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Investigation on Capacitive Voltage Transformers (CVT) Failure at 220 KV Switchyard

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Abstract: ***In a high voltage system, the Instrumentation transformers are vital for measurement and protection. Any unexpected behaviour during their operation or commissioning can raise serious concerns and potential operational risks. An investigation was conducted to identify the root cause of the failure of the on CVT failure at 220 KV Switchyard.***

Keywords: Capacitive Voltage Transformers, Capacitive Voltage Divider, Electromagnetic Unit

1. Introduction

Instrumentation transformers are essential components in power distribution and transmission networks. Their primary role is to step down large system voltages and currents into lower, standardized values that can be safely used by measuring instruments and protective relays.

There are two main categories of instrument transformers, each serving a distinct function:
- **Current Transformers (CTs):** These provide an accurate scaled-down replica of the primary current, enabling safe and precise measurement or protection.
- **Voltage Transformers (VTs):** These transform high system voltages into safe, measurable values that represent the operating voltage of the network.

Voltage transformers are further classified into two major construction types: **inductive** and **capacitive**.
1) **Inductive Voltage Transformers (IVTs):** These are constructed similarly to power transformers, typically consisting of a laminated steel core with both primary and secondary windings wound around it.
2) **Capacitive Voltage Transformers (CVTs):** It work on voltage divider principle. It has two key components: a Capacitive Voltage Divider (CVD) and an Electromagnetic Unit (EMU). It is also known as coupling capacitor voltage transformer (CCVT).

Parts of Capacitive Voltage Transformer (CVT)
a) The **Capacitive Voltage Divider (CVD)** is the first stage of voltage reduction. The **CVD** takes the **primary system voltage** applied at the high-voltage (HV) terminal (top of the capacitor stack) and reduces it to an **intermediate voltage**, typically around **22 kV**.

This intermediate voltage is then supplied to the second major component, the **Electromagnetic Unit (EMU)**, which further transforms it to the standard secondary voltage (e.g., 110 V or 100 V) suitable for measurement, protection, and metering. The CVD is constructed from **one or more hermetically sealed capacitor elements**, stacked vertically depending on the rated primary system voltage.

An additional feature of the capacitor stack is its ability to **inject and extract high-frequency signals** into the power line conductor. This allows CVTs to be used in **Power Line Carrier Communication (PLCC)** systems for:
- Substation **feeder distance protection relays**
- **Supervision and telemetry** functions
- **Voice communications** between substations

This dual functionality (voltage transformation and communication) makes CVTs highly versatile and valuable, particularly in high-voltage transmission networks making their design cost-effective and widely adopted in power distribution and transmission networks, particularly at system voltages of 66 kV and above.

b) The **Electromagnetic Unit (EMU)** is the second key component of a Capacitive Voltage Transformer (CVT). It performs the final transformation of the intermediate voltage (from the CVD) into a standardized secondary voltage suitable for measurement, protection, and metering.

The EMU consists of two main elements:
- **Step-down Transformer:** Further reduces the intermediate voltage (typically ~11-22 kV) supplied by the CVD to the standard secondary level (e.g., 110 V or 100 V).
- **Compensation Reactor:** Provides an inductive reactance that balances the capacitive reactance introduced by the CVD. This ensures that the secondary output accurately represents the true primary system voltage, free from distortions caused by the divider's capacitance.

