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A CESI Company

Sustained Overvoltage due to Zero-Sequence Resonance for Shunt Compensated Transmission Lines

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Overview of Presentation

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- Zero-Sequence Resonance — Background
- Zero-Sequence Resonance — Mitigation Options
- Case Study — Large Wind Plant
- EMTP Simulation Results
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EnerNex Service Areas

Multiple disciplines coming together to solve the complex challenges facing the industry today

TACTICALPERSPECTIVE

STRATEGIC PERSPECTIVE

Electric Energy Systems Engineering & Analysis	Renewable & Distributed Energy Integration & Interconnection	Grid Technology Consulting	Grid Modernization	Electric Industry Evolution
Transmission & distribution utility studies, complex modeling & simulation	Solar & wind modeling, integration & interconnection studies	Cybersecurity, IEC 61850, utility procurement assistance, vendor due diligence, pre-certification testing, communications, cyber assurance	AMI, ADMS, DERMS, DR, enterprise architecture, microgrids, grid modernization, roadmaps	Strategic planning, business case development, change management, regulatory support

REPRESENTATIVE TYPES OF WORK

Zero-Sequence Resonance — Background

Zero-Sequence Resonance — Background

What is zero-sequence resonance?

- Zero-sequence resonance is a condition in electrical systems where the zero sequence impedance of a network creates a series resonant circuit during breaker unbalanced phase operation, leading to potential overvoltages.
- It is caused by the interaction between shunt reactors and phase capacitance in a disconnected phase, coupled with energy from energized phases.

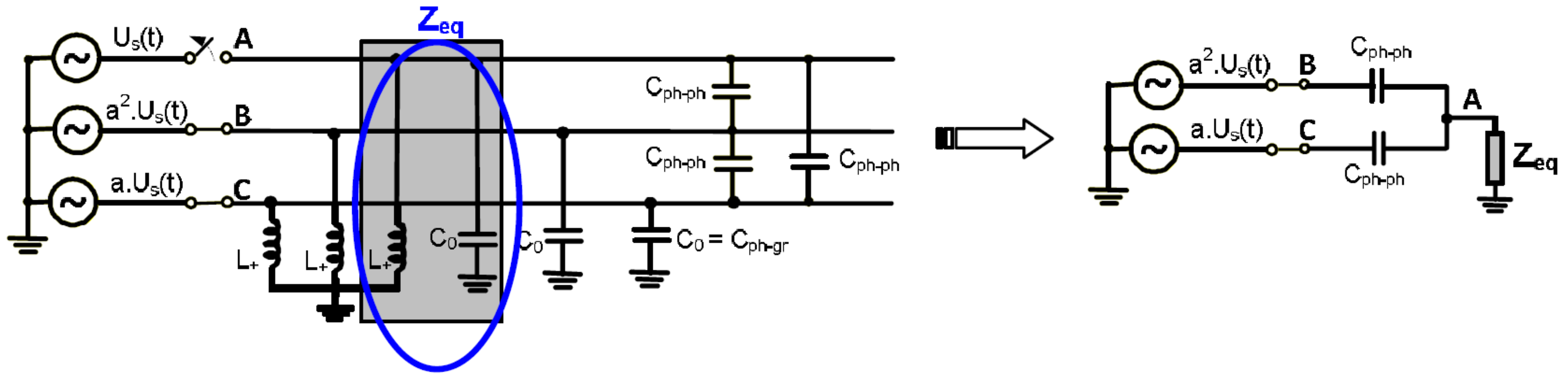

Figure 4-3 Simplified Equivalent Circuit during Single-Phase Opening

Reference: [CIGRE WG C4.307 (2014) Resonance and Ferroresonance in Power Networks]

Zero-Sequence Resonance - Background

When does zero-sequence resonance occur?

- Main elements required to form a series resonant circuit
  - Shunt reactors directly connected to a transmission circuit.
  - Inter-phase capacitive coupling.
  - At least one phase is disconnected.
  - At least one phase is energized.

