Resonance-Induced Overvoltages on Parallel Transmission Lines: Causes, Events, and Mitigation Strategies

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***Abstract*— Parallel high-voltage transmission lines are susceptible to induced voltages and resonance phenomena that can produce damaging overvoltages under certain operating conditions. This paper investigates such conditions on 230 kV and 345 kV transmission corridors with long parallel sections, focusing on two historical events involving a single-pole-open condition and a stuck breaker condition. Detailed Electromagnetic Transient (EMT) simulations, developed using NV Energy system data, replicate the observed overvoltages, reactor saturation, and protective relay operations. The analysis confirms that resonance near the fundamental frequency can sustain open-phase voltages above 1.5 per unit, drive shunt reactors into saturation, and initiate protection on unfaulted phases. Mitigation studies demonstrate that properly configured neutral grounding reactors reduce sustained voltages to below 1.05 per unit and limit transient overvoltages to within equipment withstand levels. The findings provide validated, field-based guidance for identifying high-risk transmission corridors and applying cost-effective mitigation strategies to improve system reliability and safety.**

***Index Terms*-- Protection relays, electromagnetic transient simulations, resonance-induced overvoltage, parallel transmission lines, mutual coupling, shunt reactor saturation, neutral grounding reactor, single-pole tripping.**

I. Introduction

Long, parallel high-voltage transmission lines are vulnerable to induced voltages on de-energized or single-pole-open phases, particularly when mutual coupling and the line-to-ground capacitance interact with the shunt reactor inductance to form resonance conditions near the fundamental frequency. Under these conditions, sustained overvoltages, shunt reactor saturation, and misoperation of protection schemes can occur.

Early work in [1] and [2] showed that shunt reactors could suppress secondary arcs in single-pole switching and provided charts relating arc current and recovery voltage to shunt compensation. These studies laid the foundation but did not address EMT modeling or validation with event records. In [2], harmonic resonance on parallel EHV lines was analyzed, showing that certain line lengths and configurations can amplify harmonic components. The work in [3] combined analytical modeling and field measurements to quantify induced voltages and currents under various terminations, focusing on steady-state conditions without modeling saturable reactors or fault-related resonance. In [4], induced voltages were investigated considering transposition, conductor geometry, and mutual impedance, producing accurate theoretical estimates but without validation against high-speed event data or fundamental-frequency resonance analysis. The study in [5] examined switching transients in de-energized double-circuit lines, demonstrating that the switching instant can nearly double transient overvoltages. However, the work predated modern frequency-dependent EMT tools and did not assess practical mitigation strategies.

While prior studies advanced understanding of induced voltages and resonance, key gaps remain: (a) reproducing real-world events with EMT models that include frequency-dependent lines and nonlinear reactor behavior, (b) validating simulations against field measurements, and (c) evaluating neutral reactor placement under varying contingencies.

In Northern Nevada, parallel 230-kV and 345-kV lines share corridors with strong coupling. Recent events in 2021 and 2022 showed that single-pole tripping and stuck breakers produced open-phase voltages up to 1.63 pu, driving reactors into saturation and triggering misoperations on healthy phases.

The contributions of this paper are as follows:

1) Utilize detailed EMT simulation results, validated by the Utility Company, to analyze real utility events and identify key mechanisms leading to induced overvoltages and resonance in parallel 230 kV and 345 kV lines.

2) Interpret simulation findings with historical event data, highlighting operational scenarios, such as single-pole tripping and stuck-breaker events, most prone to problematic resonance.

3) Evaluate neutral grounding reactors as a mitigation strategy.

4) Integrate event records, simulation outputs, and protection performance into a set of practical recommendations for planning, operation, and protection engineering in similar transmission corridors.

The remainder of this paper is organized as follows: Section II describes the system and historical events. Section III analyses the events. Section IV discusses the EMT modeling and simulation results. Section V discusses

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mitigation effectiveness. Section VI concludes with recommendations for design and operation.

