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Improving Stability through Wide Area Measurements

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WAM, WAC, Stability, PMU, Power Oscillation Damping (POD).

1 INTRODUCTION

This paper focuses on PMU application for power system stability, protection and control.

Synchronised Phasors are relatively new technology and applications based on Phasor data are still being developed all over the world. What is somewhat lacking is a lot of operational experience with PMU data. A simulation environment which could bring together Power System components and Phasor Data (along with communication) together would be very useful.

Section II introduces such a simulation environment that has been created using a real time power system simulator to observe and create solutions for a variety of stability and protection related conditions.

Section III introduces test systems which have been created and the type of PMU data used to analyse the problem and the results obtained. The methods used include modal analysis to identify small signal instability and angular instability detection.

2 PMU SIMULATION AND VIRTUAL TEST ENVIRONMENT

The Opal-RTTM real time simulator, which has the capability to run Simulink® models in real time, has been leveraged to provide an environment that can be used to prototype and test closed loop applications. Figure 1 shows the representation of a system that allows the use of a Phasor Data Concentrator (PDC) as a part of the test environment

Creating an IEE C37.118 PMU data stream opens up the possibility of bringing the EMS software and hence visualization also into the simulation.

The PMU blocks are embedded inside the simulation and provide C37.118 output directly through the Ethernet port. This removes the need for additional analogue output conversion hardware and real PMU's while allowing fast changes to PMU characteristics (filtering or response time) and allowing dynamic feedback from the external control systems directly to the simulation environment. Additional constraints are also built in, for example settable frame rate and simulation of loss of data.

3 SYSTEM STUDY

3.1 Small Signal Stability

The problem of small signal stability has been well defined in [4] but it is worth looking at the dynamics in a simple way. Oscillations are typically setup after a disturbance or a transient event and are generally attributed to the interactions between the automatic control systems.

