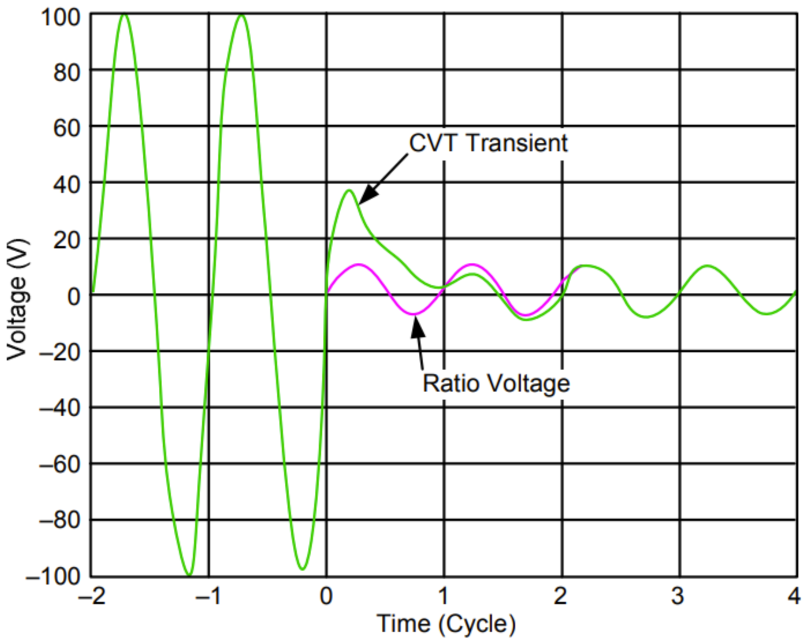


Transient Response to CVT (1)

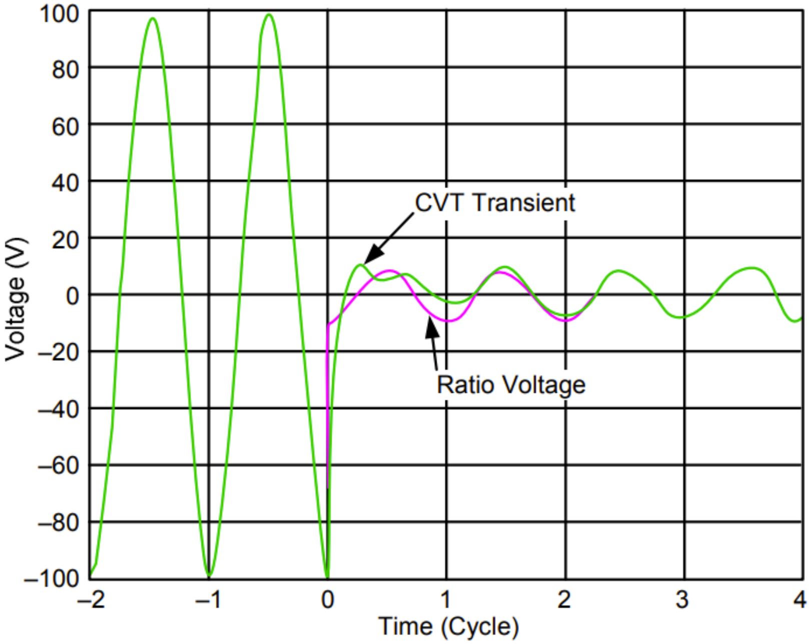
Point on Wave (Voltage) at Fault

- The energy stored in the compensating reactor is the same as the energy stored in the effective capacitance. The worst-case or longest transient response occurs when the maximum energy is stored in capacitor or when the primary voltage is at a zero crossing.

Fault at Zero Voltage Angle



Fault at Peak Voltage



Transient Response to CVT (2)

Magnitude of Tap and Stack Capacitance

- As the equivalent capacitance ($C_E = C_1 + C_2$) becomes larger, the capacitive reactance becomes smaller, resulting in a smaller discharge transient. However, increasing the value of C_E also increases transient duration.

CVT Burden

- The burden to be used for CVT testing includes inductive reactance. As the burden is increased, the primary current consists of the excitation current plus the load current;
- The greater the burden, the greater the energy storage in the reactive components and the greater the transient response at zero crossing fault initiation. A purely resistive or unity power factor burden does not store energy, but it does affect damping and the time constant (L/R).

