

Small Signal Sensitivity Technique for Determining Inter-connector Transfer Limits

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Abstract – A new simulation technique has been developed for determining oscillatory stability transfer limit of an inter-connector. The small signal sensitivity algorithm calculates the rate of change of small signal oscillatory damping with respect to the change in inter-connector power transfer. The significant level of correlation between the derivative of small signal damping and the small change in power transfer makes the determination of transfer limit possible. Empirical formulas of damping constant with respect to inter-connector power transfers are then developed. This technique has been successfully applied to determine the small signal transfer limits of the South Australia - Victoria (SA-VIC) inter-connector and Queensland-New South Wales inter-connector (QNI) in the Australian National Electricity Market (NEM). From the QNI transfer limit study, it is observed that the effect of voltage stability takes over the oscillatory stability at high power transfer. The application and limitation of this technique is further discussed.

Index Terms—Oscillatory stability, sensitivity study.

I. INTRODUCTION

Engineers and researchers have studied the cause and nature of different power system stability problems for decades. The theories have now been well understood and documented [1]. With better power system plant models and analysis tools, large disturbance events such as fault and voltage collapses can be accurately reproduced by simulation. Relatively little notice is given to the investigation of oscillatory stability because:

- The time differential of any of the system signals (voltage, angle and power flow) is seen as ambient noise which is too small to be analyzed;
- The ambient noise which is mostly the fluctuation in system loads is random in nature and not repeatable;
- Lack of understanding of the signals to be captured and analyzed and monitoring facilities; and
- Lack of accurate small signal models and analysis techniques.

The Plant Model Working Group (PMWG) has started investigating the small signal oscillatory stability ever since the commissioning of the Queensland – New South Wales Inter-connector (QNI). Queensland University of Technology (QUT) and TransGrid have collaboratively developed a real-time Oscillatory Monitoring System (OSM) and a technique to measure system damping performances. Monitors have been installed in four load centers, i.e. South Pine (Queensland), Sydney West (New South Wales), Rowville (Victoria) and Para (South Australia) to measure the voltage-angle differences. The frequencies and damping magnitudes of the inter-area modes present in the Eastern Australian network can be calculated based on the frequency spectrum of the time-differential of the voltage-angle difference measurements between two sites [2, 3]. Following the calibration of the small signal models [4], the Inter-Network Test Working Group (INTWG) researched into a technique that can determine small signal transfer limits of the NEM inter-connectors. This paper details the methodology in determining the transfer limits of the SA-VIC inter-connector (in 2011) and QNI (in 2013).

II. BACKGROUND

A. SA-VIC inter-connector and QNI

The SA-VIC inter-connector starts from Heywood terminal station in Victoria (VIC) through South East to Taillem Bend in South Australia (SA). The span of the inter-connector is over 400 km. It is a double-circuit 275 kV line that connects SA to the rest of the NEM network.

The QNI comprises of a double-circuit 330 kV line from Armidale to Dumaresq in NSW, to Bulli Creek and Braemar in Queensland (QLD), and double-circuit 275 kV lines from Braemar to Tarong Power Station and Western Downs in QLD. The length of the QNI connection from Armidale to Tarong is around 556 km.

B. Inter-network test limits

The pre-test analysis that was carried out in preparation for each of inter-network tests over the period 2002 – 2005 did not indicate that damping would be insufficient under the relevant power transfers. However, it was the lack of damping

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observations under power transfer conditions that approximated the above levels, and uncertainty about whether the analysis could be extrapolated with reasonable certainty that caused the matters to remain unresolved. As a consequence of past inter-network tests being incomplete, on-line monitoring of damping is required to be active for the following inter-regional power transfer conditions:

- SA-VIC transfer (Heywood + Murraylink) above 420 MW
- QNI transfer to NSW is above 950 MW

C. Study objectives

With more generators connecting into the NEM and continuous load growth, it is imperative to maximize the transfer capabilities of these inter-connectors. The objective is to assess whether it is feasible to increase the oscillatory stability limits of these inter-connectors and if so, determine the new transfer limits.