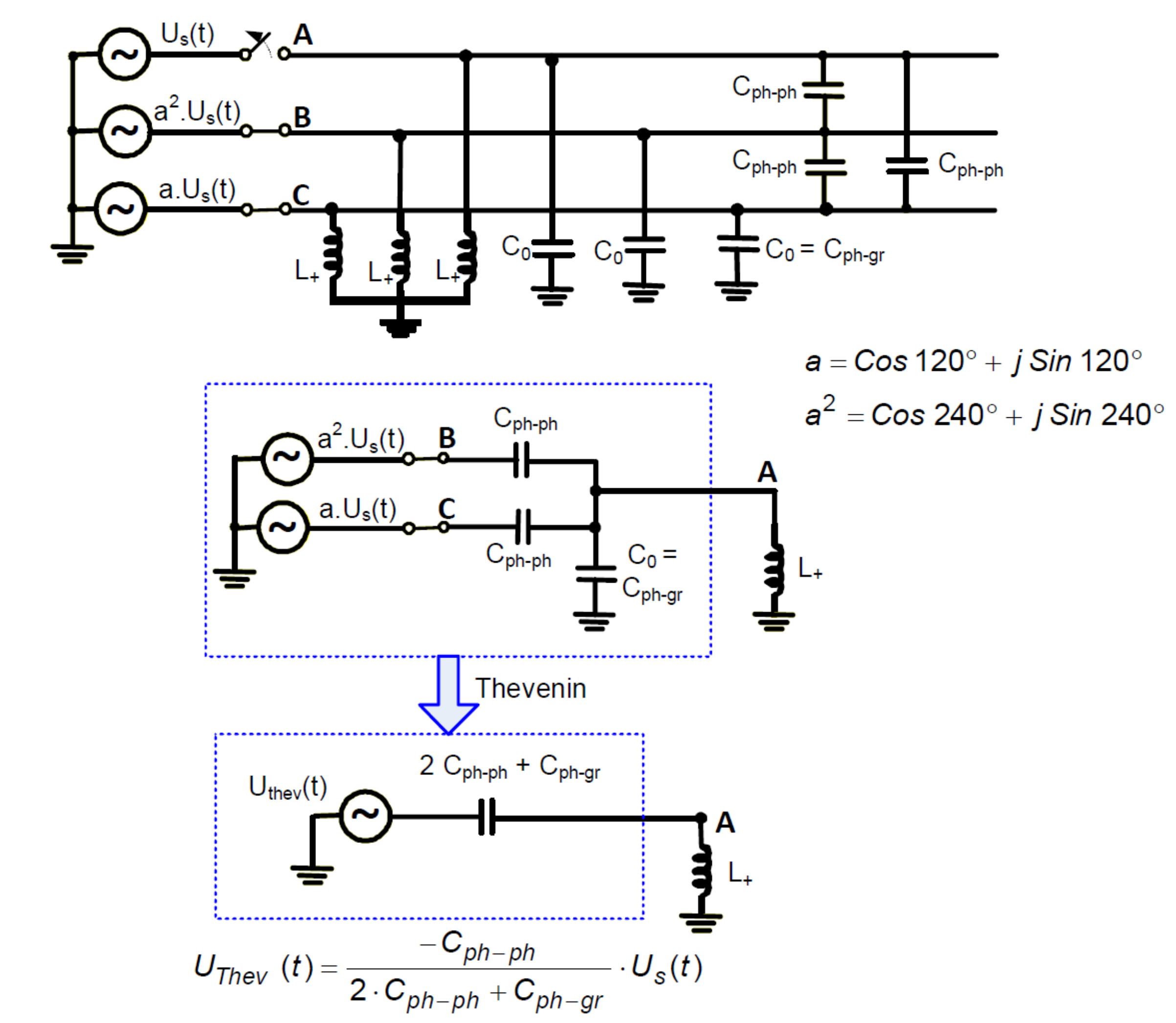

Figure 4-4 Simplified circuit for the analysis of Line Resonance

Reference: [CIGRE WG C4.307 (2014) Resonance and Ferroresonance in Power Networks]

Zero-Sequence Resonance - Background

What is reason of uneven/unbalanced phase operation?

- Intentional
  - Single-phase tripping schemes applied to improve system reliability and stability.
- Unintentional
  - Misoperation of circuit breakers or POW control, i.e., one or two poles getting stuck during an opening or closing.

