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Study Committee C4

Power System Technical Performance

Paper ID - 11099

Framework for Identification of Subsynchronous Oscillations Risks

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Motivation

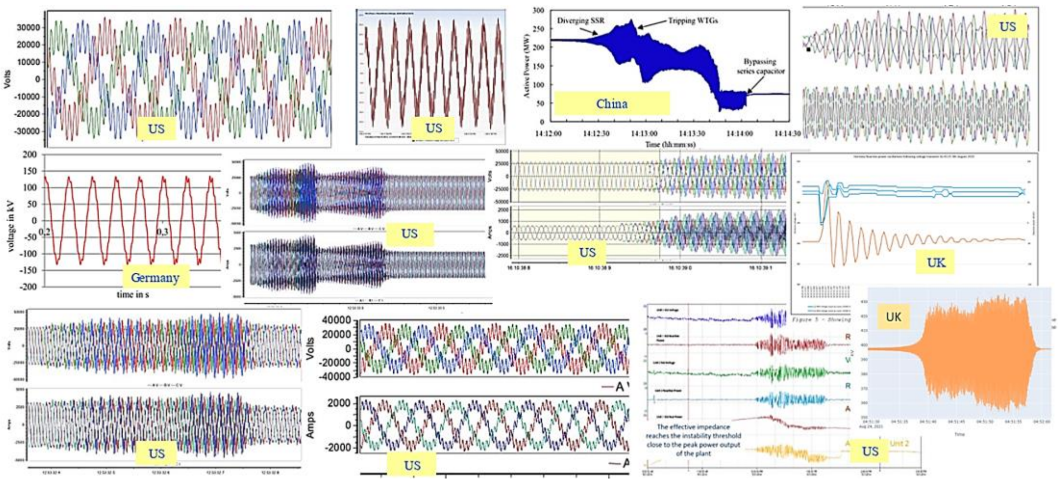
- Interaction of the electrical network with rotating machines is a known phenomenon since the **first recorded event in 1970 in Mohave, USA.**
- Before 2000, majority of the events were purely electro-mechanical interactions where electrical modes of the system interacted with the mechanical modes of rotating machines. This phenomenon is called **Subsynchronous Resonance (SSR).**
- As the share of Inverter Based Resources (IBRs) increased, such as large offshore windfarms, HVDC interconnectors, large solar and battery storage systems, Subsynchronous Oscillations (SSOs) have evolved into interactions between electrical and control modes. This phenomenon is termed as **Subsynchronous Controller Interaction (SSCI).**
- From 2009 onwards, SSCI has been the dominant cause for all reported events and there is a clear increase in the frequency of these events across the world.
- The fundamental reason for SSO in any system is the existence of **poorly damped oscillatory modes** which can be induced by the interaction between different technology types.
- A network event can lead to unacceptable SSOs leading to **negative impact on generating plants** such as commutation failure, deloading of windfarms, loss of embedded generations etc
- Commercially available **conventional analysis tools do not offer bespoke solutions** to analyse SSO, perform root cause analysis and develop mitigation actions.

Current Challenges

- Controller interaction studies are difficult because –
  - **complex and difficult** to identify without exhaustive electromagnetic transient (EMT) studies,
  - **difficult to identify the equipment** or assets participating in the interaction,
  - assessing the **degree of participation of equipment parameters** in poorly damped modes is difficult, and
  - future reinforcement decisions and network changes, such as the connection of new sites, can introduce **new modes in the system**, making compliance studies based on limited scenarios insufficient.
- Current compliance studies are limited to a small number of scenarios due to **computational constraints**.
- Proprietary **models are usually 'black box' (compiled).** So, impossible to ascertain the source of the problem.
- A plant compliant under a limited number of scenarios does not guarantee a stable operation as the network changes in future.

