A Practical Sub-syhchronous Oscillation in an Offshore Wind Power Plant: Modelling, Analysis and Validation

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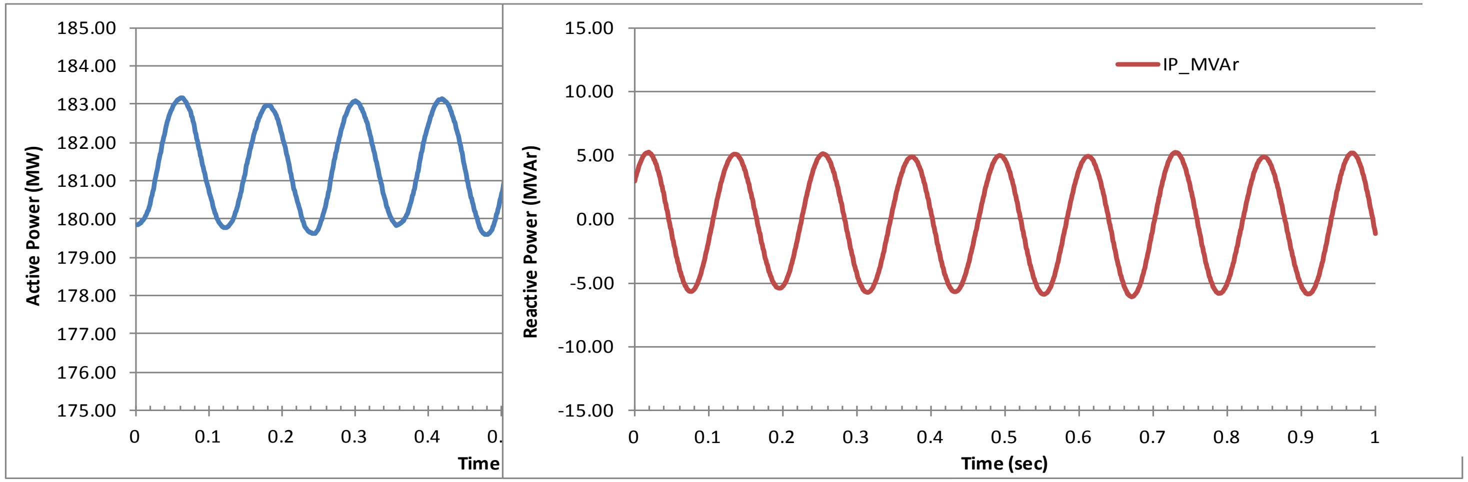
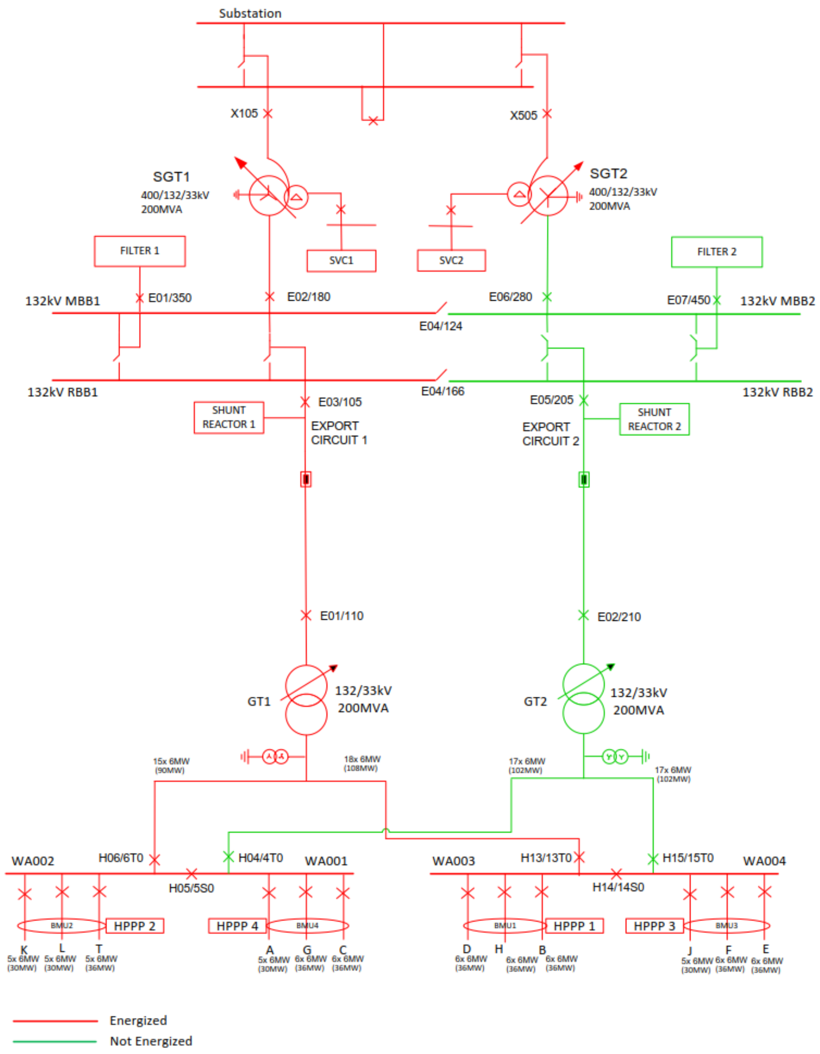
Contents

Introduction

Sub-synchronous Oscillation in an Offshore Wind Power Plant

- 67 SWT-6.0MW turbines, total capacity 402MW
- Stable during all normal operations
- Contingency operation when 1 of 2 HV exporting cables was in service
    - Extremely weak grid with 1.2~1.5 SCR at MV turbine
    - Sub-synchronous oscillation starts when the WPP producs more than 140MW
    - Oscillation frequency was around 8.5Hz