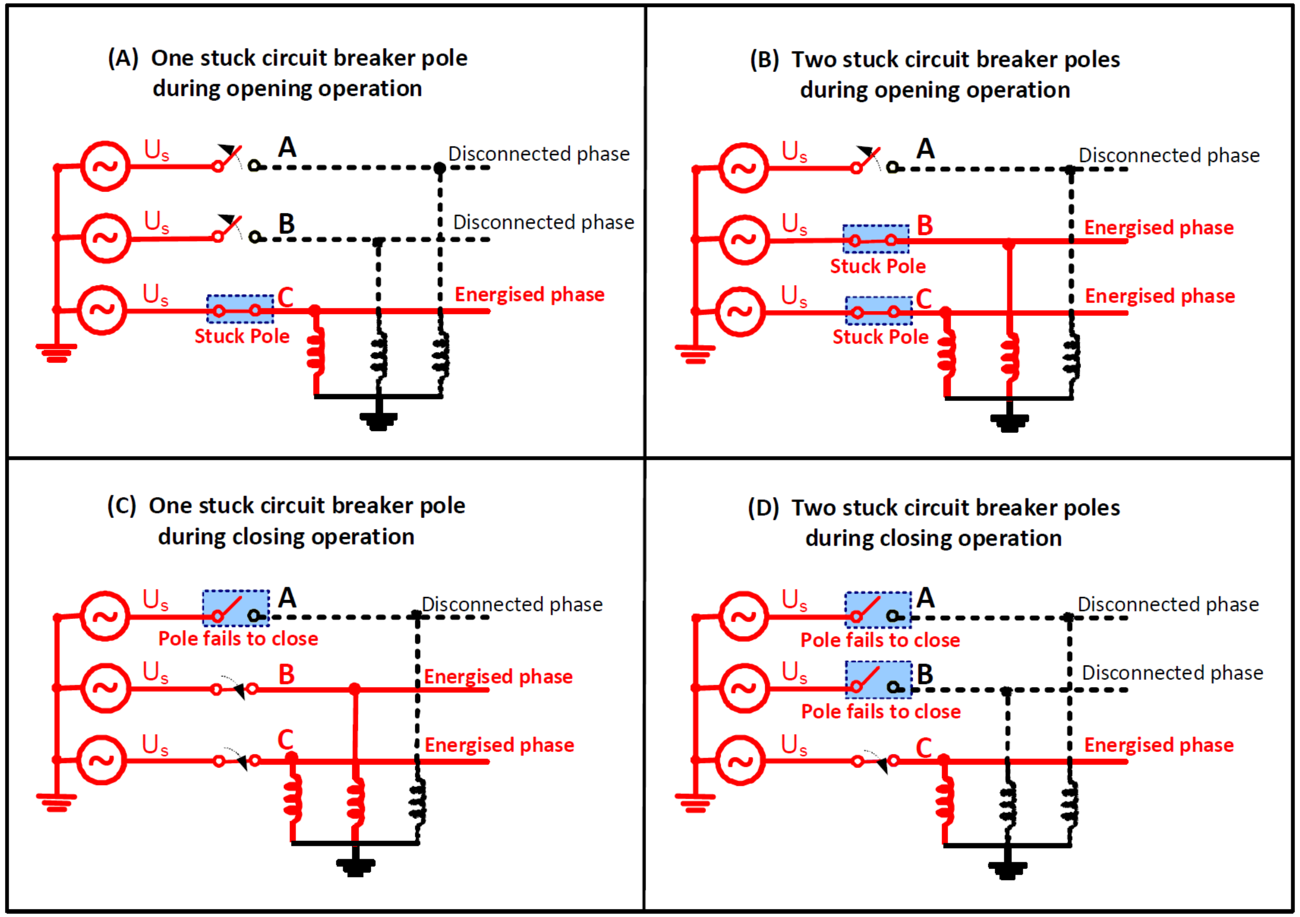

Figure 3-2 Uneven phase operation due to circuit breaker misoperation

Reference: [CIGRE WG C4.307 (2014) Resonance and Ferroresonance in Power Networks]

Zero-Sequence Resonance - Background

What is the impact of zero-sequence resonance?

- Resonance leads to sustained overvoltages.
- Resonant condition lasts till the uneven phase operation remains.
- Typically, protection will limit the duration of the uneven phase operation to less than 1 – 2 seconds.
- Large resonant overvoltages – even for a short duration - can damage the equipment.

https://www.inmr.com/practical-considerations-in-surge-protection/

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Zero-Sequence Resonance — Mitigation Options

Mitigation Options

Mitigation Type	Mitigation Option	Additional Details
Passive	Avoid shunt compensation degrees leading to resonance or near-resonance	The required amount of shunt compensation can be split between the line and the station (busbar or transformer tertiary winding) to limit the amount of compensation attached to a de-energized circuit.
Passive	Install Neutral Grounding Reactor (NGR) to detune zero-sequence resonances	The installation of NGR must be coordinated with the performance of Single-Phase Auto-Reclosing (SPAR) schemes. Adequate insulation levels must be specified for phase and neutral reactors. There is a requirement to adequately specify the energy duty of surge arresters across the phase and neutral reactors.
Passive	Install Neutral Resistors to damp zero-sequence resonances	Adequate insulation levels must be specified for phase reactors and neutral resistors.
Passive	Unground neutral point of shunt reactors	Adequate insulation levels must be specified for phase reactors. There is a requirement to adequately specify the energy duty of surge arresters across the phase reactors.
Passive	Select the type of Shunt Reactors depending on magnetic coupling between phases	Three-legged core type reactors have strong magnetic coupling, which shifts zero-sequence resonances to lower degrees of shunt compensation. Single-phase, 3-phase shell-type, or 3-phase 4/5 legged core reactors will shift zero-sequence resonances to lower degrees of shunt compensation.
Passive	Avoid the use of single-phase switching	This measure will mitigate resonance associated with SPAR; however, it does not prevent resonance arising from circuit breaker misoperation or stuck poles.

Reference: [CIGRE WG C4.307 (2014) Resonance and Ferroresonance in Power Networks]

Mitigation Options (Continued…)

Mitigation Type	Mitigation Option	Additional Details
Active	Install circuit breaker failure and pole discrepancy protection schemes.	The objective is to quickly disconnect the remaining energized phases in the same circuit in order to remove the excitation in the resonant circuit. Timing must be coordinated between SPAR dead-time and TOV withstand of line apparatus. The CB failure protection will guarantee that the energized phase(s)/circuit is disconnected in a timely manner – i.e., removing the excitation to the resonant circuit.
Active	Install Special Protection Scheme to disconnect the selected phase reactor(s) upon detection of an uneven phase operation.	It requires the installation of a circuit breaker with independent phase operation on the shunt reactors.
Active	Install Special Protection Scheme to close the selected phase grounding switch(es) in parallel with phase reactor(s) upon detection of an uneven phase operation.	The objective is to by-pass the phase reactor in the open phase(s), therefore removing the resonant circuit.