Objects of Investigation

- **Combine cutting edge techniques** from different domains to investigate controller interaction studies.
- **Develop an SSO analysis framework** that can be applied to both existing and new connections.
- **Reduce computational overhead** so that a large volume of scenarios can be analysed.
- **Reduce manual intervention** by engineers as much as possible so that the analysis can run unattended.
- **Develop a tool** for the SO based on the SSO analysis framework



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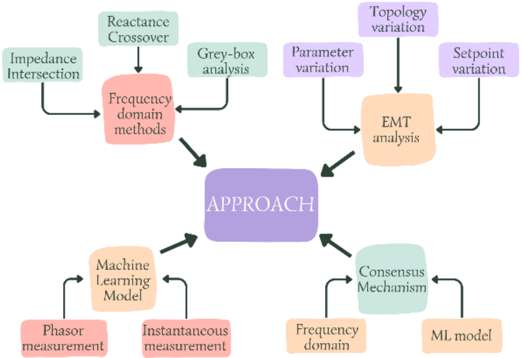
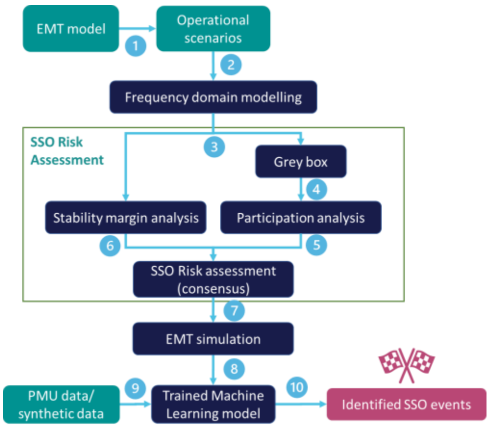
Our Method and Approach

- A versatile tool that can be used with any network configuration such as
  - sequence coupling on both apparatus and grid side
  - Several IBRs connected to the same substation
  - Networks having compiled proprietary models



SSO Analysis Framework

- End to end automated process with minimal manual intervention
- A non-linear EMT model is converted to a linearised model first to filter out operational scenarios with no SSO risk – **Steps 1 to 6**
- Scenarios having potential risks are studied in EMT – **Step 7**
- ML model is used to identify SSO in the results variables – **Steps 8 to 10**

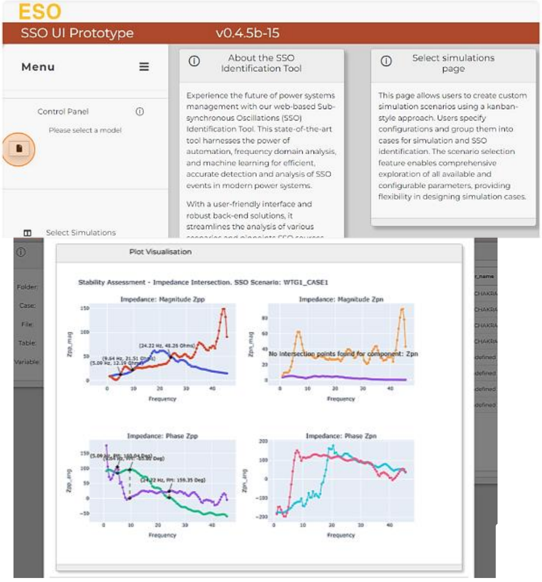


Key features

SISO/MIMO forms	Single Input Single Output (SISO) and Multi Input Multi Output (MIMO) methods for impedance calculation
Sequence coupling	Full matrix calculation of apparatus and grid side impedance
Single/multi injection	Single sequential frequency injection and multi-frequency injection techniques for impedance estimation
Eigenvalue analysis	Small signal analysis based on eigenvalues and participation factors, even for 'black box' proprietary models (compiled models).
Machine learning	Automated near real-time SSO identification from PMU data (or simulated data) using machine learning models
User Interface	A modern user interface with a unique 'scenario generator' function that allows the creation of several operational scenarios in any PSCAD model
Results visualisation	Integrated interactive visualization platform to explore scenario results

Tool Interface

- A web-browser based user interface developed in JavaScript with integrated visualisation.