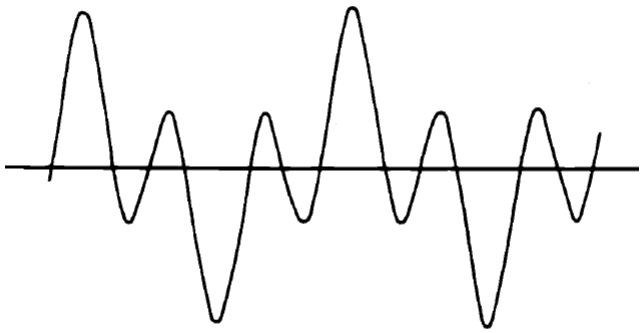
Turns Ratio and Excitation Current

- A higher turns ratio in the step-down transformer decreases the primary current by magnifying the burden.
- The smaller the current, the less energy is stored in the capacitor. From the perspective of the burden, the capacitance and inductance can be reflected to the secondary by n^2.
- Transformers with larger turns ratios (e.g., 15 kV to 20 kV/66.4 V) produce transients of lesser magnitude but longer duration. As the primary current is at non-unity power factor, sub-nominal frequency oscillations can occur and larger primary currents produce greater transients. Therefore, transformers are designed to minimize excitation current.

Ferroresonance in Capacitive Voltage Transformer (CVT)

Ferroresonance

- Exciting reactance Lm (changing, due to saturation) of auxiliary transformer and capacitance C_E of potential divider form a resonant circuit that can oscillate at a sub-normal frequency.
- If subjected to a voltage impulse, this circuit may oscillate and pass through a range of frequencies.
- If the basic frequency of this circuit is slightly less than one-third of the system frequency, energy can be absorbed from the system, causing the oscillation to build up. This results in a progressive build-up until the oscillation stabilizes as a sustained third sub-harmonic of the system.

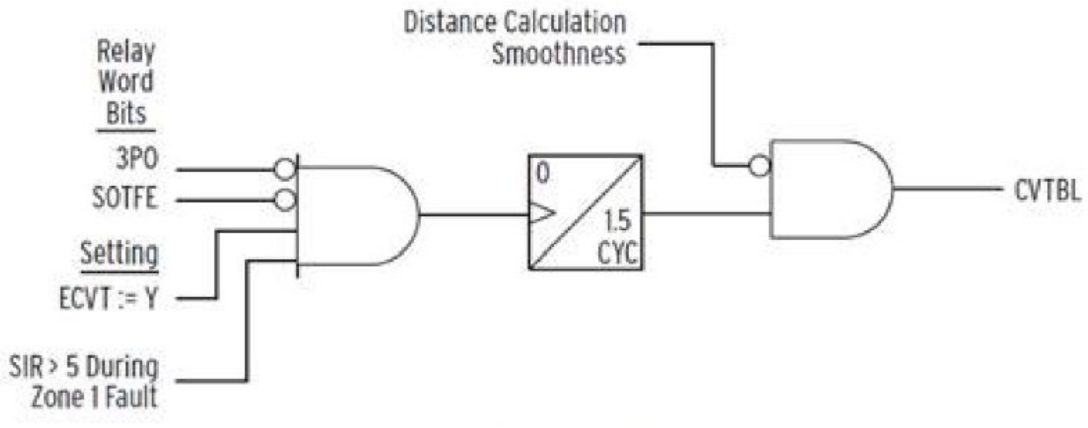


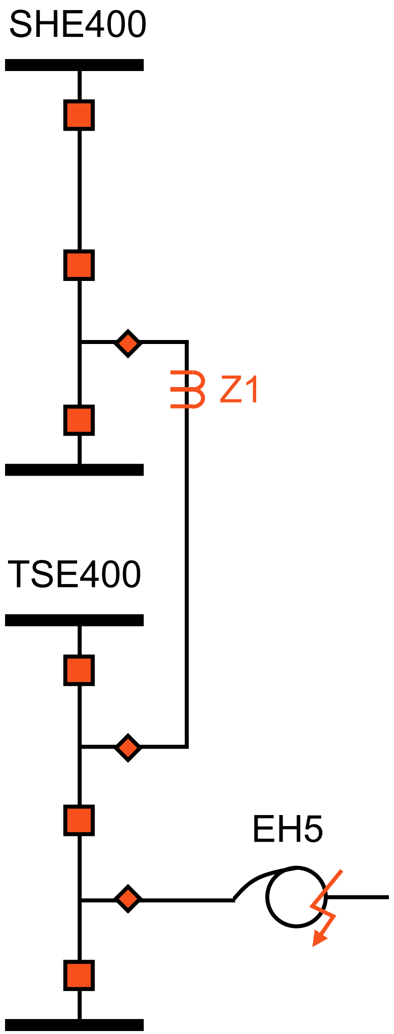
Effect of CVT to Protective Relays

1. **Frequency relays** depend on the speed of operation and normally require a time delay.
2. **Undervoltage/overvoltage relays** cannot respond to instant voltage changes, so a time delay is preferable.
3. **Distance relays** can experience errors in measurement, both over-reach and under-reach, due to CVT transients. Slower responding relays are not affected.
4. **Directional relays** can have momentary directional errors for relays without time delay.