D. Damping criteria in the National Electricity Rules

The National Electricity Rules (NER) considers the power system damping to be adequate if after the most critical credible contingency event, simulations calibrated against past performance indicate that the halving time of the least damped electromechanical mode of oscillation is not more than five seconds. The power system damping operational performance criterion also states that at a given operating point, real-time monitoring or available test results show that there is less than a 10 percent probability that the halving time of the least damped mode of oscillation will exceed ten seconds, and that the average halving time of the least damped mode of oscillation is not more than five seconds [5].

E. The challenges

The following are key challenges for these two projects:

- Oscillatory stability is not a single problem – the study has to simultaneously address to the changes in the 3 inter-area modes in the NEM [1]: QNI mode, I25 (2.5rad/s) mode and I35 (3.5rad/s) mode.
- The study has to address to system normal and contingent conditions.
- The study has to meet both planning and operational requirements according to the NER.
- There is no established methodology for this study.
- The power system operating conditions are continuously changing.

F. Approach

As this project is the first of its kind, no established method could be used as reference. The following conservative approach was adopted to solve the problem step by step:

1. Examine historic damping results (derived both by measurement and simulation) and correlate with inter-connector flows. Terabytes of OSM and Operation and Planning Data Management System

(OPDMS) data from 2008 to 2009 was used for the SA-VIC study, and from 2011 to 2012 for the QNI study.

2. Perform sensitivity studies to understand the effect of system changes to system damping.
3. Extrapolate the results at and beyond constrained limits and observe if there is any correlation of damping to inter-connector flows for both system normal and contingencies.
4. Determine and recommend new small signal stability limits.

III. SENSITIVITY OF SMALL SIGNAL DAMPING

The inter-area mode system damping performances calculated by the calibrated NEM small signal models aligned well with the OSM measurement at the existing inter-connector transfer level. While it is possible to calculate the damping performance at a higher transfer level by adjusting the inter-connector flow of any system snapshot, the result of one single case carries no statistical meaning as there could be endless number of possible operating conditions. Furthermore, it is more important to measure the rate of change of system damping with respect to the change of inter-connector power transfer.

The “delta-sigma delta-P” method aims to determine the relationship between a small change in inter-connector power transfer and the corresponding change in inter-area mode damping. Figure 1 illustrates the methodology. A set of over 500 lightly damped system snapshots (loadflow and calibrated small signal dynamic models from OPDMS) according to the OSM data set is firstly selected. This is labelled as Set B. The damping responses of the three inter-area modes are then calculated using simulation package MUDPACK [6]. Two additional sets of snapshots are generated by reducing transfer by 50 MW (Set A), and increasing transfer by 50 MW (Set C). Similarly, the corresponding damping responses from Set A and Set C are calculated.

The changes in damping ($\Delta\delta_{A \rightarrow B}$ and $\Delta\delta_{B \rightarrow C}$) can be calculated by subtraction between adjacent pair Set A / Set B and Set B / Set C. The results are then plotted against the original power transfer. Figure 2 illustrates the change in I25 mode damping for a 50 MW increase in SA-VIC transfer for a collection of 1,800 lightly damped cases selected between January and November 2009. The result shows that:

- There is very good correlation of change in damping for the I25 mode damping to a 50 MW change in power transfer.
- Interpreting Figure 2:
 - a positive sensitivity value under export conditions means that an increase in transfer (i.e. increase in export) results in an increase in the damping coefficient (i.e. reduced damping) – i.e. increasing export reduces damping;
 - a negative sensitivity value under import conditions means that an increase in transfer (i.e.