Small-signal stability of power converter-based Power systems

Frequency-Domain Model (FDM) based Stability Approach

- Admittance/Impedance-based approach
- Nyquist stability criterion
- Easy to understand and use, require less information about the system
- Difficult to reveal the root causes of system instability and therefore limited information for control systems tuning

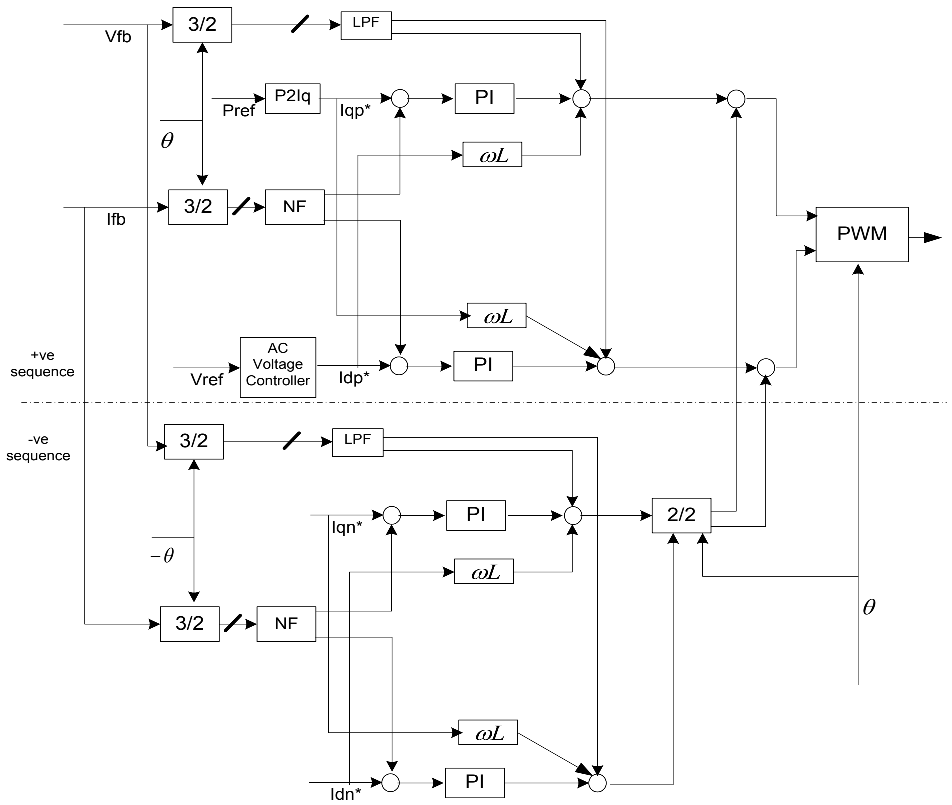
State-space Representation (SSR) based Stability Approach

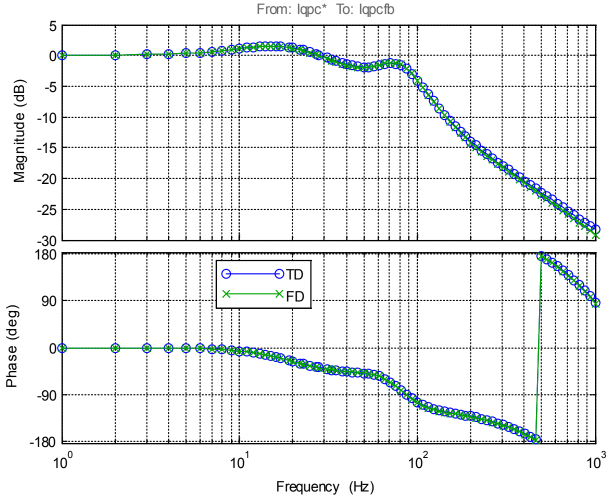
- Closed-loop study approach, Eignevalue analysis
- Lyapunov StabilityTheory: there is always a stability region around the equilibrium for a stable small-signal linearized system
- LTI system is stable if and only if all the eigenvalues of state matrix of closed-loop system are located in Left Half Plane (LHP)
- Possibility to reveal the relationship of control states and stability of the system
- Require comprehensive information about the control systems and system parameters which are not always easy to obtain

State-space Representation Modelling

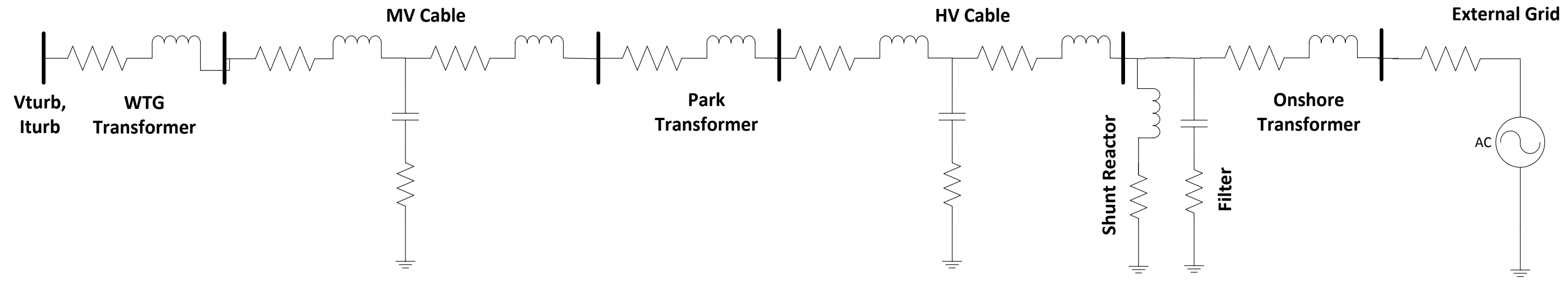
Modelling of Net-side VSC in SSR

- A dual feedback control loops: positive and negative sequence control.
- Outer loops are active power control and voltage control.
- DQ Synchronous Rotating Frame (SRF) implementation is employed to mimic the actual design of power converter control.
- Small-signal behavior of PLL is included and modelled to precisely replicate sub-synchronous dynamic of small-signal stability.
- All actual delays including PWM delay, S&H delays, LPFs, Notch fileters are included.
- The Net-side VSC model in DQ SRF has been benchmarked against Full Order Model in Time Domain (FOM TD).