Figure 2 shows a damped and un-damped oscillation

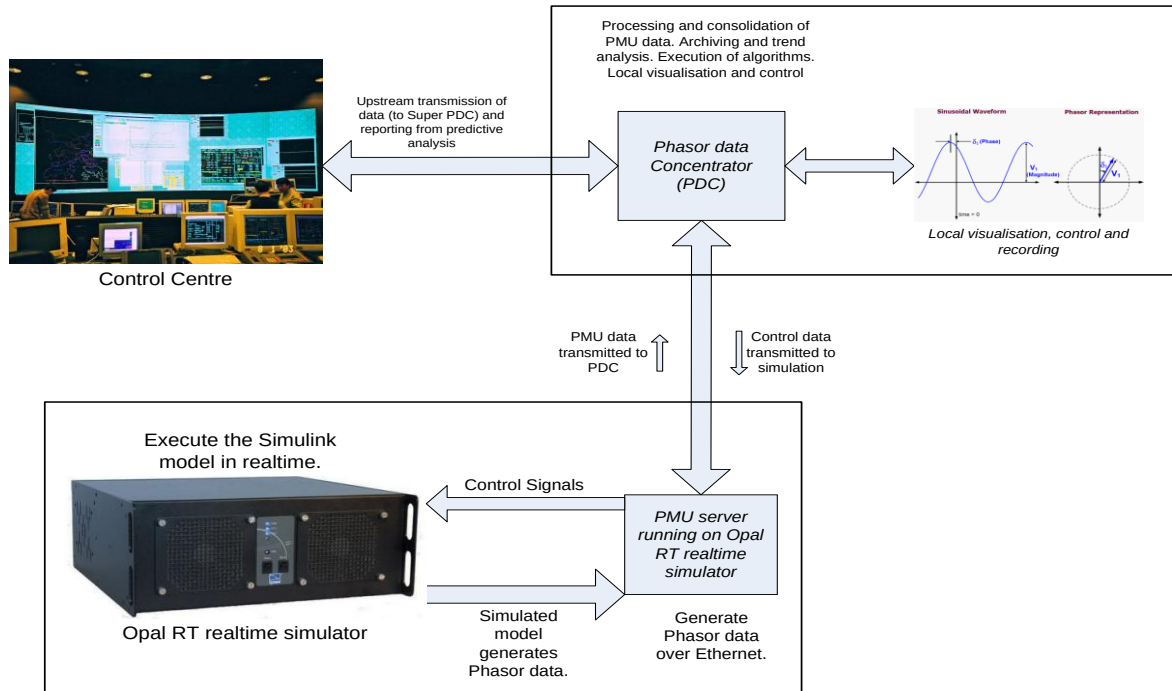


Fig. 1: PMU simulation and Closing the loop

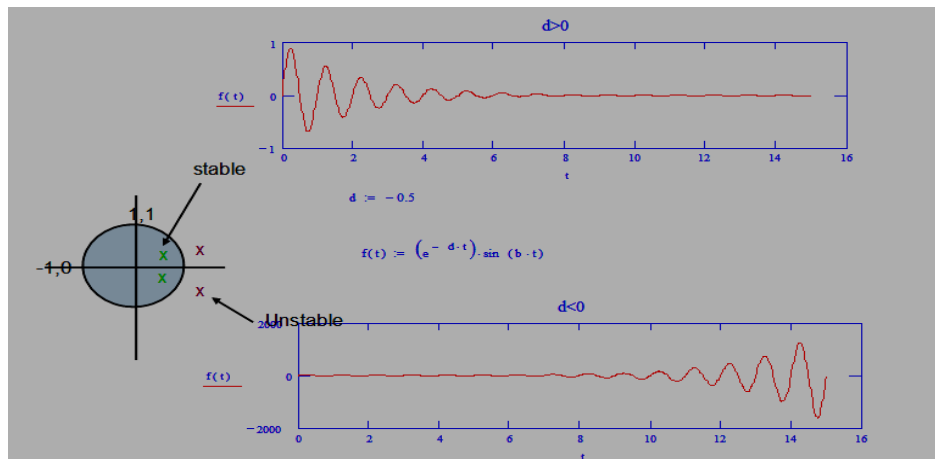


Fig. 2: Damped and Un-damped Oscillation with Poles plotted in z-domain

Oscillatory frequencies are complex frequencies and Eigen value analysis produces complex poles. If the complex conjugate poles are plotted in z-domain, then the poles for a well damped oscillation will lie inside the unit circle and for an unstable oscillation, they will lie outside the unit circle.

A test system [2] has been used to validate PMU based modal analysis and angular stability applications. The system has been modified to provide PMU data and the load has been split to enable load shedding.

The system in Ref [2] was modified to include PMU models and allow islanding through tripping of line circuit breakers.

3.2 Oscillation Monitoring and Stability

A classical two area system has been modelled where 4000 MW out of a total load of 5000 MW of local load is supplied by one Generator at Bus 3. The line surge impedance loading (SIL) is just under 1000MW. A single phase to ground fault is applied at 0.1 sec and cleared after 100 milli-seconds. Oscillations are setup but damped by the action of the power system stabilizers (Figure 3).

Through visual inspection (Figure 4) it would appear that the system is very well damped and the action of PSS damps any oscillations following fault clearance.

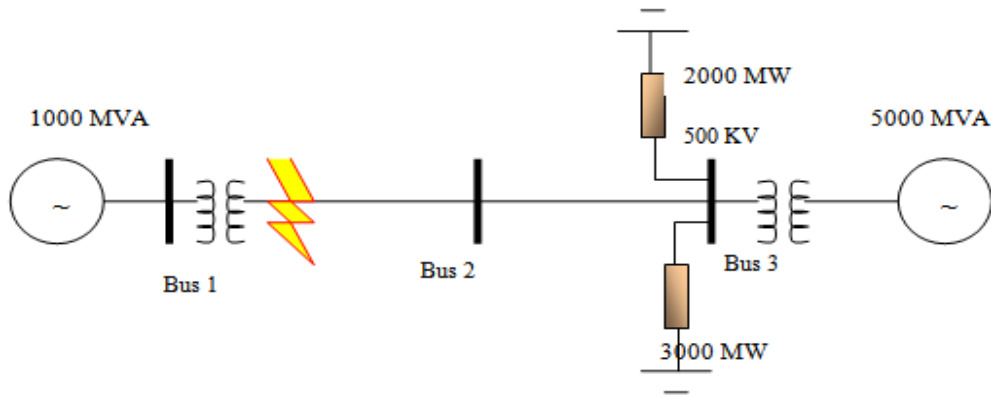


Fig. 3: Test System created for Oscillatory Monitoring from [2]