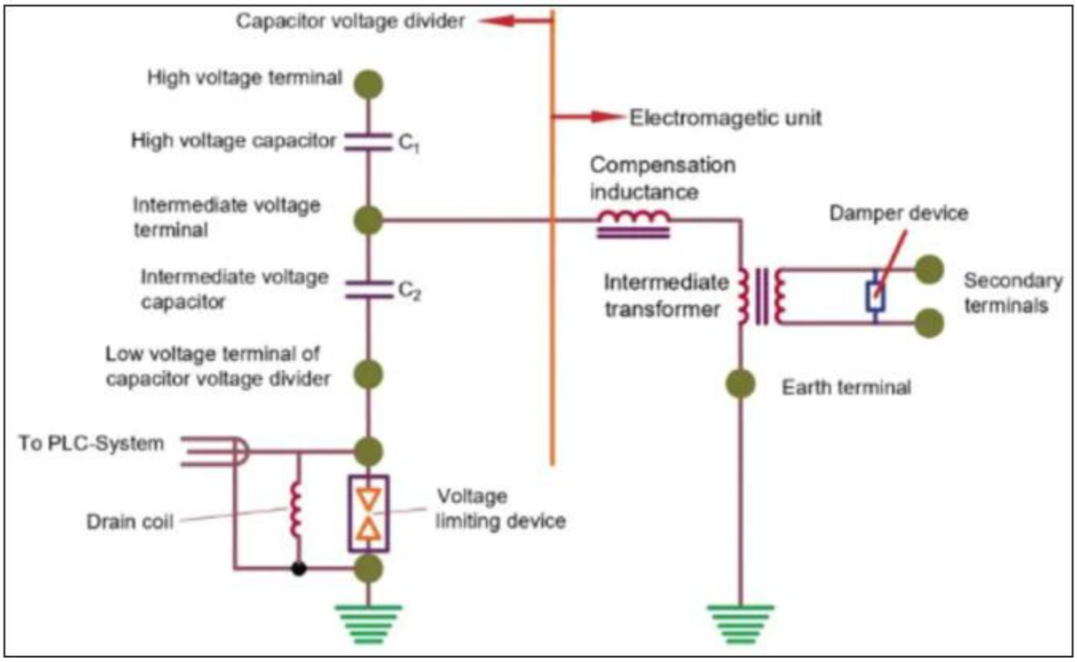


Figure 1: (https://www.electricalvolt.com)

c) Resonance unit in CVTs and the Role of the Damping Circuit

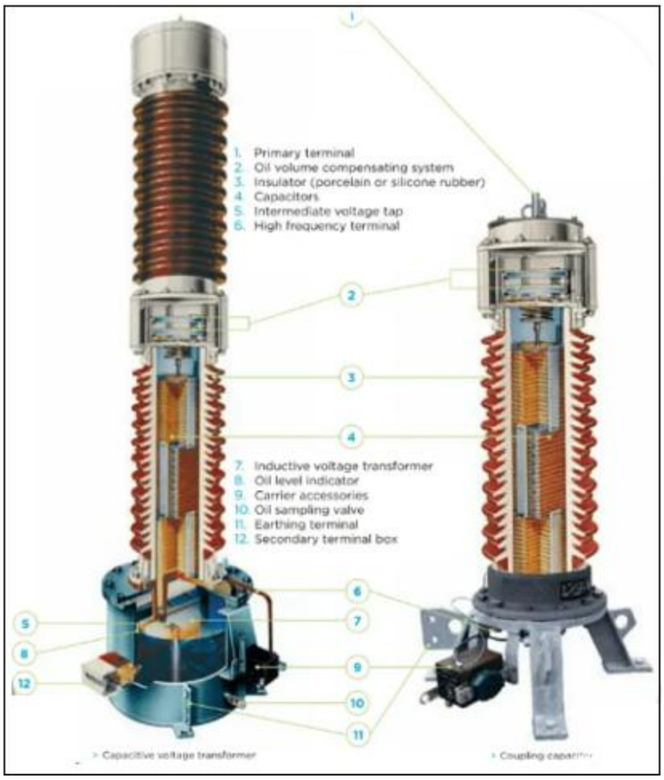
A **Capacitive Voltage Transformer (CVT)** behaves as a combined **capacitive–inductive circuit** due to the presence of the capacitor divider (CVD), compensation reactor, and transformer windings. Like any LC circuit, it has a **natural resonant frequency**. i.e. XL= XC,

$$\omega L = \frac{1}{\omega(C_1 + C_2)}$$

This resonance can be excited by certain **network disturbances**, such as switching transients, faults, or harmonics. If resonance occurs:

- The **iron core of the EMU transformer** may saturate,
- Excessive **heating** can develop,
- Leading to **insulation breakdown** and possible CVT failure.