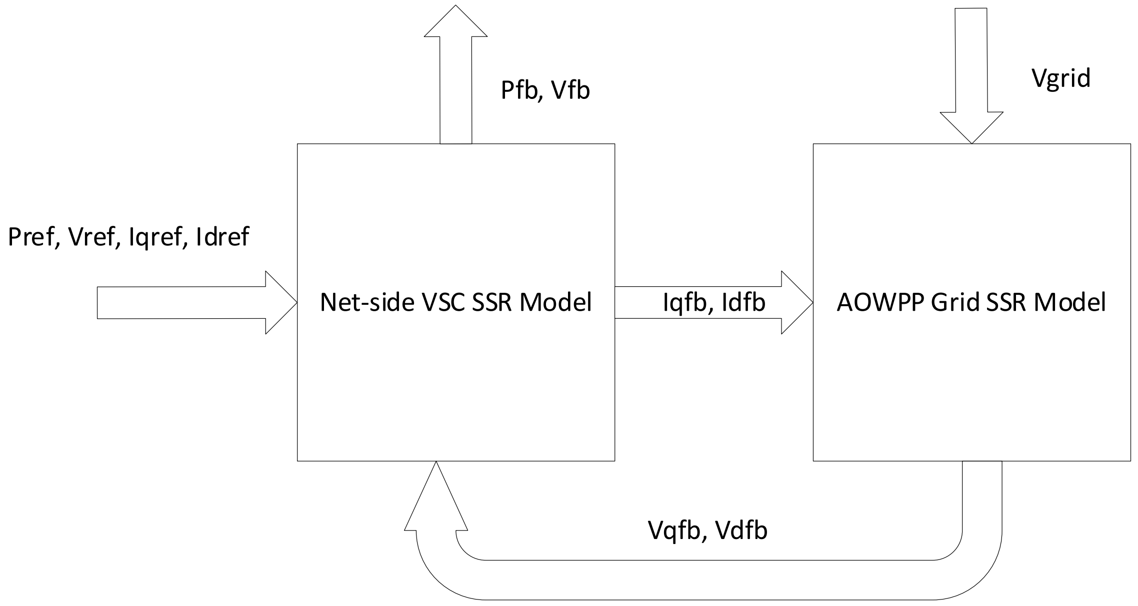
Modelling of AOWPP Grid in SSR



- Supplier’s data are used to construct models of electrical components.
- External Grid is modelled as the Thevenion equivalent based on short-circuit capacity provided by TSO.
- AOWPP Grid is modelled in grid SRF to conveniently integrate with Net-side VSC DQ SRF model.
- PLL ensures the frame alignment between grid SRF and DQ SRF.

Integraton of Net-side VSC Model and AOWPP Grid Model

- Both parts are modelled in Matlab as state-space matrix representation (SSR).
- Interconnection interface is defined at LV side of wind turbine transformer.
- A steady state power flow calculator is used to define the operation points based on inputs as Pref, Vref, Vgrid.
- A complete closed-loop system SSR SRF model is formed for stability analysis.



$$[\dot{X}] = A[X] + B\begin{bmatrix} P_{ref} \\ V_{ref} \\ Iq_{ref} \\ Id_{ref} \\ \cdots \end{bmatrix}$$

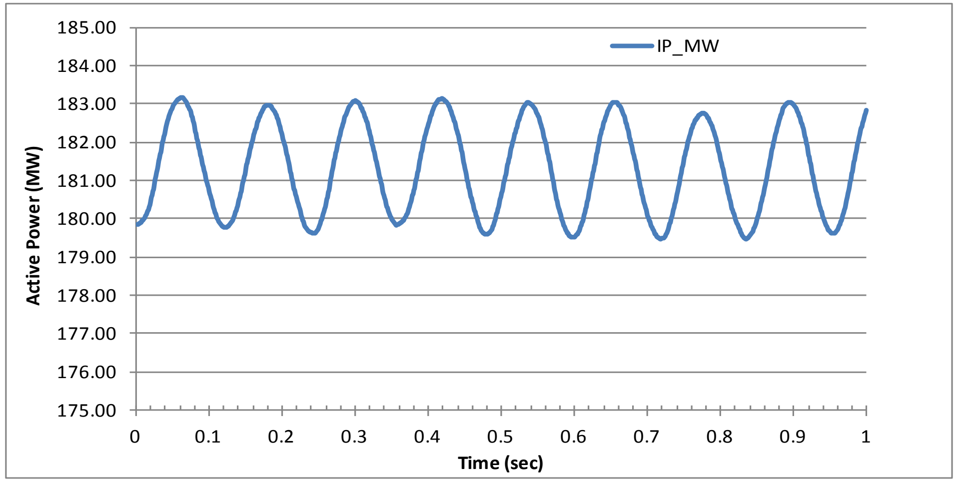
$$\begin{bmatrix} P_{fb} \\ V_{fb} \\ Iq_{fb} \\ Id_{fb} \\ \cdots \end{bmatrix} = C[X] + D\begin{bmatrix} P_{ref} \\ V_{ref} \\ Iq_{ref} \\ Id_{ref} \\ \cdots \end{bmatrix}$$