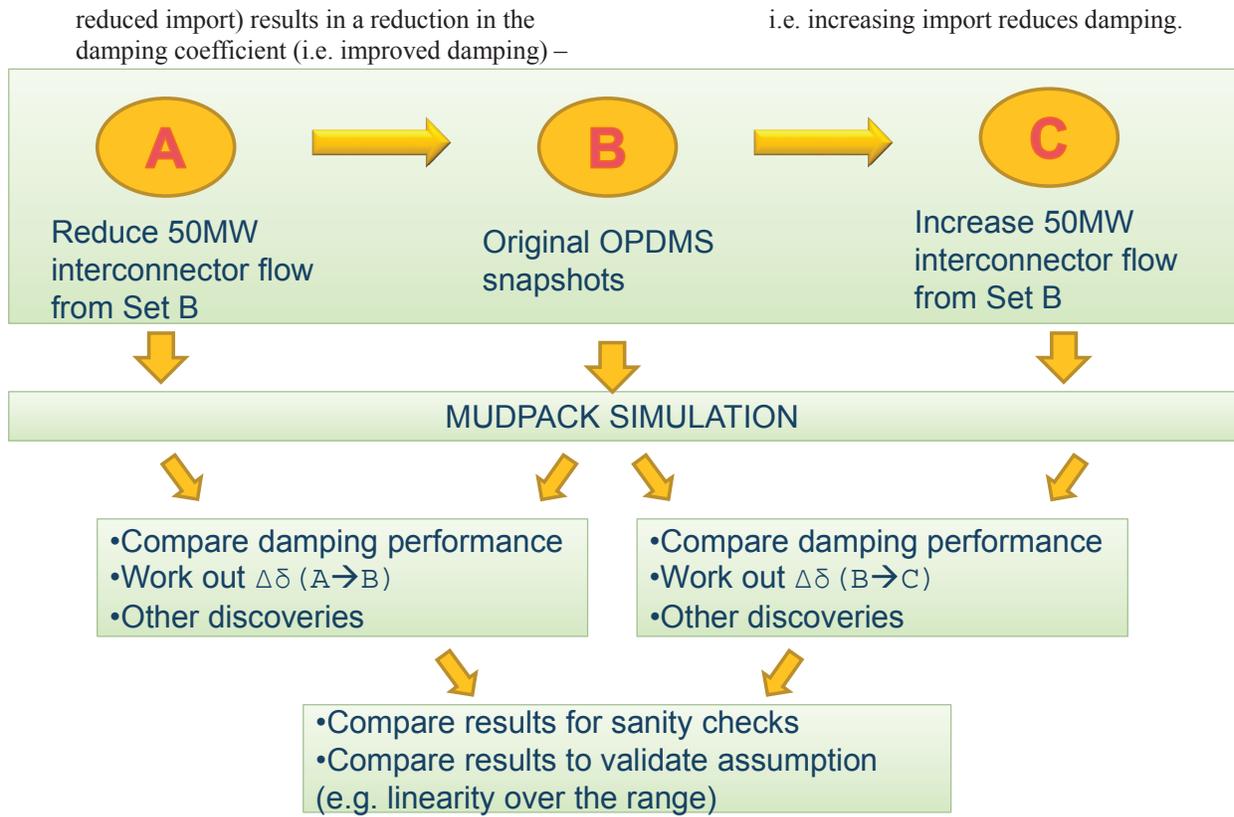


Figure 1. Process chart for sensitivity calculation – delta-sigma delta-P method

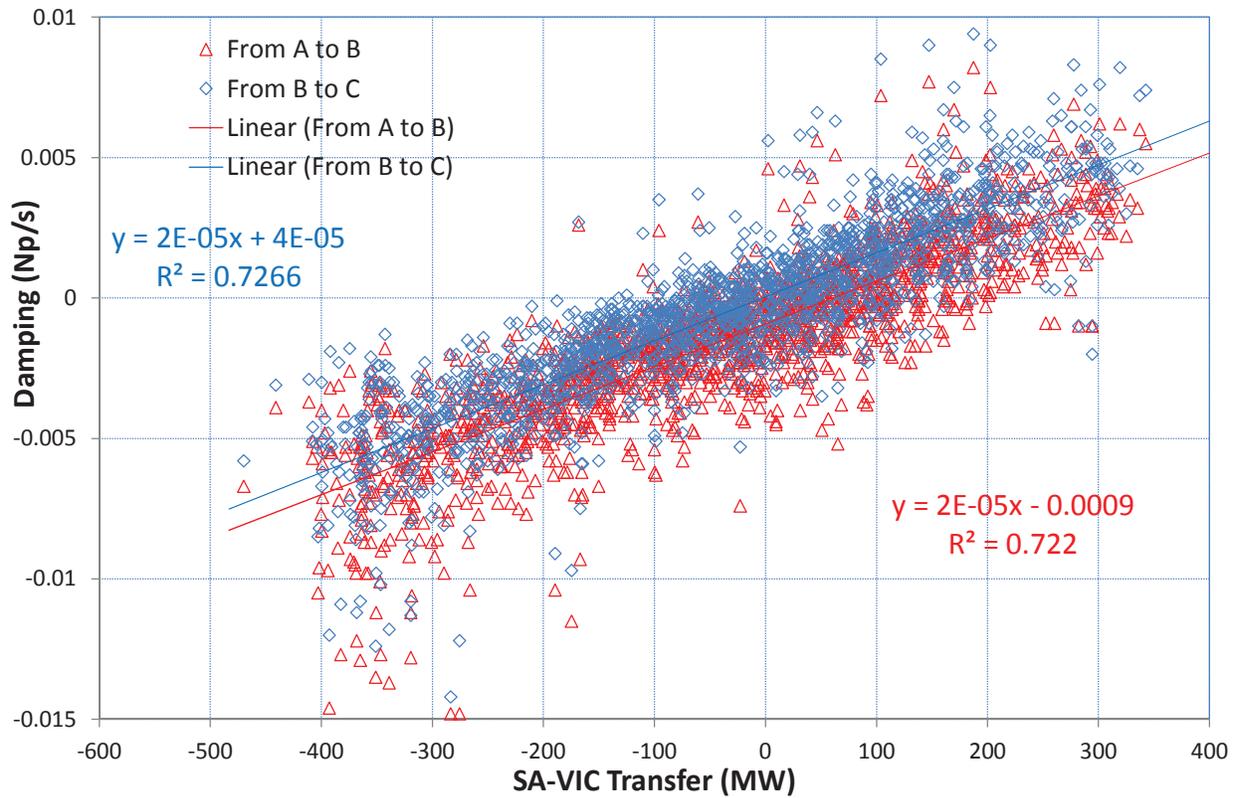


Figure 2. 125 mode damping sensitivity for a 50 MW change in SA-VIC transfer

- The slopes of the trend line (from A to B) and trend line (from B to C) are similar, indicating that:
 - The sensitivity results for increasing and decreasing transfer are consistent.
 - The slight difference in offset between the two trend lines can be explained by Figure 3 – this offset in the sensitivities is a result of the finite increments in transfer applied in the studies and the slight difference in slope of the curve around the operating point, as shown by Figure 3.
- The linear relationship between the change in damping and change in power transfer indicates a quadratic relationship between the actual damping and power transfer level.

IV. EMPIRICAL FORMULA

Due to the high correlation between the change in system damping to the change in inter-connector transfer, a linear equation can be established:

$$\frac{d\sigma}{dP} = aP + b \quad (1)$$

where

σ = coefficient (nepers/sec)

P = inter-connector flow (MW)

a and b are coefficient of the linear equations calculated using linear interpolation.

By integrating equation (1), an empirical quadratic formula can be formed:

$$\sigma = 0.5aP^2 + bP + c \quad (2)$$

where the coefficient c is a variable which sets the damping level when the power transfer is 0.

V. RESULTS

A. SA-VIC inter-connector

The SA-VIC small signal transfer limit was calculated in 2010. Figure 4 shows the predicted I25 mode damping trajectory overlaid on existing measured OSM data. The results show high degree of correlations between QNI and I25 mode damping performances to the change in SA-VIC flow [7]. In December 2010, AEMO advised the SA-VIC combined small signal transfer limit increased from the original 460 MW to 580 MW unconditional [8].