II. System And Historical Events Description

The study system includes long 230 kV and 345 kV circuits with extended parallel sections sharing transmission structures, creating strong electromagnetic coupling that can excite resonance during switching or fault conditions. For the 345 kV network, the parallel circuits span long distances, with each line typically terminated at both ends by shunt reactors for voltage control under light load. Under open-phase conditions, such as after single-pole tripping or a breaker failure, the combination of line-to-ground capacitance on the open phase and the shunt reactor inductance can form a resonant circuit with a natural frequency close to 60 Hz. When resonance is excited, the open-phase voltage can sustain levels well above nominal, often exceeding 1.5 pu, and the reactor current can surpass neutral overcurrent trip thresholds. Figure-1 shows a simplified schematic of the system under study.

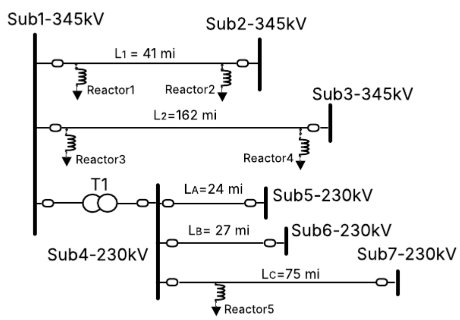

Figure 1. Simplified schematic of the system under study

For the 230 kV network, long parallel circuits exist between major load and generation centers. While the physical line lengths are shorter than in the 345 kV network, the close electrical proximity still allows induced voltages to appear on de-energized lines during switching or energization events. Although the 230 kV cases studied did not exhibit sustained fundamental-frequency resonance to the same degree as the 345 kV cases, mutual coupling during transients has produced measurable open-phase voltages and residual currents that require consideration in system operation.

A. Event 1 (October 4, 2022):

On October 4, 2022, at 5:54 AM, the 345 kV line between Sub1 and Sub2 experienced a single-pole trip initiated by line current differential protection due to communication channel asymmetry. The voltage on the open phase rose to approximately 325 kV (1.63 pu), causing the shunt reactors at both Sub1 and Sub2 to saturate. This saturation produced a high zero-sequence current that operated the instantaneous neutral overcurrent protection on the Sub1 reactor, resulting in three-pole tripping of the line.

B. Event 2 (July 16, 2021):

On July 16, 2021, a 345 kV parallel circuit experienced an open-phase condition after a breaker failure during switching. The line was initially de-energized. During an energization attempt, the remote terminal remained open while a closing operation was initiated at the local terminal. The closing operation resulted in an unbalanced condition in which two phases were successfully energized while one phase failed to close, leaving the circuit radial with one open phase and the shunt reactor still connected at the local terminal. This configuration created a true open-phase condition on a radial line. The resulting interaction between the open phase's line-to-ground capacitance and phase-to-phase capacitances and the connected shunt reactor produced a sustained overvoltage of about 1.5–1.63 pu, driving the reactor into saturation. The high zero-sequence current exceeded the neutral overcurrent threshold, tripping the line reactor and showing that even without a fault, open-phase resonance can lead to protection misoperation and equipment stress.

These events show that both 345 kV and 230 kV networks are prone to induced voltages and resonance in long parallel corridors, with 345 kV lines facing higher risk of sustained overvoltage near the fundamental frequency.

III. Event Analysis

This section analyzes the two major events described in Section II, with focus on their sequence of operations, overvoltage characteristics, harmonic content, and impact on protection schemes.

A. Event 1 Analysis

At 5:54 AM, a single-pole trip occurred on the 345 kV circuit between Sub1 and Sub2 due to line differential protection operating on communication channel asymmetry. The open phase voltage rose to ~325 kV (1.63 pu) for about one second and sustained by near-fundamental-frequency resonance in the zero-sequence network formed by the line capacitance and the shunt reactors connected at both line terminals. Mutual coupling from an adjacent line may have amplified the overvoltage, driving the shunt reactors into magnetic saturation, with phase currents reaching ~2 pu and residual current ~3 pu, exceeding the neutral overcurrent threshold and causing a three-pole trip. Such conditions, even over short durations, can impose significant electrical and mechanical stress on reactor components and associated protection systems.