Site Oscillation Replication in Simulations

Site Oscillation Replication in Simulations (1/2)

Facts of Site Oscillation

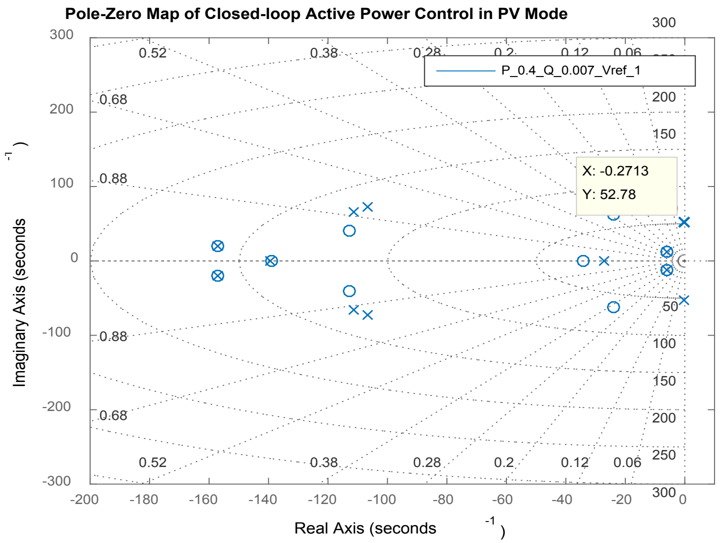
- Contingency opeartion: single exporting-cable operation
- SCR at MV terminal of turbine transformer reduces to 1.2~1.5
- Appx. 60 WTs were in operation
- Sub-synchronous oscillation started to build up when total power export exceeded 140MW, resulting in each WT producing appx. 40% of rated power
- The oscillation frequency was around 8.5Hz

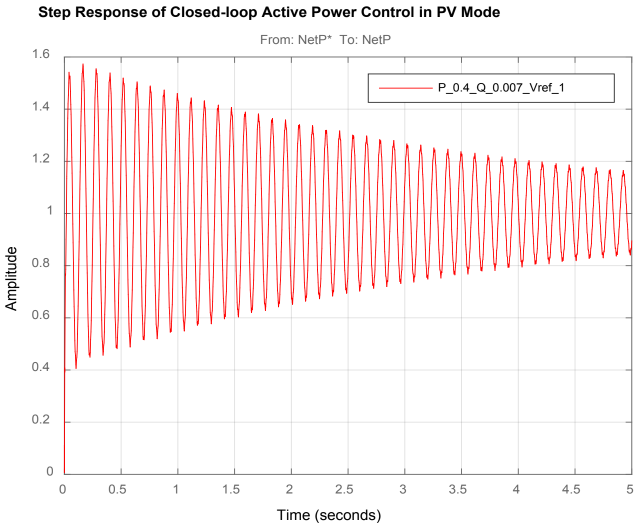


Simulation Scenarios

- Test case 1: 60WTs, P = 0.4*Pn, Vref = 1.0 p.u.