Reference: [CIGRE WG C4.307 (2014) Resonance and Ferroresonance in Power Networks]

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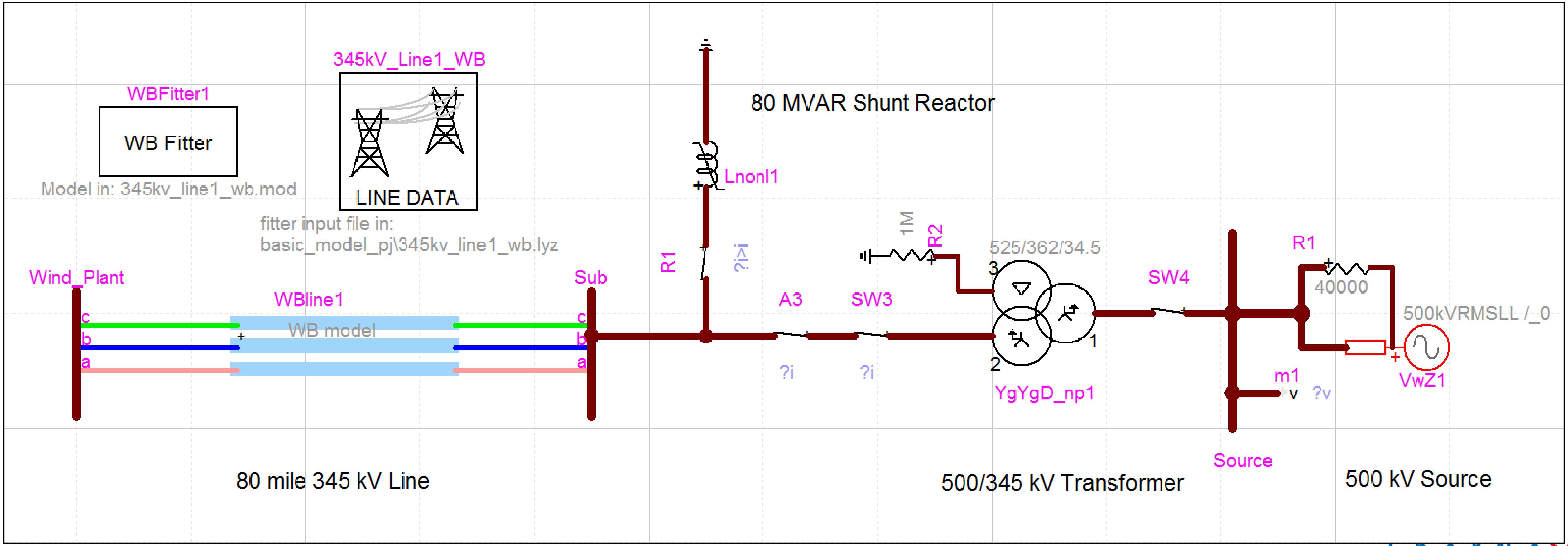
Case Study — Large Wind Plant