Figure 2 shows the phase currents, phase voltages, zero-sequence voltage ($3V_0$), and key digital protection signals from the Sub1 line differential relay recorded during Event 1. After the single-pole trip, the open-phase voltage rises to about 1.63 pu. The current waveform becomes noticeably distorted which is a clear indicator of magnetic core saturation. The top pane illustrates the phase currents, where the faulted phase current drops close to zero while the healthy-phase currents remain steady. The second pane shows the voltages, with the open-phase waveform distortion developing as the overvoltage persists. The third pane shows the corresponding growth of $3V_0$ during the resonant condition. The bottom pane records the operation of key protection elements, capturing the single-pole trip on phase C followed by a three-pole trip initiated by the reactor lockout.

Figure 3 presents the harmonic analysis and raw current waveforms recorded by the Sub 1 shunt reactor relay during the same event. The harmonic spectrum in the upper pane confirms the presence of odd harmonics. The middle pane shows the increase in current caused by overexcitation of the shunt reactors due to the C phase overvoltage on the line. Overexcitation drives reactor core saturation, raising current to about 2 pu at 1.63 pu voltage, while phase alignment increased residual current to approximately 3 pu. The lower pane includes the neutral instantaneous overcurrent trip signal, marking the initiation of the reactor lockout. The total harmonic distortion is measured at approximately 13.13%.

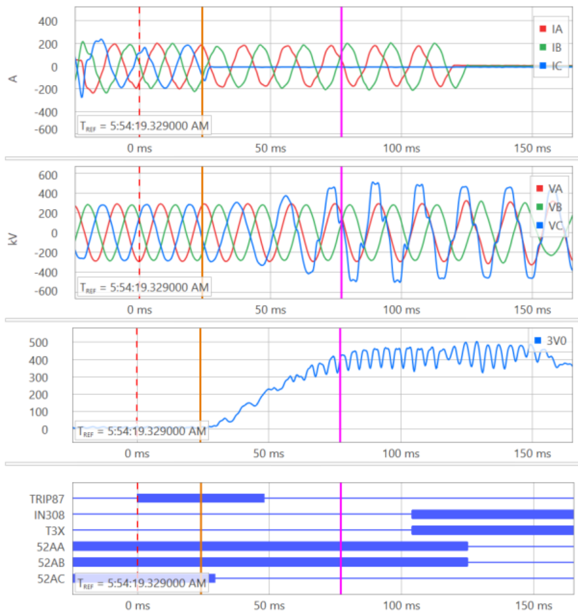

Figure 2. Sub1 relay record showing phase currents, phase voltages, zero-sequence voltage ($3V_0$), and trip sequence during Event 1.

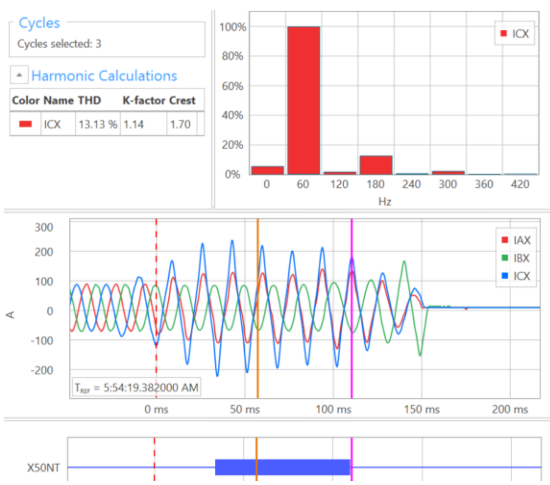

Figure 3. Sub1 shunt reactor relay record showing harmonic content, overexcitation current rise, and neutral overcurrent trip.