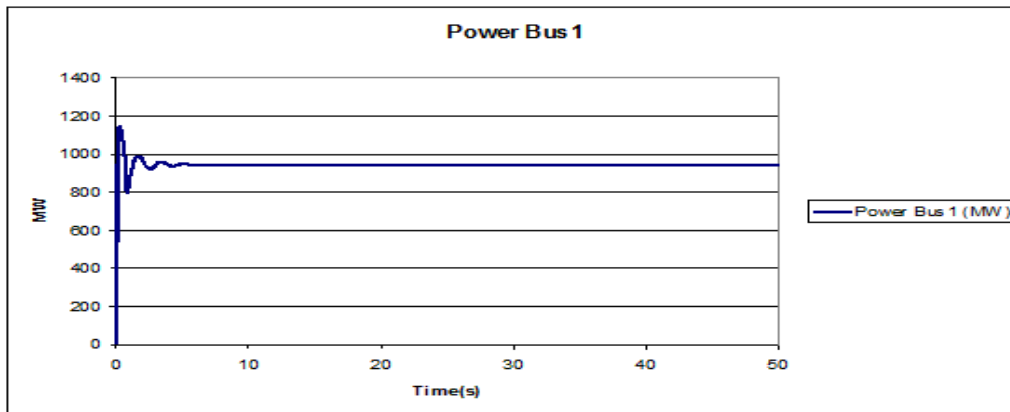


Fig. 4: Oscillations observed in Active Power at Bus 1 after fault clearance

Modal analysis done using PMU data from Bus1 (active power) shows a heavily damped oscillation of 0.58 Hz just after fault clearance and a continuous oscillation of 0.027 Hz, the results come very close to the frequencies mentioned in [2] (0.6 Hz and 0.025 Hz).

This is borne by Figures 5 & 6, which show the Damping ratio (thin yellow line) and Frequency (thick red points) in Hz of the two identified modes. The damping for the 0.58 Hz mode is quite high and consistent (about 21%) but for the 0.027 mode it can be seen from figure 6 that the damping calculation result is more inconsistent but mostly close to zero. The variation the damping is mainly due to the very small magnitude of the inter area mode but the plot of the complex poles in the z-domain (Figure 7) gives a much better idea of what is happening.