Case Study: Circuit Description

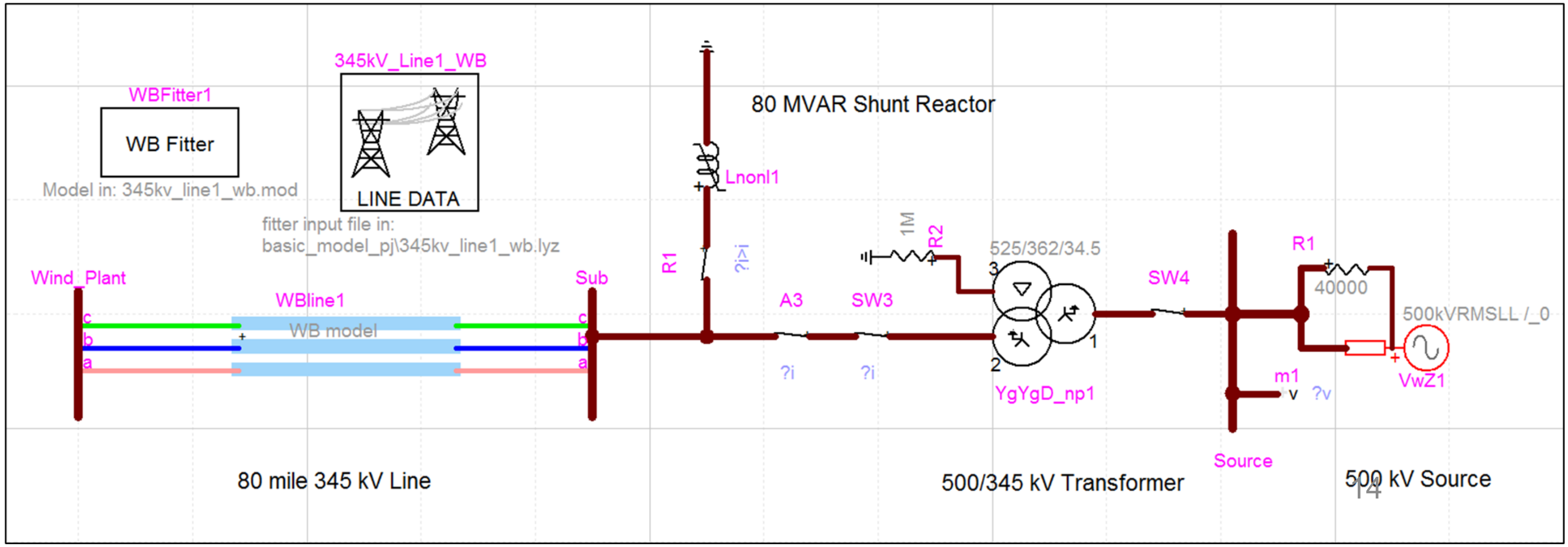
A large wind project in the USA



Case Study: Simulated Scenarios

- Simulated fifty-six (56) scenarios for unbalanced (1 or 2 poles stuck) breaker operations (open→close and close→open).
  - Energization without neutral grounding reactor— 18 Scenarios
  - Energization with 30% neutral grounding reactor— 18 Scenarios
  - De-energization with 30% neutral grounding reactor— 20 Scenarios
- The simulated scenarios include the switching of breakers for
  - 345 kV line(s)
  - Shunt Reactor
  - Wind plant each main power transformer (MPT)


Photo by Ad van Santen on Unsplash

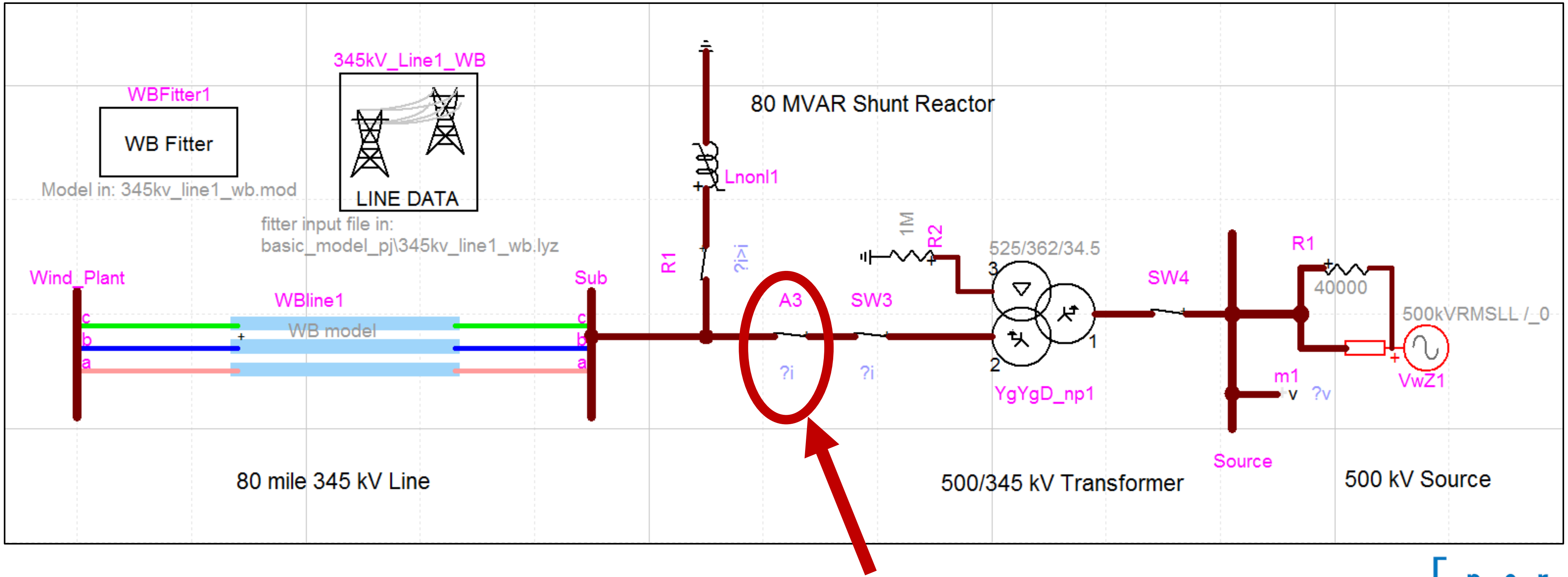


EMTP Simulation Results

Energization without Neutral Grounding Reactor

One of the cases generates zero-sequence resonant condition

- 345 kV line energization with shunt reactor when wind plant source equivalents are not connected
  - Breaker A3 Phase C pole remains stuck open.