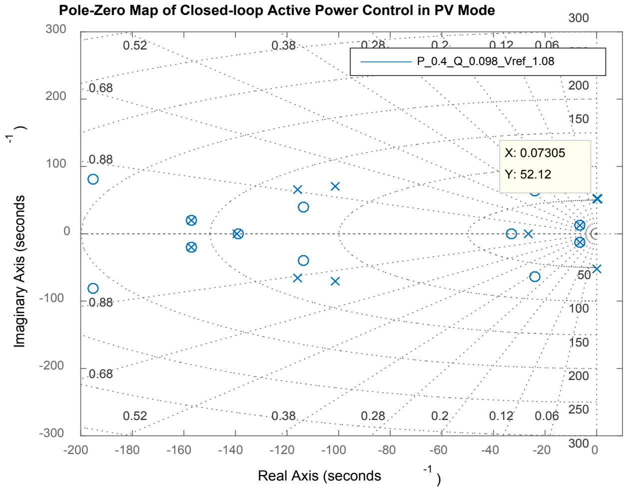
F_os = 8.4 Hz

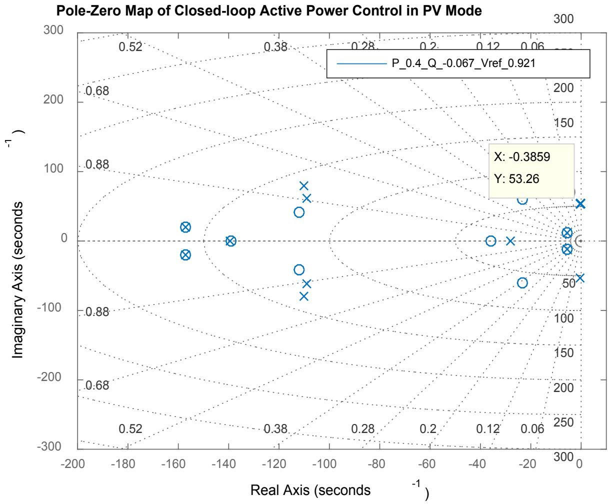


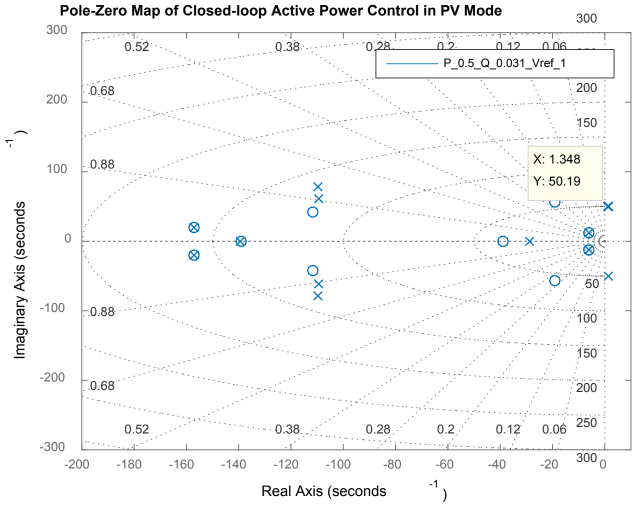


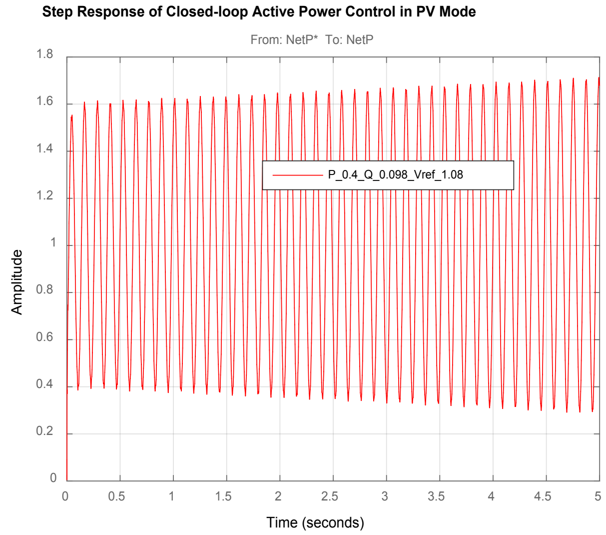
Site Oscillation Replication in Simulations (2/2)

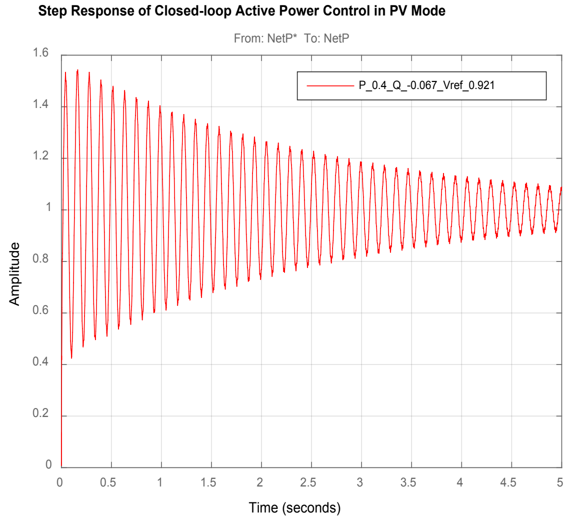
Test case 2: P = 0.4*Pn, Vref = 1.08, F_os =8.3Hz Test case 3: P = 0.4*Pn, Vref = 0.92, F_os =8.5Hz Test case 3: P = 0.5*Pn, Vref = 1.0, F_os =8.0Hz