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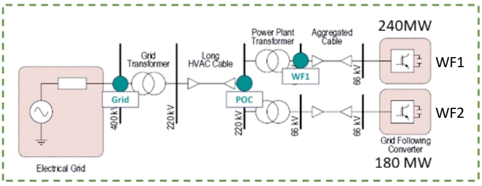
Limitations of SISO form

- Presence of elements such as PLL, dc-link voltage control system, P and Q controllers, salient pole synchronous machines etc introduces **Mirror Frequency Coupling (MFC)**
- This means that systems that are linear time invariant (LTI) in the *dq* domain **may not be LTI in the phase domain** due to coupling between sequences.
- **MFC is dominant at low frequencies** i.e., in the subsynchronous range and the correct calculation of the impedance transfer function has an impact on the stability conclusions.
- **Modified sequence domain** impedance calculation ensures that any LTI system in the *dq* domain is also LTI in the sequence domain.

$$\begin{bmatrix} I_p(s+jw) \\ I_n(s-jw) \end{bmatrix} = \begin{bmatrix} Y_{pp}(s) & Y_{pn}(s) \\ Y_{np}(s) & Y_{nn}(s) \end{bmatrix} \begin{bmatrix} V_p(s+jw) \\ V_n(s-jw) \end{bmatrix} = \mathbf{Y_{pn}(s)} \begin{bmatrix} V_p(s+jw) \\ V_n(s-jw) \end{bmatrix}$$

Experimental Setup

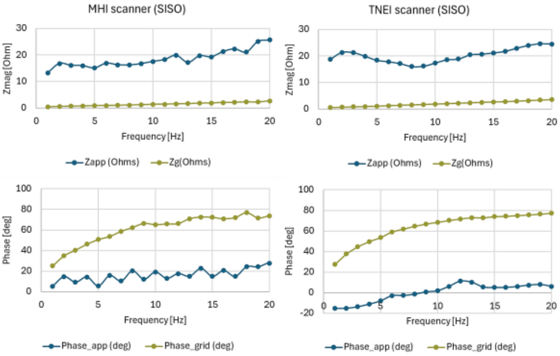
- The CIGRE benchmark model for multi-frequency stability analysis, developed by WG C4.49, is used for all case studies.



- Subsynchronous oscillations can be induced in the model by applying a three phase fault on the export cables under reduced fault level (750MVA ≈ 1.8 SCR)

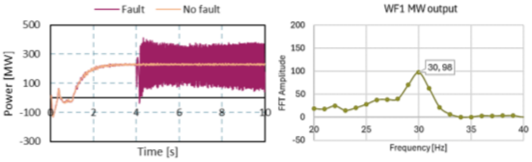
SSO Case study – SISO scan

- The CIGRE benchmark system is scanned using the MHI scanner and the TNEI scanner for grid fault level 750 MVA.
- **No impedance intersection** observed between grid and apparatus



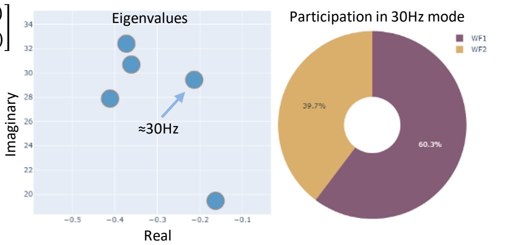
SSO Case study – EMT

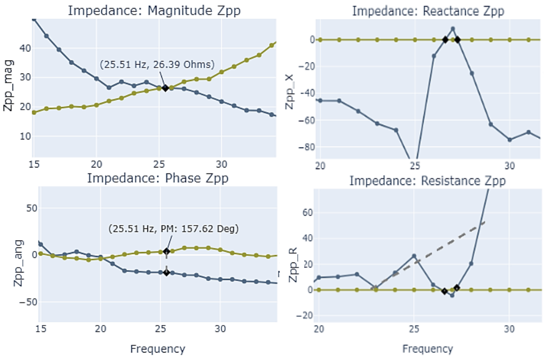
- 3 phase fault applied at 4 secs and cleared after 60ms; fault applied on WF1 export cable
- Around **30Hz oscillation** observed in wind farm power output



SSO Case study – MIMO scan

- Full matrix calculation. Stability assessed based on three frequency domain methods.





Conclusion

- SISO analysis is not suitable for networks exhibiting mirror frequency coupling behaviour.
- Full matrix calculation is necessary for analysis in the subsynchronous range.
- Time domain results are compared with frequency domain outcomes to show that a linear analysis (frequency domain) can capture the oscillation modes seen in EMT results, even for 'black box' compiled models.
- The tool will allow SOs to screen large volume of scenarios to identify SSO events in complex networks.