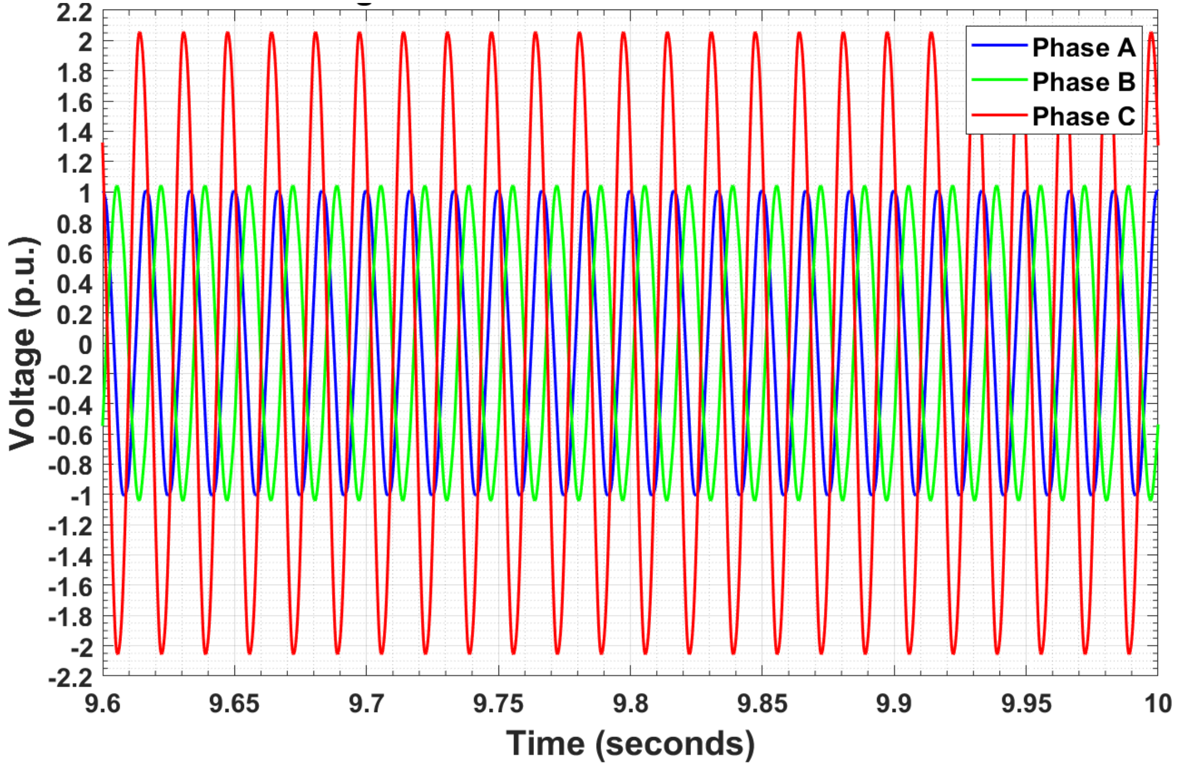


Energization without Neutral Grounding Reactor

One of the cases generates zero-sequence resonant condition

- This leads to a sustained high overvoltage at 345 kV side buses on the open Phase C— the highest steady-state voltage of 2.057 p.u. is observed at the wind plant substation.
- The system's operation for even around 1.4 sec at this resonance caused overvoltage results in 345 kV arrester duties beyond their capacity.
- The rest of the cases do not show any power frequency resonance.

Voltage (steady-state) at 345 kV side of the Wind Plant

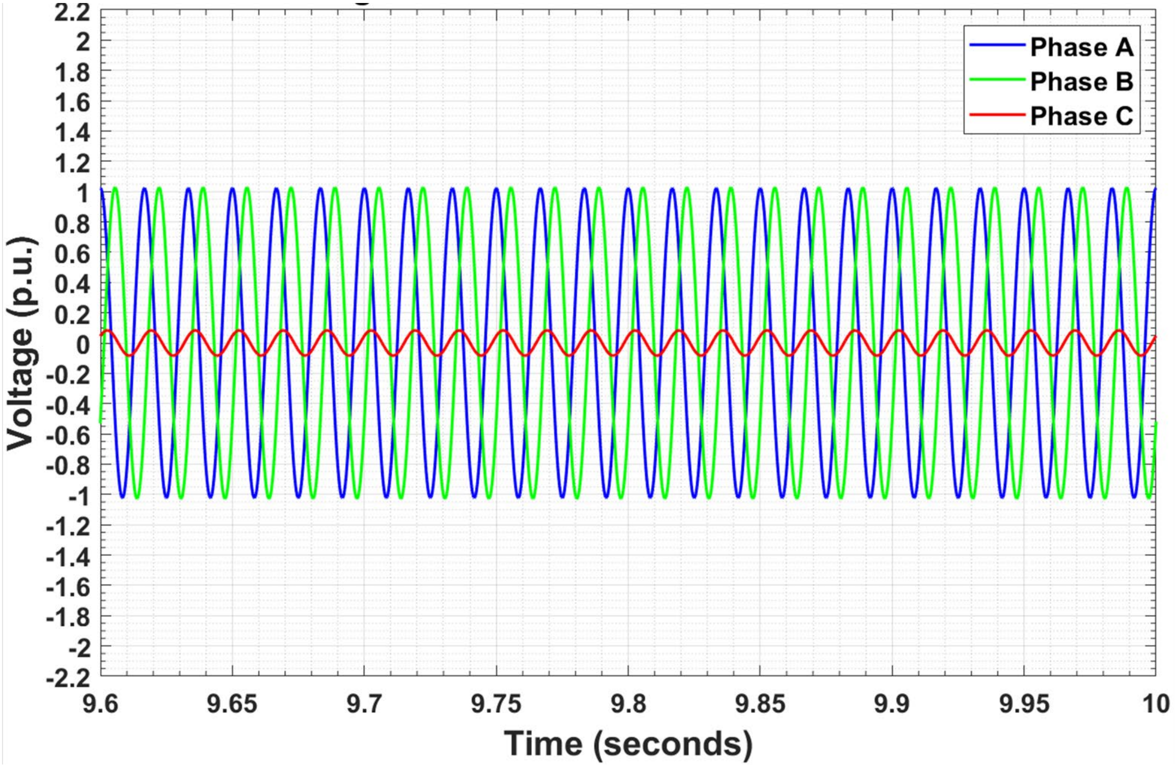


Energization with Neutral Grounding Reactor (NGR)

