Topic 2 – Analytical methods for determination of stable operation of IBRs in a future power system

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1. Introduction

For continuing to maintain a stable and viable operation of the grid, it is important to consider the different changes to the grid such as the increasing share of inverter-based resources (IBRs) expected in the Australian power networks. There are different aspects to stability that must be considered, such as large signal, small signal and voltage stability – this topic 2 focuses on small signal stability. For evaluating small-signal stability of a network, detailed information about the network structure/connectivity as well as information about the different devices connected to the network is needed. The linear models of individual devices are systematically connected together using the network information to form the model of the system that can be used to analyse the stability of the entire network. For IBRs, the small-signal model can be constructed by modelling the control structure in detail, when available. This approach also yields information about the control state variables that are potentially involved in an oscillatory mode. However, this information may not always be available to the network modelers, and IBR original equipment manufacturers (OEMs) often share blackbox models that represent their IBRs. In such cases, another approach is to utilize a frequency domain admittance/impedance scan for the blackbox model identification. Another challenge for assessing the small-signal stability for a large network such as the Australian power grid is that the individual devices' small signal characteristics may depend on their operating point, in turn impacting the system-wide dynamic characteristics and oscillatory modes. Thus, the small-signal stability characteristics are expected vary per the time of the day/week/year, as loading and generation mix conditions vary. Hence, this project aims to assess the potential pathways to evaluate changes in small signal stability characteristics when moving across different operating points.

In Stage 2 of this project, a time series power flow analysis of the synthetic network representing the area served by National Electricity Market (NEM) was conducted. Cases representing a future high penetration of IBRs were considered, and after optimizing the voltage profile for 24 power flow cases, the impact on stability in terms of short circuit strength and dynamic simulations were considered. In parallel, two methods for estimating the IBR admittance/impedance characteristics at any given operating point were developed and tested in a small-network.

In the previous Stage 3 of the project, the two methods for estimating the IBR admittance/impedance were further compared, and one of the methods was applied on a model with known control structure, that was treated as a blackbox. The small-signal model corresponding to the synthetic NEM network was systematically created, and an illustrative procedure to incorporate the IBR impedance models in the small-signal stability analysis was developed and applied to some of the IBRs in the synthetic NEM network.

In this Stage 4 work, the project aims to tackle two critical topics – stability margin evaluation and small signal stability screening methods – from the original topics identified in the research plan submitted to CSIRO in 2021.

In this stage of the project, the effort is further extended by applying the procedure to integrate IBR impedance/admittance based models to small signal analysis by utilizing OEM IBR blackbox models. This effort is undertaken to uncover any practical challenges (and corresponding potential mitigations) in applying the procedure developed in the previous stages of the project to actual blackbox IBR models similar to what a network operator/modeler would receive. In the research conducted in the previous stages, it was observed that the operating point has a large impact on the IBR characteristics in the lower frequency range less than 10 Hz – hence, another parallel effort in this stage of the research examines whether frequency domain IBR impedance/admittance characteristics obtained using positive sequence domain models are able to accurately represent the small-signal stability characteristics including the variations due to operating point changes. If successful, the use of positive sequence models instead of (or in conjunction with) EMT domain models is expected to greatly reduce the time and computational resources required to perform the frequency domain scans, especially at lower frequencies. The project plan also includes another effort to assess the impact of obtaining different services such as voltage support and frequency support from IBRs on the small signal characteristics of the IBRs.

2. Research completed

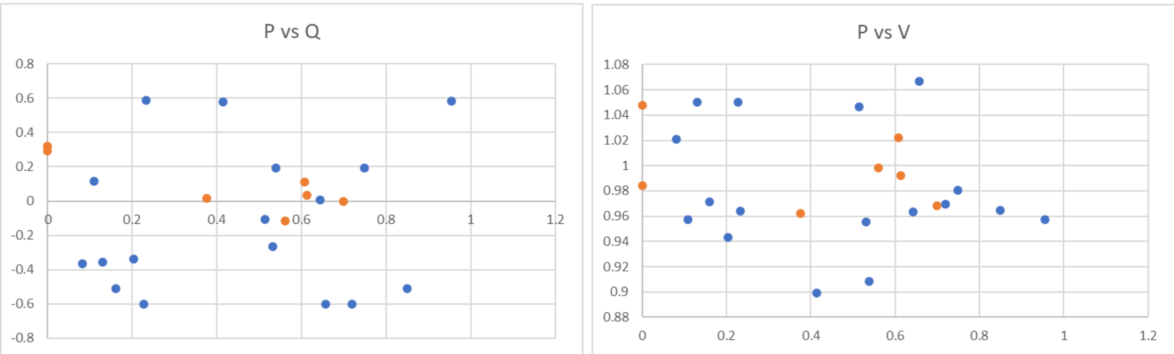
2.1 Impedance models of OEM IBRs

In a small-signal analysis framework, representing the different devices such as synchronous machines and IBRs in detail, modelling the control equations in detail is the norm. However, sometimes the control structure of the devices may not be fully known i.e., there might be black box models used/supplied for simulating a network. For such situations, the impedance or admittance characteristics of a device may be used to approximate how the device will interact with the rest of the network/devices for assessing small signal stability.

The overall procedure to incorporate a model using its impedance/admittance frequency characteristics can be broken into several steps, as given below.