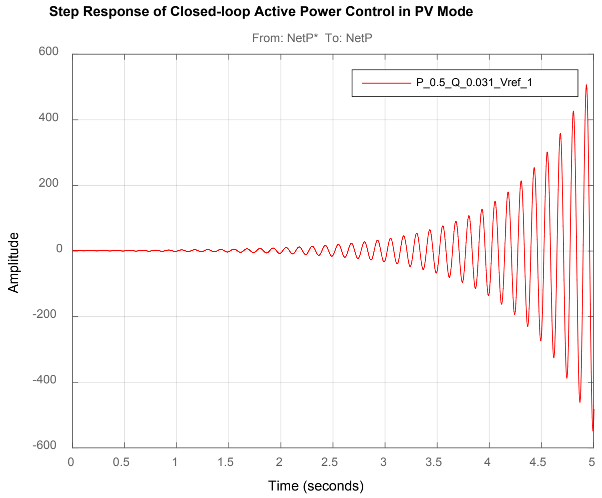










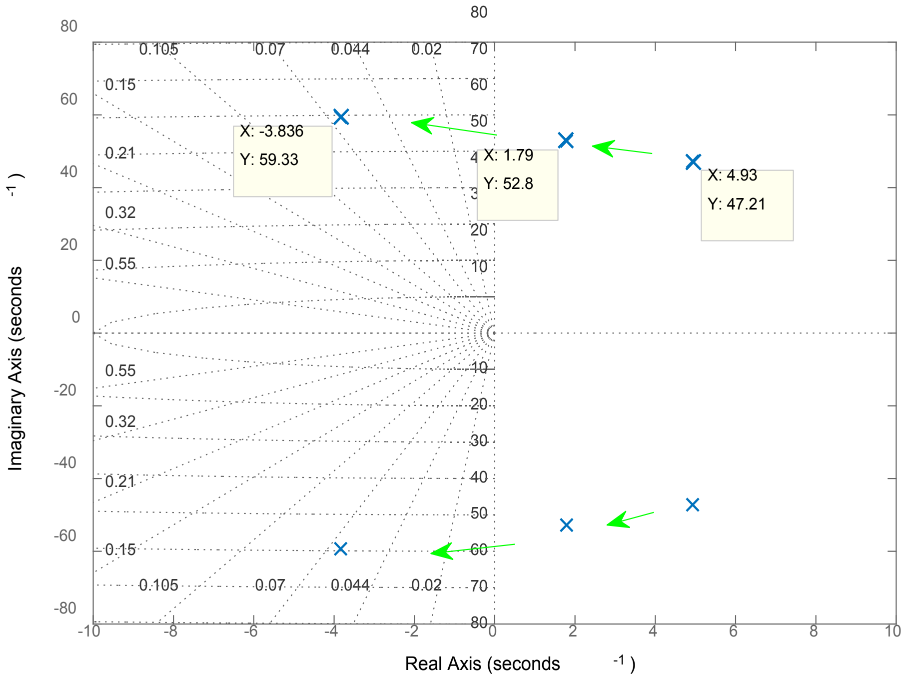


Control Tuning for Stabilization of Oscillation

Control Tuning Approach and Robustness Criteria

Control Tuning Approach based on relocation of critical poles

- **Rationality**: the LTI system stability depends on if and if only all the poles of state matrix are located in LHP.
- **Objective**: Relocation of unstable poles back in stable region LHP by tuning control parameters.



Robustness Criteria

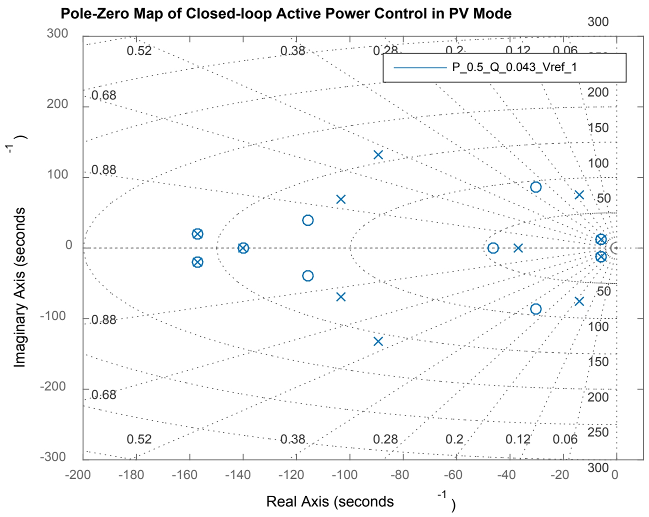
The robustness criteria is measuring the robustness of a system against external disturbances, expected system changes such as fault level etc.

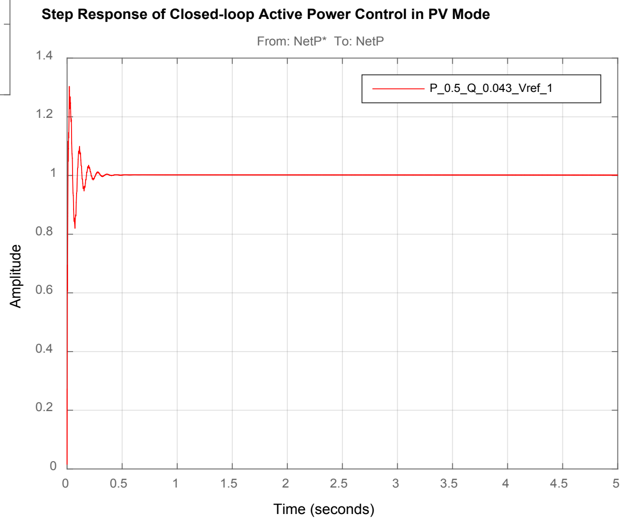
- *Step response overshoot should be less than 35%*
- *Step response setting time should be less than 1s*

System Performance with Optimized Control

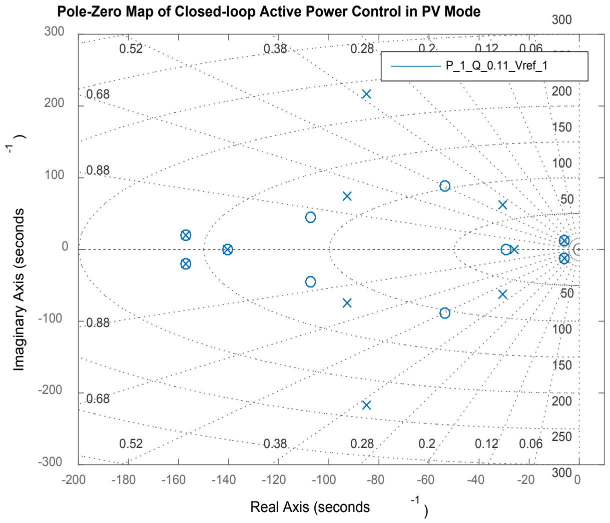
A set of optimized control parameters was identified based on above stability approach and robustness criteria

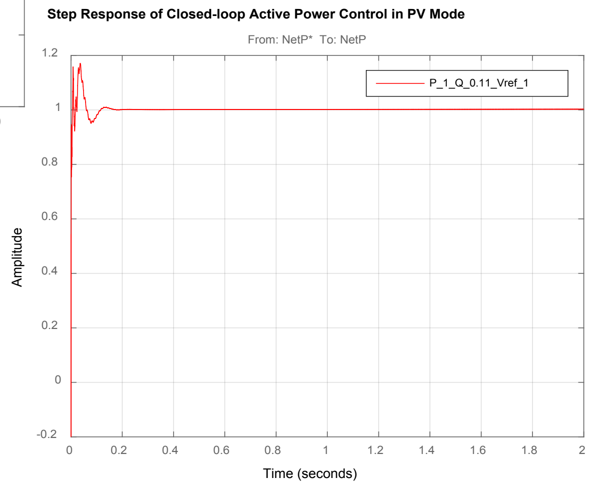
Test case 1: Single exporting-cable, 67WTs, P = 0.5*Pn, Vref = 1.0