All energization cases repeated with 30% NGR (452 ohms or 1.2H)

- The addition of NGR mitigates zero-sequence resonance for the problematic scenario.
  - The maximum steady-state voltage is 1.031 p.u.
- The rest of the cases do not show any new power frequency resonance.

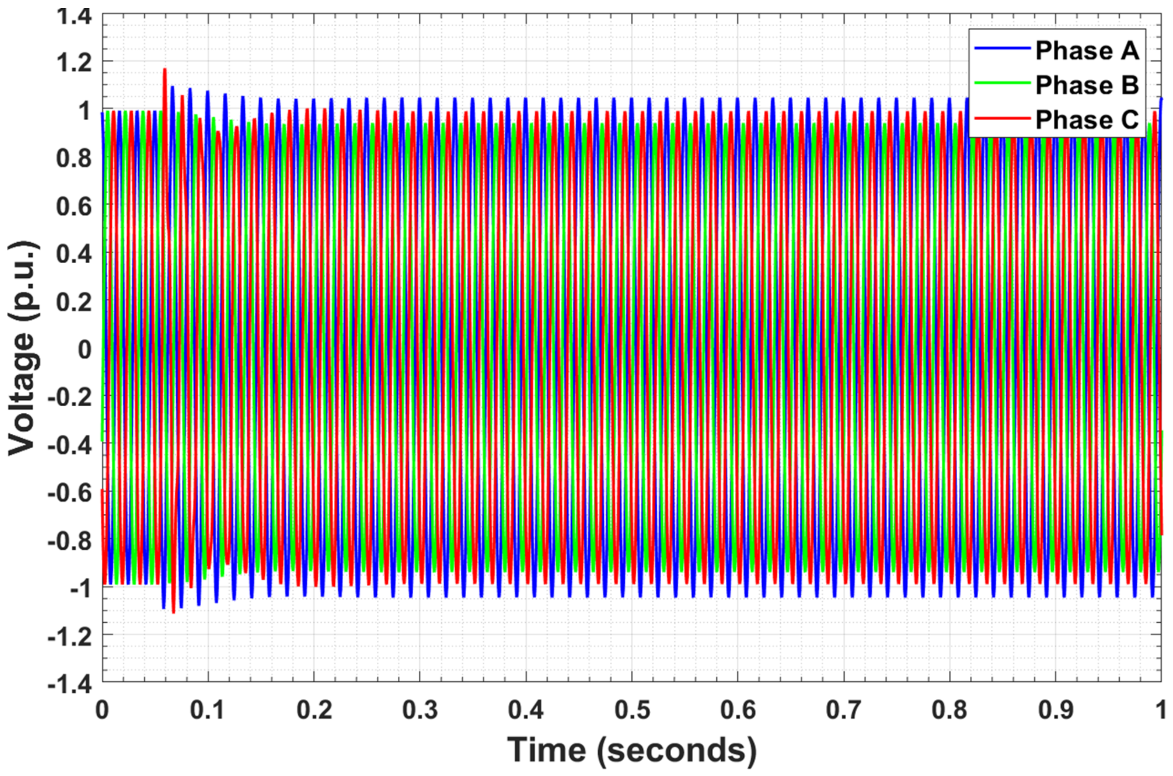
Voltage (steady-state) at 345 kV side of the Wind Plant



De-Energization with Neutral Grounding Reactor (NGR)

➢ None of the cases show resonance or high overvoltage due to unbalanced breaker operation.