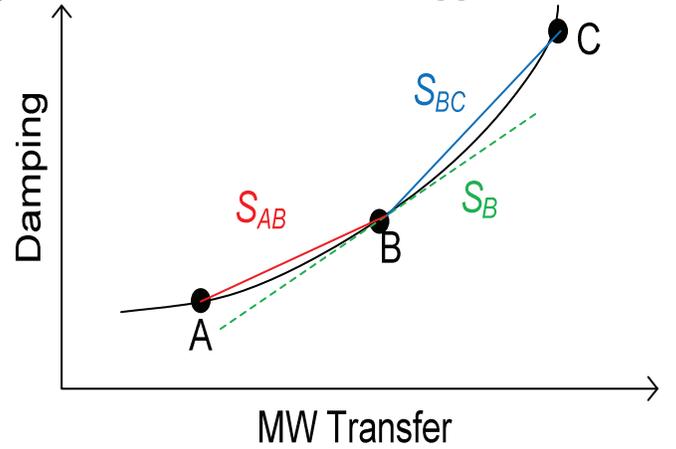


Figure 3. Comparisons of slopes

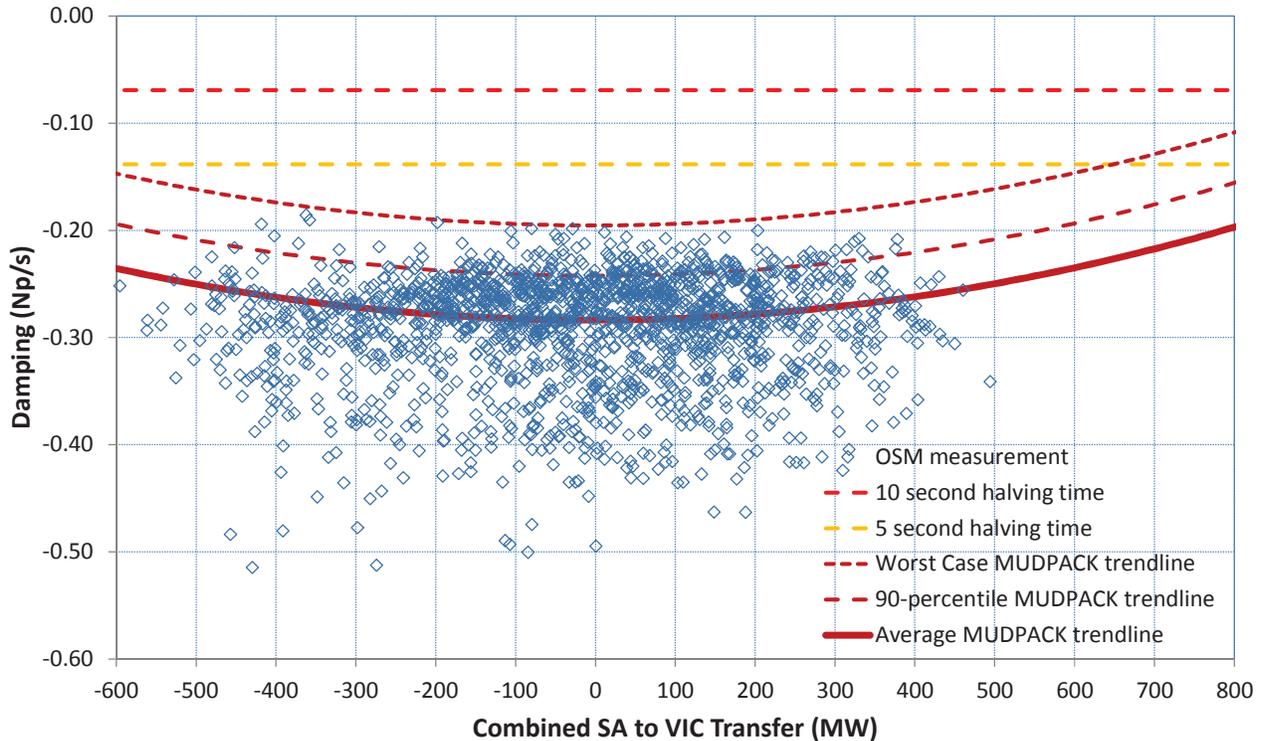


Figure 4. Plot of I25 mode damping equations (50%, 90% and 100% percentile) for different SA-VIC transfer levels