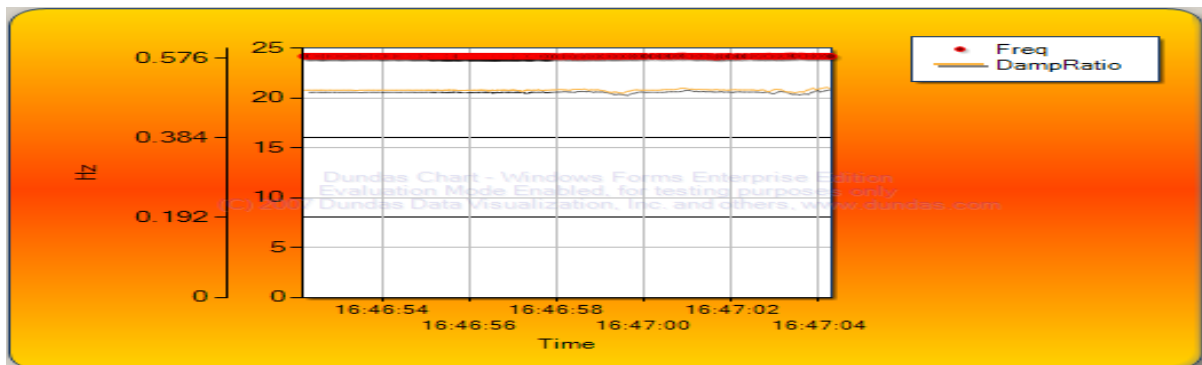


Fig. 5: Modal Analysis showing the heavily damped 0.58 Hz mode

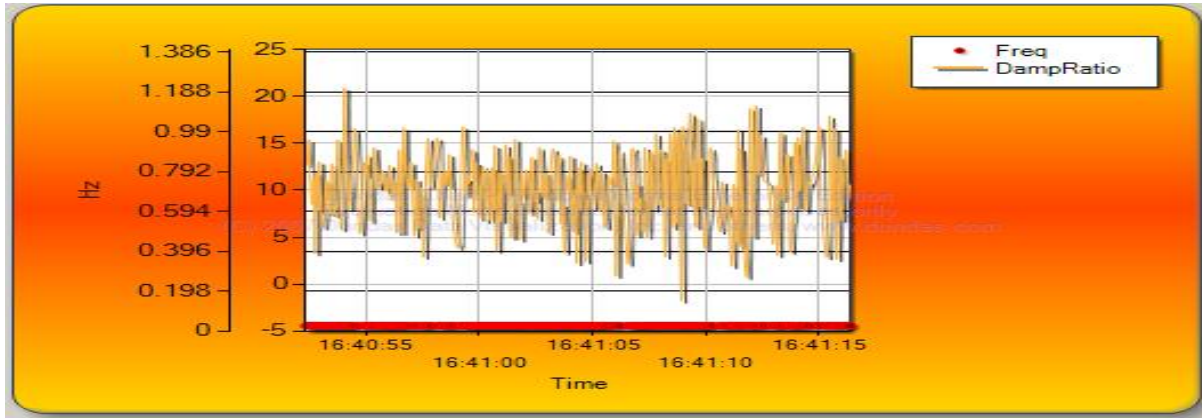


Fig. 6: Modal Analysis showing the un-damped 0.027 Hz mode

The Plot of the poles of the Eigen vectors shows the two modes on the z-plane. For the damped 0.58Hz mode the poles lie inside the unit circle but for the oscillatory 0.027 Hz the poles lie on the unit circle itself, indicating that the quasi stable state for which oscillation will not grow or decay. But it does indicate that the power system stabilizers need to be improved to provide damping for that inter-area frequency.

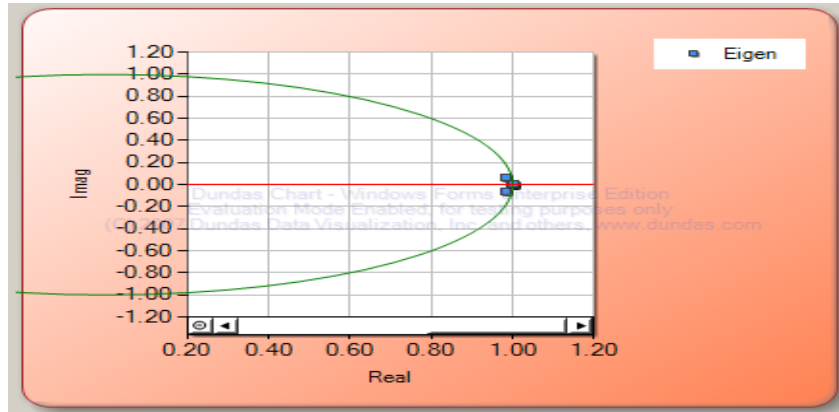


Fig. 7: The Poles of the Eigen Vectors shown on the Z-plane for the 0.58 Hz and 0.025Hz modes

3.3 Power Oscillation Damping using HVDC

A two area system has been used for this study with parallel DC and AC connections. Both Area 1 and Area 2 (see Figure 8) have large ideal sources. The power flow is from Area 1 to 2 with Area 1 also containing a small 150 MVA generator. Area 2 has a larger 500 MVA generator.

A standard 12-pulse controllable thyristor converter HVDC system is used for this study. Filters and converter transformers are included in the model.

Figure 8 shows the model evaluated in Simulink®.