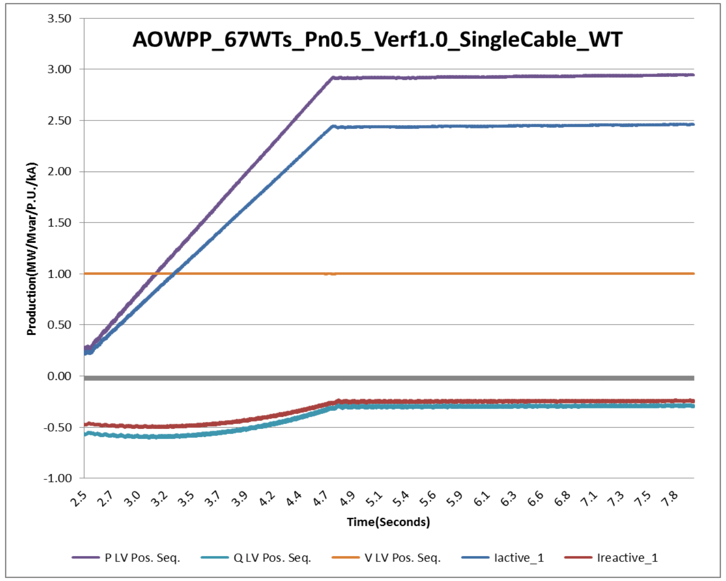
Test case 2: Normal operation, 67WTs, P = Pn, Vref = 1.0



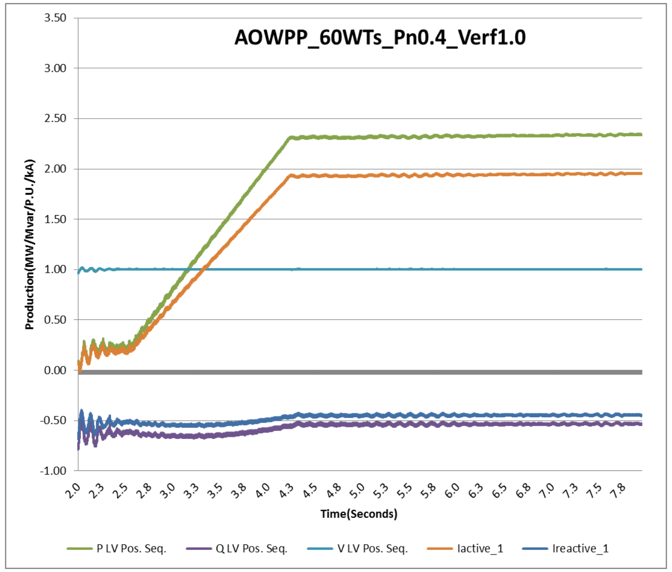


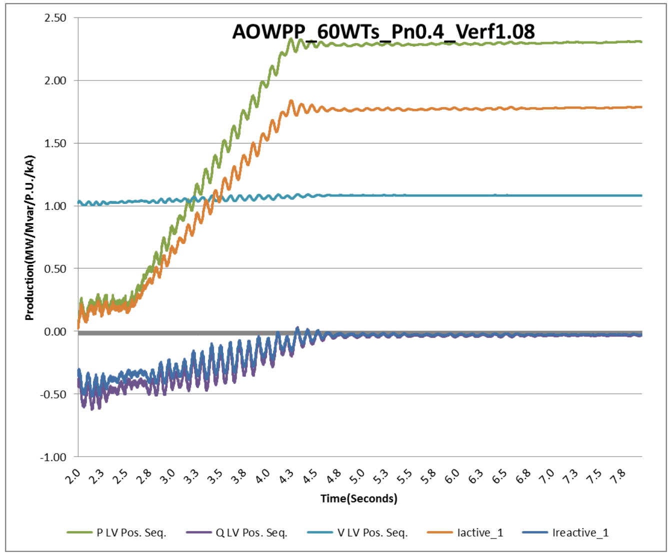
Benchmarking in PSCAD

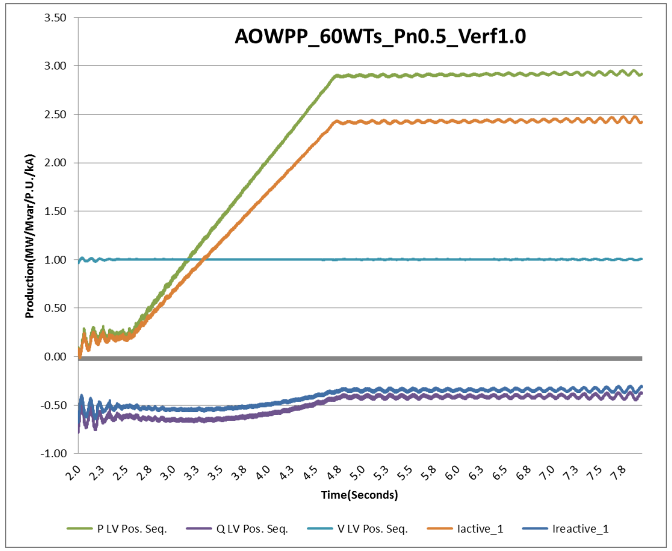
Site Oscillation Replication in PSCAD



- **Full-Order-Model PSCAD consists of the mechanical, electrocal components and corresponding control systems**
- **PSCAD is able to replicate the site oscillations under similar opeartion conditions as the Eigenvalue-based SSR stability approach**
- **PSCAD with optimized control shows the sytem oscilaltions have been stablized in max. Power production**