PGG084 – SEL421 CVT Setting Change

- In 2013, there was a genuine internal fault on TSE Tx EH5. The circuit was tripped on transformer main protection. However, SHE – TSE 2 was simultaneously tripped on distance protection. The distance relay SEL421 at SHE was found mal-operated in Zone-1 for the remote transformer fault (transient overreach).
- To improve relay stability, CVT transient logic shall be enabled as advised by manufacturer. Putting setting “ECVT” to “Y”, the logic could prevent the zone-1 element from mal-operation when distance calculation is not smooth and Source Impedance Ratio > 5. (typed SEL)
- If the distance calculation is not smooth, e.g. using CVT in system, ECVT = Y so that Zone 1 is blocked for 1.5 cycles when SIR > 5. Zone 1 will not be blocked if SIR < 5.



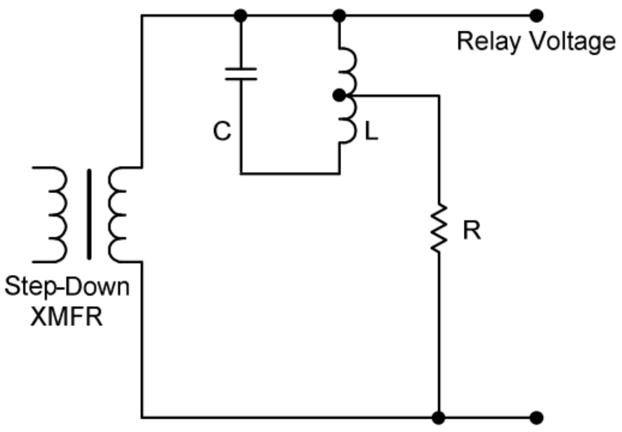


Transient Response to CVT (3)

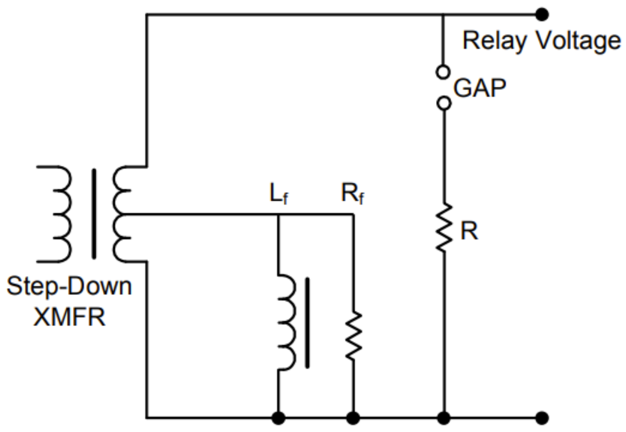
Ferroresonance Suppression Circuit

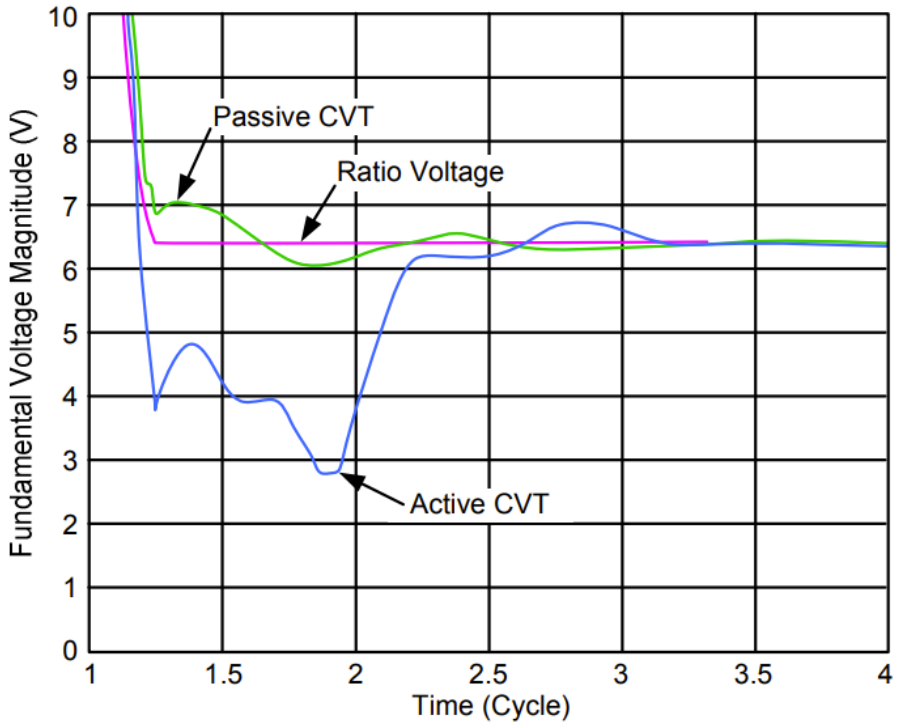
- All CVTs require ferro-resonance damping. The composition of the ferro-resonance suppression circuit dramatically affects the CVT transient response.
- Active ferro-resonance suppression circuits (AFSCs) contain capacitors and inductors, which are both active energy storage devices, and introduce added time delay in the CVT secondary voltage output.
- Passive ferro-resonance suppression circuit (PFSC) uses resistance and has little effect on the transient.