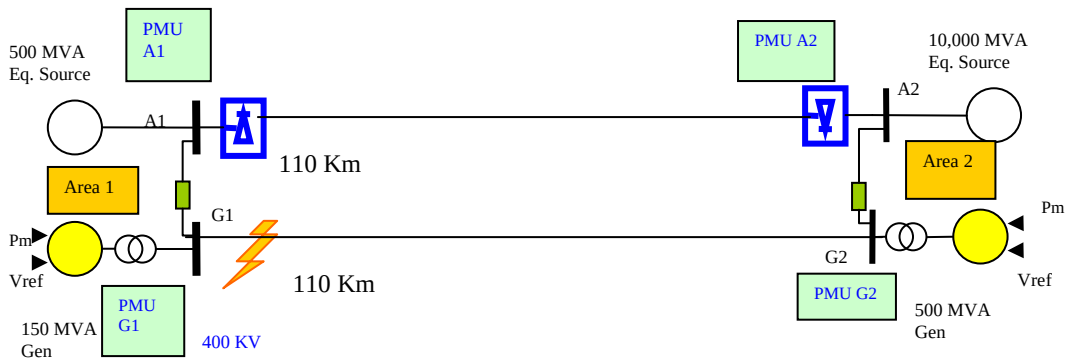


Fig. 8: Test System for HVDC Power Oscillation Damping

When steady state is reached, an A phase to Ground fault is applied near the G1 bus at 18 seconds and cleared by tripping the AC line after 100 milli seconds.

Figure 9 shows the effect of applying Power oscillation damping. The plot shows the active power as seen at bus A1 for no POD, conventional POD and POD derived from PMU's at buses A1 & A2. The trace labelled 'Without POD' shows the active power without any damping control, 'With POD' refers to conventional damping control and the trace 'PMU POD' shows the active power when PMU measurements from buses A1 & A2 are used to derive the power modulation signal.

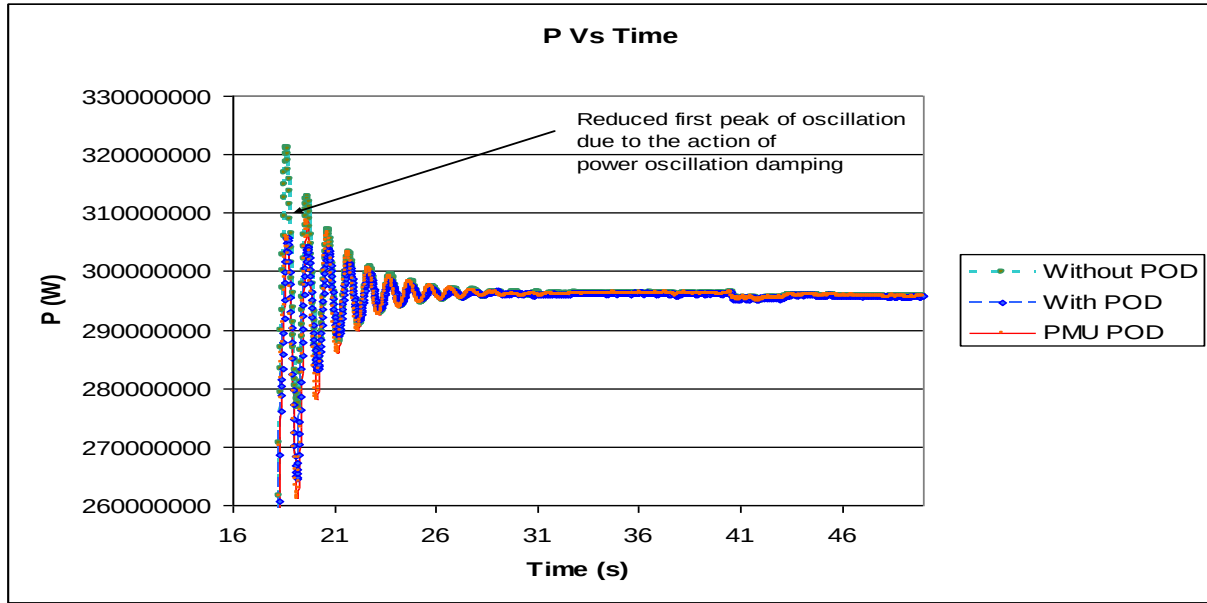


Fig. 9: Active Power at Bus A1

As expected, the POD feature has a positive effect on damping. There is some difference between the PMU measurement based POD and conventional POD. Although the measurements are driven by the same source (buses A1 & A2).

The conventional POD is faster to respond as it is based on instantaneous measurement whereas PMU based measurements are updated only once a cycle (maximum data transmission rate 50 frames/second).

This leads to the obvious conclusion that conventional POD will respond faster than PMU based POD for transient conditions but the issue of combining the two has not been addressed in the above mentioned case along with more dynamic conditions after the transient period has elapsed.

Since the electrical separation between buses G1 and A1 is not large ($0.2+j1.88$ ohms), a concept of an average angle has been used for Area 1 and similarly for Area 2 to derive a new modulating signal for the POD function.