Figure 4 shows the voltage–current characteristic of the shunt reactor, highlighting the transition from the linear air-core region to the nonlinear iron-core region. At voltages below approximately 1.5 per unit, the relationship is nearly linear. Once this threshold is exceeded, the slope of the curve decreases and current increases sharply for small voltage changes, illustrating the onset of core saturation and the resulting high residual currents observed during the event.

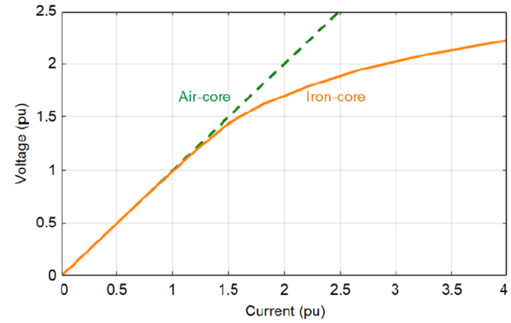

Figure 4. Typical shunt reactor voltage–current curve showing onset of iron-core saturation above 1.5 pu voltage [6].

Overexcitation drives increased excitation current and excess magnetic flux into steel components, but damage typically requires sustained heating over several seconds [7]. While a volts-per-hertz (V/Hz) curve for this specific reactor was not available, typical industry data indicates that damage thresholds are approached only after several seconds of operation. Reference [8] suggests this reactor type could withstand approximately 507 kV (line-to-line) for three seconds, but no threshold was provided for shorter durations. Given that the single-pole-open interval in this event lasted roughly one second, the protection trip likely occurred well before any material damage could develop.

It is possible the phenomenon was exacerbated by the absence of a fault arc to initially depress the open-phase voltage. However, similar overvoltage behavior has been observed in past events, including correctly cleared operations. In most cases, the open-phase voltage ramps up but remains below nominal. Notably, an event in 2011 recorded an open-phase voltage of 1.63 pu, although that incident involved a more complex set of system conditions.

The resonant frequency during single-pole-open conditions can be estimated using (1) [9]. Figure 5 shows the simplified equivalent circuit used to model the zero-sequence resonant path during a single-pole open condition, which forms the basis for the resonant frequency estimation in (1).

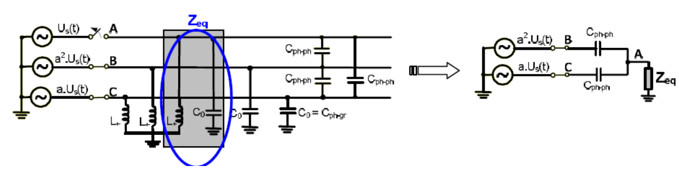

Figure 5. Simplified equivalent circuit for open-phase resonance (adapted from CIGRE C4.307 [9]).

$$f_n = \frac{1}{2\pi\sqrt{L\,(C_{\text{ph-gr}} + 2\,C_{\text{ph-ph}})}} \qquad (1)$$

where:

fn= resonant frequency (Hz)

L = shunt reactor inductance (H) as seen from the open phase

Cph–gr= line-to-ground capacitance of the open phase (F)

Cph–ph= line-to-line capacitance between the open phase and each energized phase (F)

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This expression accounts for capacitive coupling from both energized phases to the open phase. Using estimated capacitance values and nominal reactor inductance for this case yields a resonant frequency of approximately 52.9 Hz. Mutual coupling between circuits was not included in this estimate, and its inclusion could shift the resonant frequency even closer to the nominal system frequency of 60 Hz, further increasing the risk of sustained overvoltage during single-pole-open conditions.

B. Event 2 Analysis

Event 2 occurred during an energization attempt of a previously de-energized line. While the remote terminal remained open, a closing operation was initiated at the local terminal. Phases A and B closed successfully, while phase C failed to close, leaving the line radial with two energized phases and one open phase. The interaction between the open phase's capacitance, capacitive coupling to the energized phases, and the connected shunt reactor created a resonant condition with a natural frequency near the system's nominal 60 Hz. This resonance sustained an open-phase voltage in the range of 1.5 to 1.63 pu, driving the shunt reactor into saturation and generating elevated zero-sequence current.