To prevent this, a **damping circuit** is connected in parallel with one of the EMU secondary windings. The damping circuit absorbs oscillations and dissipates the resonant energy, ensuring that the CVT provides a **stable and accurate secondary voltage output** under all operating conditions.



Applications:

- **Metering:** Used to obtain accurate voltage measurements in high-voltage networks for metering and monitoring purposes.
- **Protection:** Provides dependable voltage inputs to protective relays, ensuring proper system protection and fault detection.
- **Communication:** Serves as a coupling device for transmitting communication signals through power lines in PLCC systems.

Advantages:
- Economical compared to conventional electromagnetic voltage transformers, especially suitable for very high-voltage applications.
- Compact and lightweight, allowing easier handling, installation, and maintenance.
- Ensures consistent and precise voltage output under varying operating conditions.

Disadvantages
- Slower transient response compared to electromagnetic voltage transformers (EVTs).
- Susceptible to ferro resonance.
- Accuracy affected by frequency variations
- Moisture ingress or deterioration of capacitor elements can affect accuracy and insulation.
- Cannot drive high-burden loads (Limited Burden Capacity).
- More complex design than conventional VTs.

Comparison between a Capacitive Voltage Transformer (CVT) and an Electromagnetic Voltage Transformer (VT or PT):

Parameter	Capacitive Voltage Transformer (CVT)	Electromagnetic Voltage Transformer (VT / PT)
Working Principle	Uses a capacitive voltage divider and a tuning transformer to step down voltage.	Uses electromagnetic induction between primary and secondary windings.
Construction	Combination of capacitors, inductors, and transformer elements.	Simple magnetic core with primary and secondary windings.
Accuracy (Steady State)	High accuracy for metering and protection under normal conditions.	Very high accuracy and linearity across wider load ranges.
Transient Response	Slower; may distort transient signals.	Faster, captures transients and switching surges more accurately.
Ferro resonance	Prone to ferro resonance under certain conditions.	Rarely affected by ferro resonance.
Burden Capacity	Low burden handling capability.	Higher burden handling; can drive more instruments.
Frequency Dependence	Accuracy varies slightly with frequency.	Less affected by frequency variations.
Size and Weight	Compact and lightweight, especially for high-voltage applications.	Bulky and heavy, particularly above 100 kV.
Cost	More economical at high voltages (≥132 kV).	Costly for very high voltages due to insulation requirements.
Maintenance	Requires periodic testing of capacitor health.	Comparatively low maintenance.
Applications	Common in EHV and UHV systems (132 kV and above).	Preferred in LV and MV systems (up to 66 kV).
Communication Use	Can couple signals for Power Line Carrier Communication (PLCC).	Not suitable for PLCC.

Impacts of CVT Failure in a Substation

The failure of a Capacitive Voltage Transformer (CVT) within a substation can lead to significant technical, operational, and reputational consequences. Potential impacts include:
- **Network Outages:** Loss of voltage signals may result in incorrect operation of protection schemes, leading to tripping and widespread outages.
- **Reduced Network Flexibility:** Limitations in switching and load management due to unavailable voltage measurements.
- **Safety Risks:** Increased hazards to both personnel and the public from equipment malfunction or secondary failures.
- **Collateral Equipment Damage:** Failure may induce overvoltages, maloperations, or cascading faults, damaging other equipment within the substation yard.
- **Reputational Damage:** The responsible distribution or transmission network operator may face loss of trust from stakeholders, regulators, and consumers.
- **Reliability and Security Risks:** Potential compromise of overall grid stability and secure power supply.
- **Revenue Metering Inaccuracies:** Faulty voltage measurements may result in errors in billing and financial settlements.