A new PMU based (A1, G1, A2, G2) modulating signal has been created and combined with conventional POD signal. This is driven by the fact that the main contributions to the oscillations in this system are from the generators G1 & G2.

Figure 10 shows the results as compared to using Conventional POD alone. The new trace 'With POD PMU + Gen' shows the power oscillation damping when PMU data from the generator buses (G1 & G2) is combined or mixed with PMU data from buses adjacent to the HVDC converter transformers (A1 & A2) and mixed with the conventional POD signal. Figure 10 also shows that the damping is more or less identical in the first few seconds after the disturbance. This proves that PMU data can be combined with the conventional POD signal without any adverse effects.

Further analysis needs to be done to look at the more dynamic behaviour of the system. Figure 11a shows the Power at Bus A1, 43 seconds onwards (about 15 seconds after the line is tripped). It shows an oscillation developing (only about a megawatt in amplitude) because of effects of the delayed response of some of the generator controls and their interaction with the rest of the system.

Figure 11b confirms that one of the most likely contributors is Generator 1

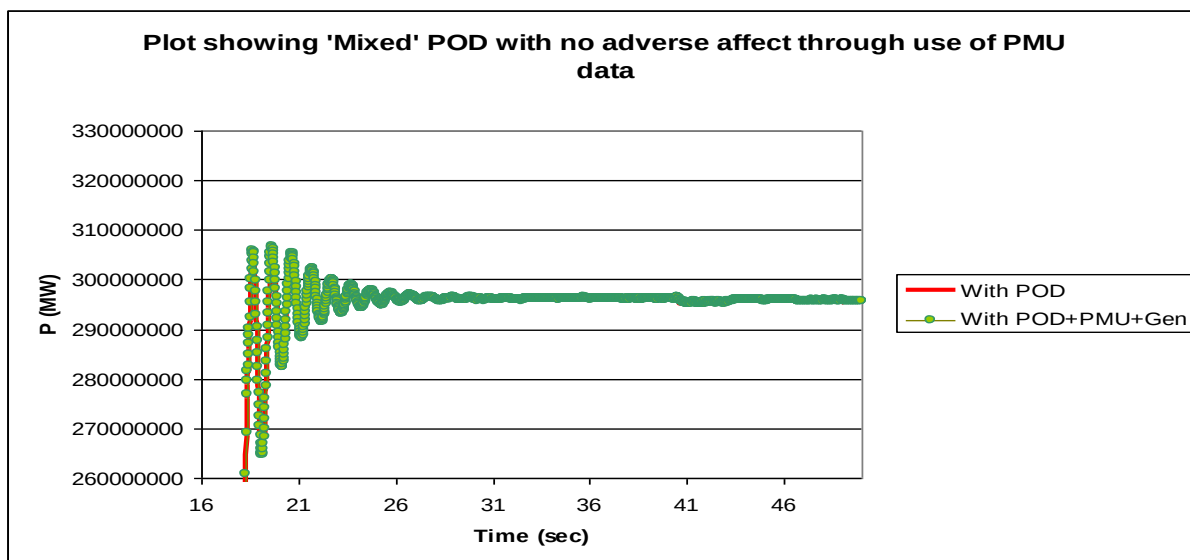


Fig. 10: Active Power at Bus A1 with Conventional and Mixed POD

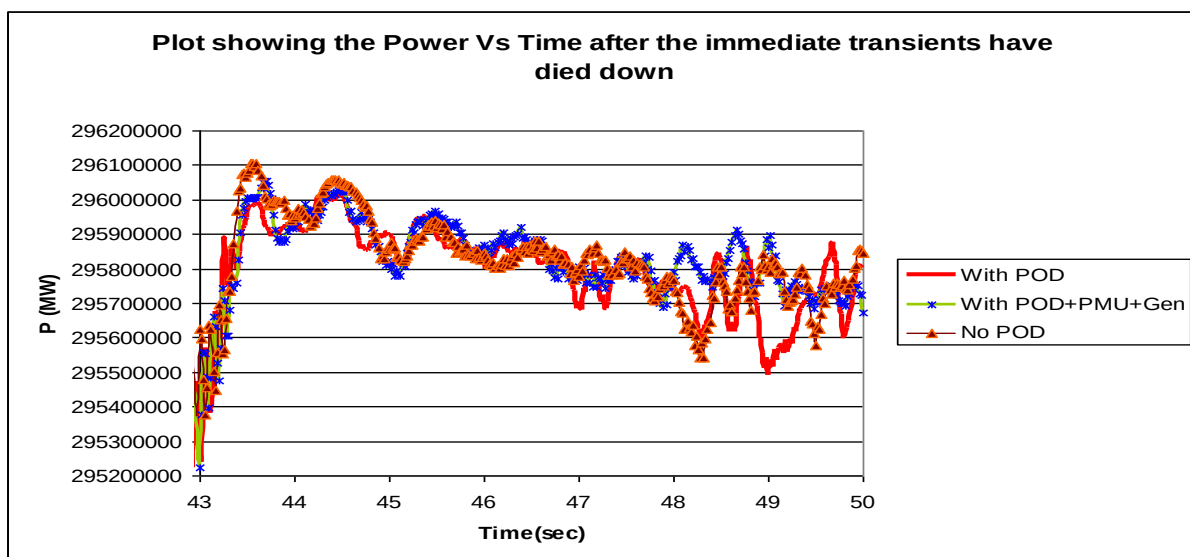


Fig. 11a: Active Power at Bus A1 with Conventional and Mixed POD (zoomed)

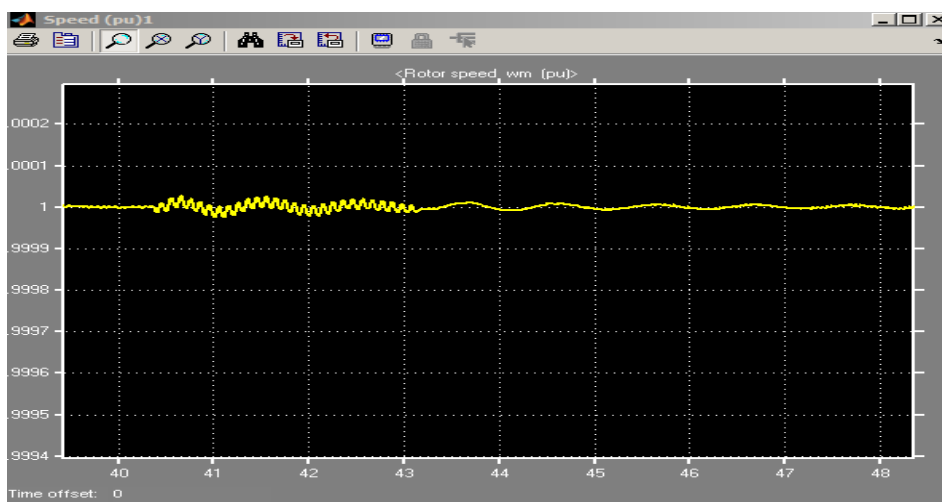


Fig. 11b: Generator 1 rotor speed in PU about 40 seconds onwards (no POD)

3.3.1 Detailed Analysis

Although the above plots visually provide a good indication of improved damping, further analysis is necessary to look at the nature of improvement. For that purpose PMU data from bus A1 is used for analysis. Bus A1 is chosen for this purpose as it is close to the HVDC line and also has more pronounced oscillations than bus A2.

The analysis focuses on the difference between conventional POD and the new mixed POD signal.

For further analysis Eigen values are plotted in z-domain (Figure 12). Only one of the complex poles is plotted to keep the plot less crowded, the other is the mirror image on the imaginary axis

The shift inwards on the real axis from the unit circle boundary especially on the right hand side of the graph demonstrates improved damping. The stray points can be ignored as they represent transient conditions but clusters of Eigen values show more permanent modes which were present for some time.