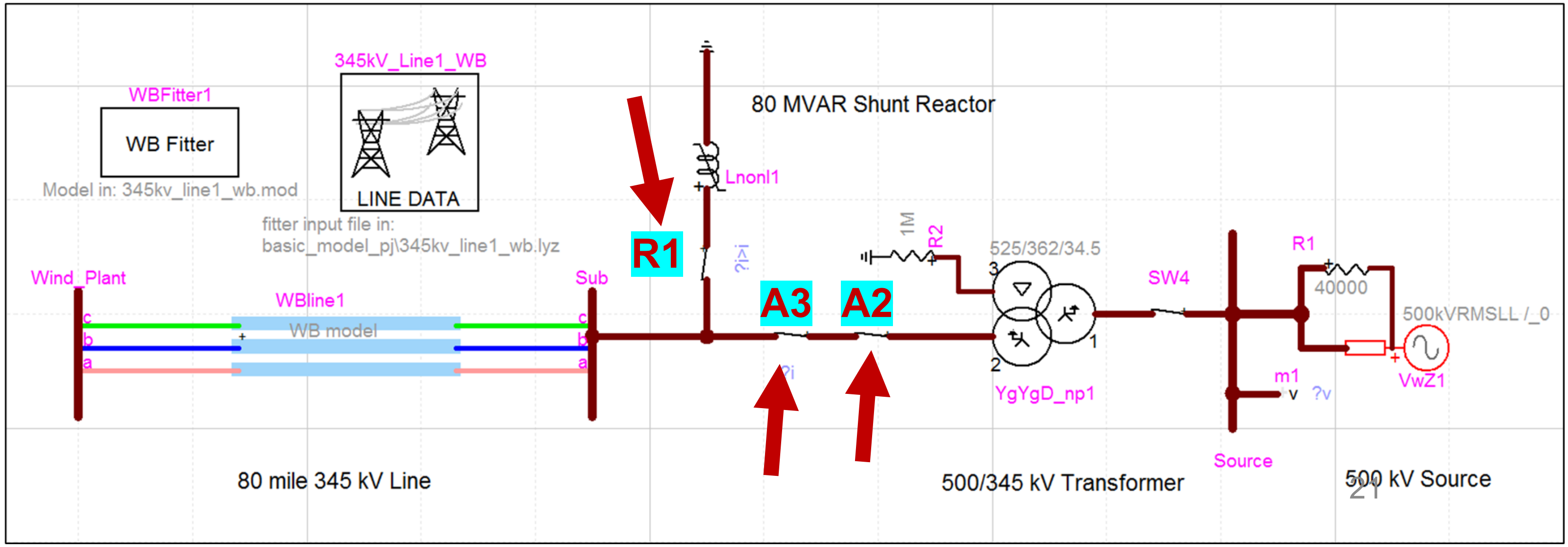
Voltage (steady-state) at 345 kV side of the Wind Plant



Active Mitigation Option for the Project

Active Mitigation for the Project

- Better alternative is to employ relay protection interlocking that eliminates the possibility of energizing the shunt reactor during stuck breaker conditions at A3. This protection scheme requires:
  - The breaker (A2) must trip if the line breaker (A3) trips. This interlocking of A2 and A3 will reduce the chances of stuck pole condition supply to the line that leads to resonance.
  - The shunt reactor breaker (R1) can only be closed after a few seconds delay when A3 is closed, and also there are no stuck breaker indications, and that the line voltage conditions on all three phases are confirmed as normal.



Summary

Summary

- Zero-sequence resonance is a condition in electrical systems where the zero sequence impedance of a network creates a series resonant circuit during breaker unbalanced phase operation, leading to potential overvoltages.
- It is caused by the interaction between shunt reactors and phase capacitance in a disconnected phase, coupled with energy from energized phases.
- Large resonant overvoltages – even for a short duration - can damage the equipment.
- A case study of a wind plant in the USA showed that passive and active measures can be used to mitigate zero-sequence resonance, e.g.,
  - Passive: Neutral Grounding Reactor
  - Active: Relay protection interlocking.

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About EnerNex, a CESI Company

EMTP®

- Founded in 2003, EnerNex is a leader in providing engineering, consulting, and research services to the electric power industry worldwide.
- Joined the world-leading electric power testing, consulting and engineering company CESI in June 2018. KEMA Labs is also part of CESI group, operating the largest independent high power and high voltage laboratories in US and Europe.
- Our focus is the electric grid and helping clients solve complex challenges.
- The EnerNex team is comprised of experienced power engineers, control systems professionals, program managers, and regulatory and business experts.

Advancing a cleaner, smarter energy system

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Who We Work With

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Utilities and Large Energy Consumers

Hawaiian Electric, Portland General Electric, Avista, intel, SDG&E, Xcel Energy, TVEC, Alliant Energy, Exelon, Toronto Hydro, LIPA Long Island Power Authority, Municipality of Anchorage, acciona Energy, SUZLON POWERING A GREENER TOMORROW, Southern California Edison, City of Burbank Water and Power Since 1913, gvec Your kind of power., OG&E, TVPPA, Dominion Energy, Burlington Electric Department, PowerForward Ohio Public Utilities Commission, ONCOR, ComEd, FirstEnergy, Duke Energy, Snohomish County PUD, cisco, SRP, Nebraska Public Power District, NV Energy, MidAmerican Energy, MGE, MISO, UI, New York Power Authority, California ISO, res power for good, aps, BH Black Hills Corporation, Entergy, Ameren, Invenergy, PSEG We make things work for you., EVERSOURCE, conEdison

Government Agencies + Research Organizations

USTDA U.S. Trade and Development Agency, U.S. Department of Energy, EPRI Electric Power Research Institute, USAID From the American People, ESIG, EEI Edison Electric Institute, NIST National Institute of Standards and Technology, CEATI International, NRECA America's Electric Cooperatives

Industry Solutions Providers & OEMs

ALSTOM, Vestas, ABB, HDR, GE, SG

Project Development Firms

Mortenson, ROSENDIN, Blattner Energy, Invenergy, NextEra Energy Resources, CEG, SGC

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