Common Causes of CVT Failure

CVTs, like other substation equipment, are subject to electrical, mechanical, and environmental stresses. Typical failure causes include:
- **Insulation Breakdown:** Deterioration of capacitor stacks or internal insulation due to aging, partial discharges, or overvoltage.
- **Moisture Ingress:** Entry of moisture into the capacitor units or EMU, leading to dielectric degradation.
- **Contamination and Pollution:** Dust, salt, or industrial pollution causing tracking and flashovers.
- **Overvoltage Stress:** Switching surges, lightning impulses, or ferro resonance conditions exceeding design limits.
- **Manufacturing Defects:** Weak points in capacitor elements or poor assembly quality.
- **Thermal Stress:** Excessive heating from overloading or poor cooling conditions.
- **Mechanical Stress:** Damage from vibration, seismic events, or improper handling during installation/ maintenance.

2. Practical Examples

Case:1

At **Hindalco Industries Ltd., Mahan, Singrauli (M.P.)**, a progressive increase in losses was observed on the **220 kV transmission line** from the **Captive Power Plant (CPP)** to the **rectifier** on a month-to-month basis.

Measurements and monitoring revealed that the **voltage outputs of the R and Y phases had increased**, irrespective of the input voltage from the CPP. Such behavior strongly indicated a **ratio error in the existing Capacitive Voltage Transformer (CVT)**. Ratio errors in a CVT can lead to inaccurate voltage measurements, To restore correct voltage measurement, the **defective CVT was replaced with a new unit**. Post-replacement monitoring confirmed that:

- **Voltage readings returned to normal levels** for all three phases.
- **Transmission line losses decreased**, improving overall efficiency.

Case 2

One day, the **CVT of the 220 kV transmission line-2 (R phase)** suddenly stopped giving output. The line was taken **under shutdown with due permission from SLDC**. A thorough inspection was carried out. All **fuses in the control panel** and **inside the secondary box of the CVT** were checked and found to be intact, indicating that the fault did not lie in the external circuitry or protection elements. Based on this observation, it was **concluded that the fault originated internally within the CVT**.

Further examination revealed that the **temperature of the CVT tank had risen to approximately 51 °C**, which is significantly higher than normal operating conditions. This abnormal heating suggested a **potential internal malfunction**, likely associated with the **Electro-Magnetic Unit (EMU)** of the CVT.

Further investigation and discussion with the **OEM** (Original Equipment Manufacturing) revealed that the **model of the CVT that installed at the plant** was equipped with a **resin-cast Electromagnetic Unit (EMU)**. Resin-cast EMUs, while robust and mechanically strong, have **limited heat dissipation capabilities**, which can lead to **higher operating temperatures** under continuous load or abnormal conditions, as observed during the recent fault.

To address this issue and improve the reliability of the CVT, the **OEM is now replacing the resin-cast EMU with a paper-wrapped EMU**, for **better heat dissipation** due to improved thermal conductivity and natural ventilation between the winding layers. This enhances **cooling of the EMU windings**, reduces the risk of overheating, and ensures more stable voltage outputs over a wide range of operating conditions.

3. Prevention and Mitigation Measures

To minimize the risks and impacts of CVT failure, utilities and operators adopt the following strategies:

- **Regular Inspection and Testing:** Routine visual inspections, insulation resistance testing, and partial discharge monitoring, Voltage unbalance, and harmonic content.
- **Condition Monitoring:** Annual Monitoring of capacitance, tan-delta (dissipation factor), to detect early degradation.
- **Proper Installation and Earthing:** Ensuring correct assembly, mechanical stability, and effective grounding practices.
- **Environmental Protection:** Use of weatherproof sealing, protective coatings, and periodic cleaning in polluted or coastal areas.
- **Surge Protection:** Installation of surge arresters to safeguard against lightning and switching overvoltage.
- **Ferro-resonance Control:** Application of damping resistors or design modifications to prevent sustained ferro-resonance.
- **Spare Management and Redundancy:** Maintaining critical spares and designing redundancy for protection and metering circuits.

Author Profile

Kumar Gautam, received the B.E degree in Electrical & Electronics Engineering from BIT Mesra in 2011. He is currently working in Hindalco Industries Ltd Mahan Aluminum Bargawan as DH – 220 KV Transformer, switchyard and transmission line. He is a Certified **Energy Manager and Energy Auditor.** His research interests are in Generators, Transformers and switchyard.

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