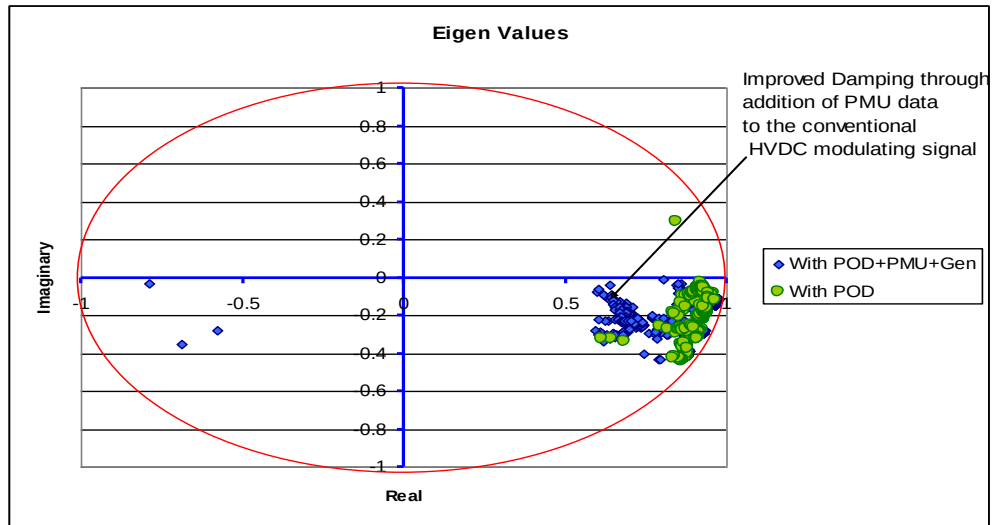


Fig. 12: Poles of Eigen values in z-domain (43 seconds onwards)

4 INTERFACE TO ENERGY MANAGEMENT SYSTEMS (EMS)

Using the PMU simulation and bringing in the Phasor data concentrator (PDC) into the loop also opens the possibility to make EMS visualisation a part of the simulation and refinement process.

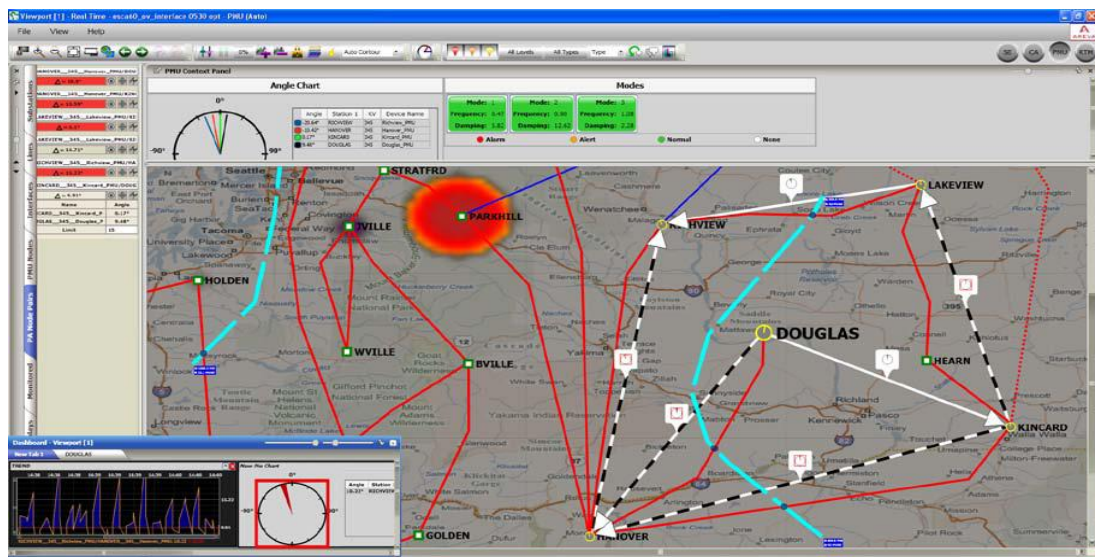


Fig. 13: Operator view of PMU data

Figure 13 shows the EMS display for phasor data

Visualisation of PMU data through simulation also helps in refining and developing EMS visualisation to be relevant for different type of PMU applications.

5 CONCLUSION

The studies have shown that an integrated simulation environment has proven to be an invaluable tool to understand the nature of PMU data along with power system behaviour.

The simulations were used to study two issues which lend themselves nicely to PMU data, small signal stability and Power Oscillation Damping using HVDC. The results prove the suitability of PMU data for such applications and the simulation and validation method chosen for creating those applications.

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- [2] Matlab SVC and PSS Model , Gilbert Sybille (Hydro-Québec).
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