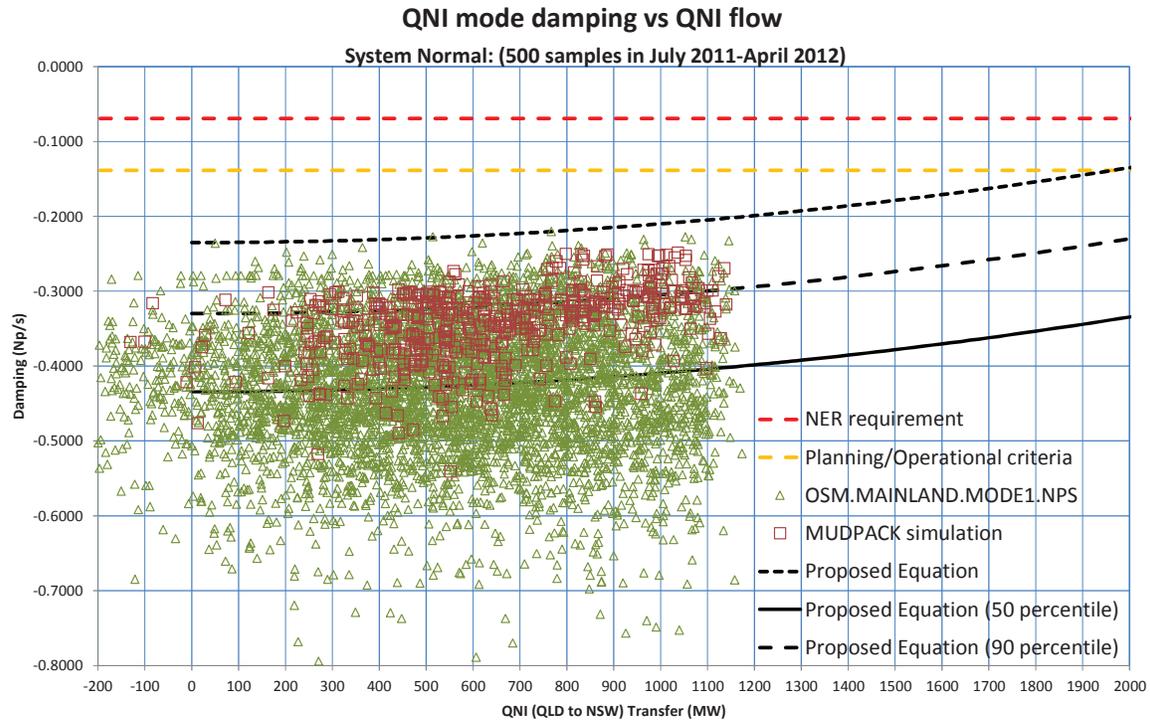


Figure 5. Plot of QNI mode damping equations (50%, 90% and 100% percentile) for different QNI transfer levels

B. QNI

With two years of operational experience with the SA-VIC flow at the new transfer level confirming the validity of the delta-sigma delta-P method in determination of transfer limit, study of the QNI small signal transfer limit was initiated in 2013. One result of the QNI study is shown in Figure 5. Based on the finding, AEMO recommended to raise the unconditional QNI limit, based on Psymetrix availability, from 950 MW to 1078 MW [9].

The QNI study on one hand demonstrated the general applicability of the delta-sigma delta-P algorithm for other inter-connector study, but on the other hand uncovered a new complexity with voltage stability issue reducing oscillatory stability transfer limit. With higher transfer capacity and longer transmission distance, studies have already shown that reactive power compensation is needed for higher power transfer level.

VI. CONCLUSION

This paper introduces a new small signal sensitivity technique in determining the oscillatory stability transfer limit. This technique has been applied in the determination of SA-VIC and QNI transfer limits. Operational experience confirm the validity of this technique. The QNI study highlighted that voltage stability has to be considered simultaneously before establishing the oscillatory stability equations.

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