Evaluating the Response of Surge Arresters to Temporary Overvoltages

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Outline

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Motivation

- Metal-Oxide Surge Arresters (MOSAs) protect equipment from transient microsecond-duration overvoltages.
- Temporary Overvoltages (TOVs) can damage surge arresters.
- Conservative evaluation based on available data needed to determine if TOV damages arrester.
Background
TOVs ...

- ... are oscillatory voltages with frequencies that have periods of a few millisecond or longer.
- ... have a limited duration that can last between a single cycle and a few hours.
- ... have magnitudes that range from above Maximum Continuous Operating Voltage (MCOV) to a few times rated voltage.
TOVs are caused by...

• ... single-phase-to-ground faults, which can cause overvoltages on the unfaulted phases.
• ... energization of long lines/cables/transformers.
• ... load rejection when one end of the line is open.
• ... interaction of capacitive and inductive elements with non-linear magnetizing characteristics (ferroresonance).
MOSAs ...

- ... consist of microcystalline metal-oxide grains that are isolated from each other by a thin intergranular phase.
- ... have highly non-linear impedances that are established at the interface between the grains and phases.
MOSAs operate in the ...

- ... leakage region during normal system condition.
- ... protective region when “clamping” prospective overvoltage to non-damaging levels. Protective region can be expressed by a number of exponential segments with varying $\alpha$. 

![Diagram](image-url)
TOVs cause MOSA damage because ...

- Excessive localized heating, resulting in irreversible changes of the metal-oxide material (worm-holing).
- Hoop-stress fracture – the center of the disk heats faster than the periphery resulting in mechanical stress and an axial crack in the outer insulated coating on the disk.
- Classic thermal instability.
Arrester Duty in Response to TOV

- Multiple low-current, long-duration discharges
  - Low current => less uniform discharge
  - Long duration => larger energy dissipated, but arrester has time to cool off
  - Hot spots and “softening” of the MOSA potentially resulting in failure even at MCOV.

- How to capture these intricacies in a TOV analysis?
Testing and Standards
Testing

• Manufacturers publish TOV curve of their arresters.

• IEEE C62.11-2012 Test
  1) Apply 50/60 Hz voltage for duration x from TOV curve to four test samples.
  2) Apply recovery voltage for 30 minutes or longer.
  3) Arrester passes if no physical damage and electrical properties not changed significantly.
Evaluation Methodologies
Evaluation Based On Energy

**General idea:** Compare arrester-absorbed energy from simulations and arrester energy rating.

**BUT:**

- Arresters do **not** have an intrinsic energy rating – rating different for different waveforms.
- Manufacturer publish only switching surge energy rating, which is different from TOV energy rating.
Estimating TOV Energy Ratings

- ... switching surge rating (from specs or typical).
- EMT simulations of the IEEE TOV test. Requires accurate VI characteristic in the low-current region.
- EMT simulation of the high-current, short duration test, and/or the low-current, long duration test. Not quite the same as a TOV, though.
- All methods above are flawed, but still have value.
Evaluation Based TOV Curve

What we know from the TOV curve:
Arrester able to withstand 50/60 Hz voltage of magnitude y for time x.

• TOV from EMT simulation of TOV-producing event
  – Per unitize simulated TOV using MCOV as base.
  – Get (1) largest peak $y_{\text{sim}}$ and (2) duration $x_{\text{sim}}$ for which the TOV is above vendor-specified level of concern.

• Get TOV curve value $y_{\text{curve}}$ that corresponds to $x_{\text{sim}}$
• Arrester can withstand TOV if $y_{\text{sim}} < y_{\text{curve}}$
Caveats of TOV Curve Method

• IEEE TOV test method does not account for distorted waveshapes.

• Engineering judgment needed regarding what is a TOV and what is a transient.

• Leave MOSA in the simulation or not?
  – Take out: MOSA clamping capability distorts TOV, difficulty to build accurate MOSA model, conservative to take them out
  – Leave in: Overly conservative for weak TOV sources.
Case Study
Typical Wind Plant Topology

- Wind Turbine Generators (WTG) generate power at LV.
- Transformer at each WTG steps up LV to MV.
- Collector system delivers WTG power to substation where voltage is stepped up to transmission level.
- Arresters installed on collector system to protect equipment from transients.
TOVs in a Wind Plant

1) Single Line to Ground (SLG) fault on collector system.
2) Collector system breaker opens and isolates collector. WTG continue to supply energy.
3) TOV develop on unfaulted phase because of
   – Loss of ground source
   – Interaction between WTG transformer impedance and capacitances (Ferroresonance)
Simulation Scenarios

**Scenario 1:** Ungrounded operation during islanding condition (no TOV mitigation).

**Scenario 2:** Grounding switch closes 20 ms after feeder breaker opens.
Sequence of Events

$t = 0$  
Simulation starts

$t = 100 \text{ ms}$  
Permanent single-phase-to-ground fault on phase A on the collector system.

$t = 167 \text{ ms}$  
Feeder circuit breaker opens

$t = 187 \text{ ms}$  
Grounding switch closes in Scenario 2

$t = 250 \text{ ms}$  
All WTGs trip
Simulated Voltage at MOSA

Scenario 1: no mitigation

Scenario 2: grounding switch
TOV Analysis, Energy

Scenario 1: no mitigation

Scenario 2: grounding switch
TOV Analysis, TOV Curve

Scenario 1: no mitigation

Scenario 2: grounding switch
TOV Analysis, TOV Curve

• **Critical Threshold**: 1.26pu (end of TOV curve)

• **Scenario 1, no mitigation**
  Threshold of concern exceeded for 85 ms
  => TOV threshold 1.69pu

• **Scenario 2, grounding switch**
  Threshold of concern exceeded for 25 ms
  => TOV threshold 1.76pu
Discussion of Case Study Results

Q1: Did arrester pass energy test in both scenarios?
A1: Yes (by a wide margin)

Q2: Did arrester pass TOV curve test in both scenarios?
A2: No – arrester failed no-mitigation scenario

Q3: Would arrester have failed without mitigation?
A3: Probably not. MOSA fails TOV curve test marginally. Engineering judgment trumps cookie cutter recipes.
Summary: Challenges

- True TOV energy-handling capability uncertain
- Possible dependence of TOV failure on peak voltage
- Difficulty to include cooling effects in analysis.
- Difficulty to model accurately the arrester response to TOVs (requires knowledge of low-current region)
Summary: Hybrid Methodology

- **Energy evaluation**: Estimate arrester’s energy handling capability and compare estimate with simulated energy from EMT simulations.

- **TOV curve evaluation**: Evaluate arrester response to a sequence of peak voltages and compare to TOV handling threshold, which can be determined from the TOV curve and the duration of the TOV the arrester is discharging.