The neutral overcurrent element operated and tripped the associated line reactor, despite the absence of any fault on the system. Event waveforms shown in Figure 6 display a stable overvoltage with minor harmonic distortion compared to Event 1, consistent with steady resonance rather than a transient build-up. The gradual increase in C-phase voltage between 0.3 s and 0.4 s reflects the build-up of the resonant condition. The open-phase voltage reaches a peak overvoltage and then reduces to a lower sustained oscillatory level as damping and losses in the network limit further growth.

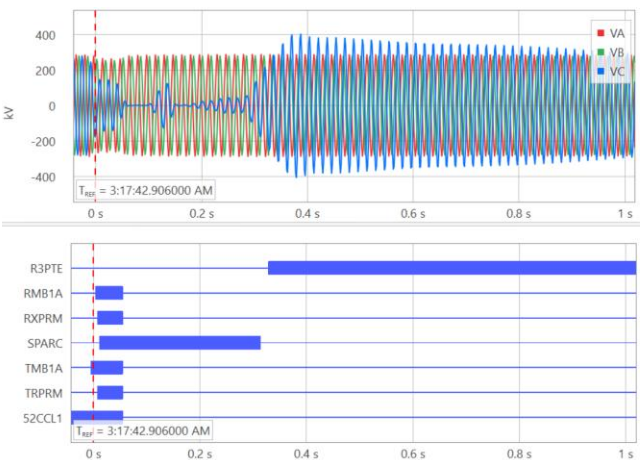

Figure 6. Open-phase voltage waveform during Event 2

These events demonstrate that sustained resonance conditions can persist until system configuration changes or breaker operations remove the resonant path, highlighting the need for both protective coordination and mitigation strategies.

IV. EMT MODELING AND SIMULATION RESULTS

The PSCAD models included frequency-dependent line representations, nonlinear shunt reactors, and mutual coupling between parallel 230 kV and 345 kV circuits. The objective was to replicate the observed behavior during field events and to evaluate the impact of mitigation measures such as neutral grounding reactors. Table I compares the measured open-phase overvoltage levels to the EMT simulation results for the two historical events. The EMT model reproduces the measured overvoltage range and sustained behavior observed in the relay/event records for both events. Minor differences are expected due to uncertainty in line parameters, representation of shunt-reactor saturation characteristics, and measurement effects such as VT scaling.

TABLE I. COMPARISON OF MEASURED VERSUS SIMULATED OPEN-PHASE VOLTAGE FOR EVENT 1 AND EVENT 2 (LINE-TO-GROUND)

Event	Measured open-phase voltage	Simulated open-phase voltage
Event 1	~325 kV (≈1.63 pu)	~320 kV (1.57 pu)
Event 2	~299–325 kV (≈1.5–1.63 pu)	~305 kV (1.53 pu)

A. Simulation Scenarios

Three representative configurations were studied:

- 230 kV Switching Event – Simulation of parallel 230 kV lines experiencing switching transients.
- 345 kV Stuck Breaker Condition – Parallel 345 kV lines with a stuck breaker leaving one pole open.
- 345 kV Single-Pole Open Condition – Sustained open-phase condition on one circuit of a parallel 345 kV line.

For each case, maximum transient voltage, steady-state voltage, and corresponding induced currents were recorded. Table II shows induced voltages on parallel 230 kV lines during switching. These results show that while the induced voltages at 230 kV are generally lower than equipment withstand levels, they can still produce measurable neutral currents that may affect protective devices. Table III shows a 345 kV stuck breaker condition without and with neutral reactor mitigation. Simulation results indicate that a neutral grounding reactor reduces both the magnitude and duration of overvoltage by over one-third, preventing reactor overexcitation.