Active FSC



Passive FSC





Test for Voltage Transformer (1)

- [x] Fence off the testing area.
- [x] Ensure the test leads, test sets and working gloves have sufficient insulation level.
- [x] Discharge the windings after each test.

Should also check if there is any **shorted condition** in VT

2.1 Insulation Test

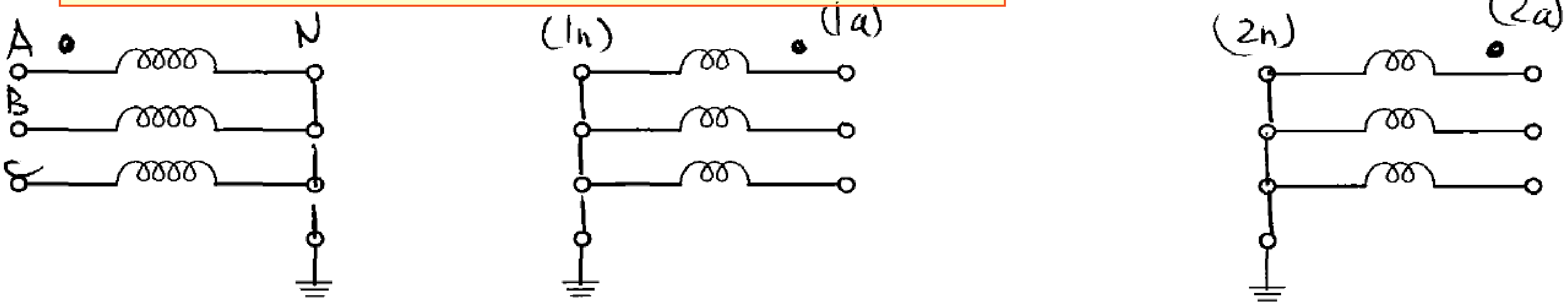
Insulation Test = Megger Test (> 2MΩ)

Instrument Used	Test Voltage	VT to Earth (M. Ohm)	VT to VT (M. Ohm)
Fluke 1507 5151257	500V	>500	>500

2.2 VT Connection and Flick Test

Flick Test = Polarity Test

- [x] Ensure the VT is not flicked from the LV side. Only flick from the HV side.



Test for Voltage Transformer (2)

2.3 Ratio Test

☑ Only apply the test voltage to the HV side NOT LV side

(i) Three phase balance injection

Primary voltage injected:

RW ___/___ V ; WB ___/___ V ; BR ___/___ V

RE __762__ V ; WE __762__ V ; BE __762__ V

Secondary voltage measured:

(1a-1n) RE __0.639__ V ; WE __0.636__ V ; BE __0.638__ V

(2a-2n) RE __0.638__ V ; WE __0.635__ V ; BE __0.637__ V

(ii) Open delta ratio test (short circuit RWB's primary winding together and apply single phase voltage w.r.t. earth potential)

Primary injected voltage: ___/___ V

Open delta voltage measured: ___/___ V

System Protection for 132kV Capacitor Bank

- Capacitor banks are switched in to compensate voltage drop across transformer after power factor improvement (i.e. raise voltage). However, due to load variation (or load rejection), the network may be subject to higher voltage than expected.
- Lifetime of capacitor depends on applied voltage and any overvoltage during normal operation.
- Capacitor cells are internally fused. Capacitor cell burning would lead to smaller reactance at the section, hence the shared voltage at other sections would *increase*.
- If a continuous power frequency overvoltage exceeds 110% of nominal voltage, the capacitor bank should be tripped after a variable time delay by an overvoltage (OV) relay.
- The variable time delay is to allow disconnection of capacitor in stage.
- It is called a system protection, as it avoids system equipment including the capacitor subject to continuous overvoltage. It does not trip the capacitor because of capacitor fault.