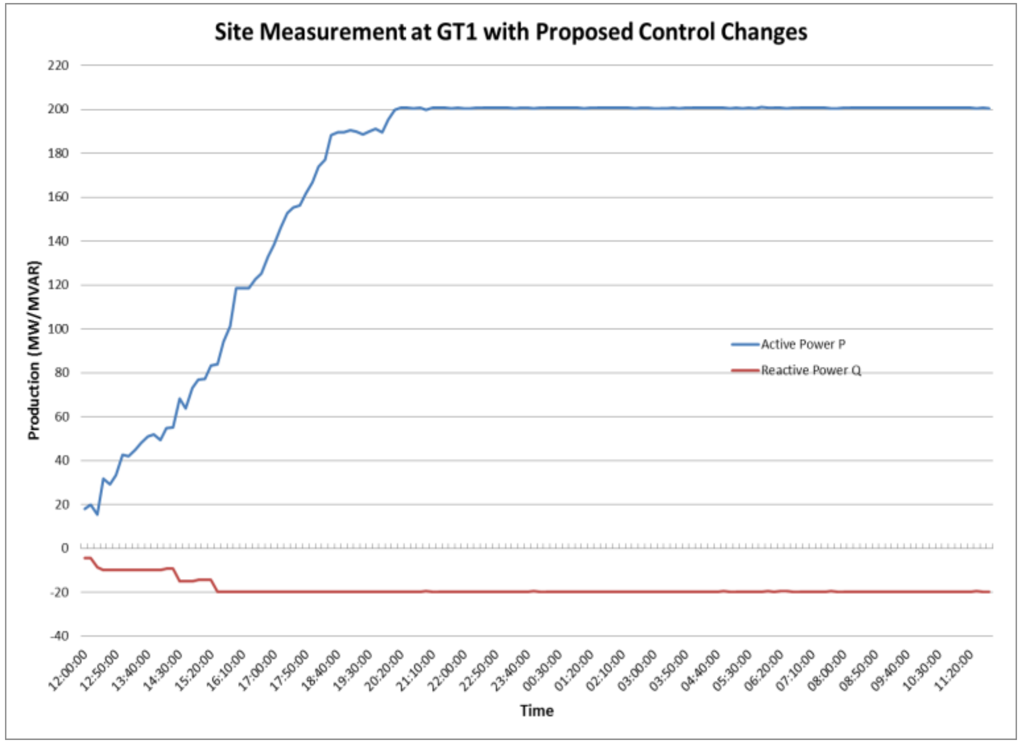


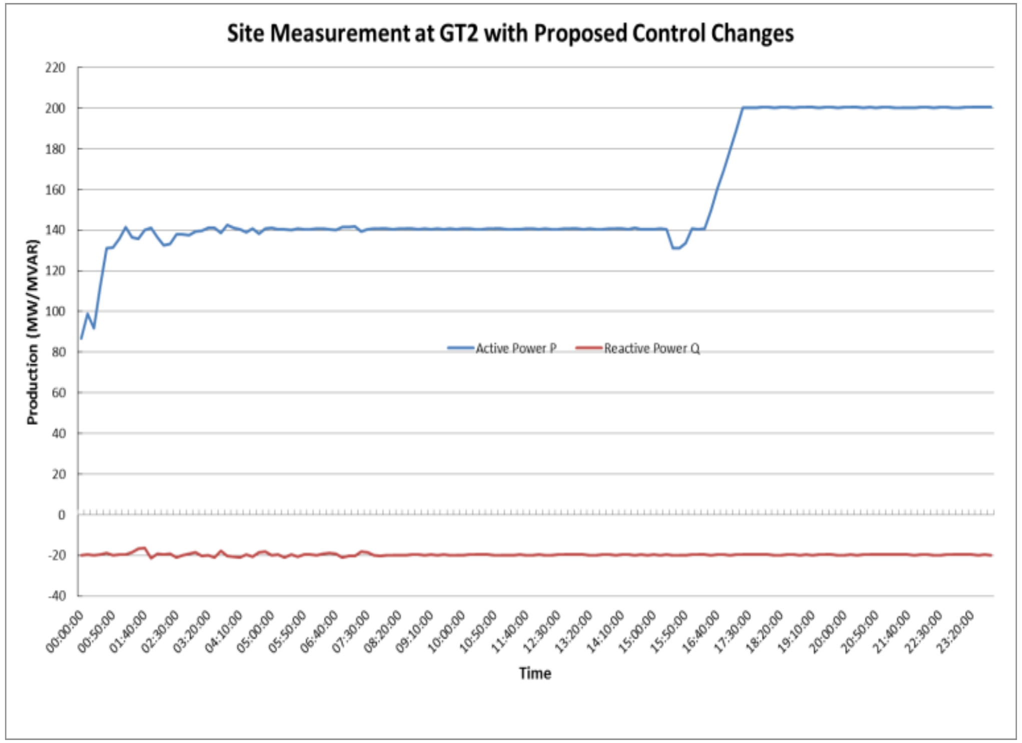


Site Validation

Site Validation with Proposed Optimized Control

- The proposed control changes of power converter were applied on site
- Contingency operations were configured once again to verify if the system is stable or not
- Site measurements show the AOWPP is able to run stably with maxim. Production in both contingency operations





Conclusion

Conclusion

- **SSR SRF based simulation modelling has successfully replicated a real site sub-synchronous oscillation**
- **The Eigenvealue-based stability analysis approach has been employed and verified**
- **The control tuning approach based on relocation of critical poles are developped and applied**
- **Robustness criteria are proposed to assess system ability against external disturbances and system changes**
- **Cross-checking in PSCAD was conducted, and very similar results were obtained**
- **Site validation was carried out to verify the system stability with proposed control changes, and therefore has verified the validity of modelling approach, control tuning approach**

Thanks for your attention!

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