TABLE II. SIMULATED INDUCED VOLTAGES ON PARALLEL 230 KV LINES DURING SWITCHING

Case	De-energized Circuit	Energized Circuit	Max Transient (kV)	Steady State (kV)	Induced Voltage (pu)
1	Line A (L_A)	Line B (L_B)	270	17	2.03
2	Line B (L_B)	Line A (L_A)	240	12	1.81
3	Line C (L_C)	Line B (L_B)	63.3	7.5	0.48

TABLE III. 345 KV STUCK BREAKER CONDITION WITHOUT AND WITH NEUTRAL REACTOR MITIGATION

Case	Shunt Compensation	Max Transient (kV)	Steady State (kV)	Reduction (%)
Base	0 Mvar	550	320	—
Mitigated	35 Mvar + Neutral Reactor	360	205	~35%

Table IV shows the 345 kV single-pole open condition. As shown, without mitigation, the single-pole open condition sustained overvoltages exceeding 5.0 pu for extended durations, closely matching field measurements from historical events.

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TABLE IV. 345 KV SINGLE-POLE OPEN CONDITION (RESONANCE NEAR 60 HZ)

Case	Shunt Compensation	Max Transient (kV)	Steady State (kV)	Induced Voltage (pu)
Base	0 Mvar	750	600	3.77
Mitigated	35 Mvar + Neutral Reactor	350	210	1.76

B. *Summary of Findings:*

Analysis of simulations and event data reveals:

- 230 kV cases exhibited moderate induced voltages, but neutral currents may still operate protection.
- 345 kV stuck breaker cases showed strong resonance potential, mitigated effectively by neutral reactors.
- 345 kV single-pole open cases presented the highest sustained overvoltages, with mitigation reducing both magnitude and duration dramatically.

V. MITIGATION STRATEGIES AND DISCUSSION

Beyond event replication, mitigation approaches were assessed through EMT simulations to address the resonance-induced overvoltages observed in both historical events:

1) *Neutral Grounding Reactors:*

Adding a high-impedance reactor in the neutral of existing shunt reactors proved highly effective in reducing sustained open-phase voltages and limiting transient overvoltages. Different impedance values were evaluated to determine an optimal balance between overvoltage suppression and acceptable neutral current levels during normal operation.

2) *Adjustment of Neutral Reactor Impedance:*

Variations in the neutral reactor impedance were analyzed to further refine mitigation performance. Results showed that moderately higher impedances reduced steady-state induced voltages while maintaining transient voltages within equipment Basic Insulation Level (BIL) limits.

For the 345 kV single-pole open scenario modeled after Event 1, adding a 2000-ohm neutral reactor in series with the existing 35 Mvar shunt reactor reduced steady-state induced voltages to below 1.05 pu and limited transient overvoltages well within BIL margins. For the stuck breaker case modeled after Event 2, adding a neutral grounding reactor substantially reduced overvoltage magnitude and duration, keeping steady-state voltages below 1.05 pu and transients within BIL limits.

In the 230 kV switching case, while induced voltages remained within equipment ratings, the addition of neutral grounding reactors provided additional margin and reduced the risk of protection misoperation due to residual currents.

Overall, adding neutral grounding reactors to existing shunt reactors proved the most practical and effective mitigation measure.

VI. CONCLUSIONS

Two open-phase resonance events on a long parallel 345 kV corridor demonstrated that interaction between line capacitance, mutual coupling, and shunt reactor impedance can sustain overvoltages exceeding 1.5 pu, drive reactor saturation, and initiate protection operation on otherwise healthy phases. EMT simulations successfully replicated both events, confirming that single-pole open and stuck-breaker conditions on 345 kV lines can exceed equipment withstand limits, while 230 kV switching scenarios produce measurable induced voltages and residual currents.

The mitigation studies showed that neutral grounding reactors applied in series with existing shunt reactors effectively suppressed both sustained and transient overvoltages, reducing steady-state voltages to below 1.05 pu and keeping transients within BIL limits. These results underscore the importance of assessing open-phase resonance risk on long parallel transmission corridors and using EMT-based studies during planning and design to identify targeted, practical mitigation measures. Among the options evaluated, neutral grounding reactors provided the most consistent and operationally practical solution.

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