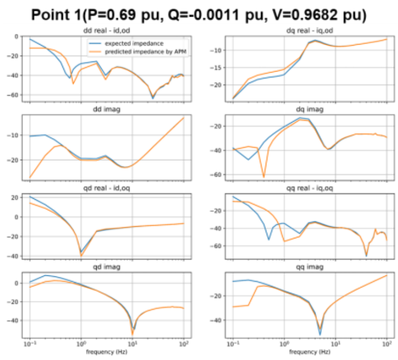
1. Obtain frequency scans for the IBR device at few select operating points
2. Use the obtained frequency scans as the training data for the IBR admittance estimation method(s).
3. From the network power flow solution, the required operating point(s) can be obtained where the device needs to be represented.
4. Using the IBR admittance prediction algorithm developed in Stage 3, the IBR admittance frequency characteristics at the required operating points are estimated. These are in the format of the admittance or impedance values for a pre-determined set of frequencies.
5. A vector fit method is then used to fit a model representing the IBR characteristics. This can be in the form of a transfer function or a state space model.
6. The state space model formed can be incorporated into the network model by converting/transforming the inputs and outputs into the required frame of reference.

To start with, the impedance characteristics of a blackbox OEM inverter is obtained from the frequency scan/admittance prediction method are compared with the frequency characteristics obtained from the analytical model. Figure 1 shows the training points used to train the model (in blue) and prediction points (in orange) for which the predictions were made. There are total of 17 operating points and 7 prediction points.

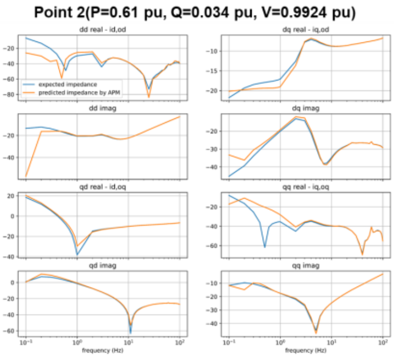


(a) (b)

Figure 1 P vs Q and P vs V graphs showing training and prediction operating points.



(a)



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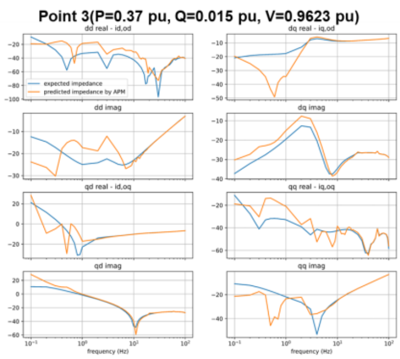

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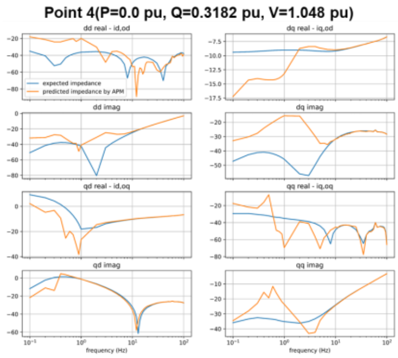

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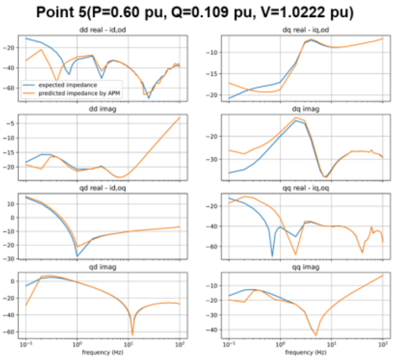

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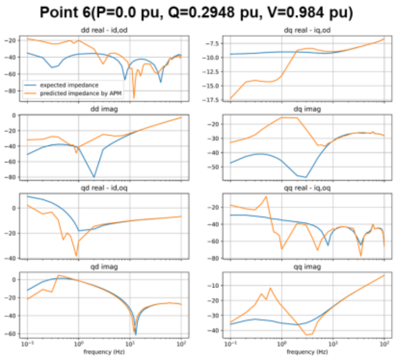

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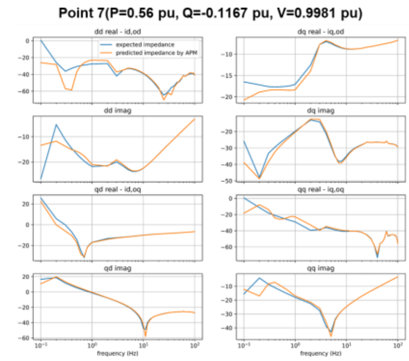

(a)

Figure 2 Comparison of expected and predicted impedance by APM for seven operating points.

Figure 2 shows the comparison of expected and predicted values. Lower frequencies less than ~10 Hz – APM may be limited in how well it replicates the IBR behaviours. For operating points 3,4, and 6 there was a poor match between prediction and expected values. One of the reasons is that operating points 3, 4, and 6 does not have any training points in their close vicinity. Two of these operating points have P as zero. Hence, as a next step we added few more training points, 6 more training points) so that they are closer to these prediction points. Note that we do not want a lot of training points as it may result in overfitting the model. Figure 3 shows the comparison of expected and predicted values after adding new training points. It can be seen that adding new training points helped in improving the prediction by the APM algorithm.

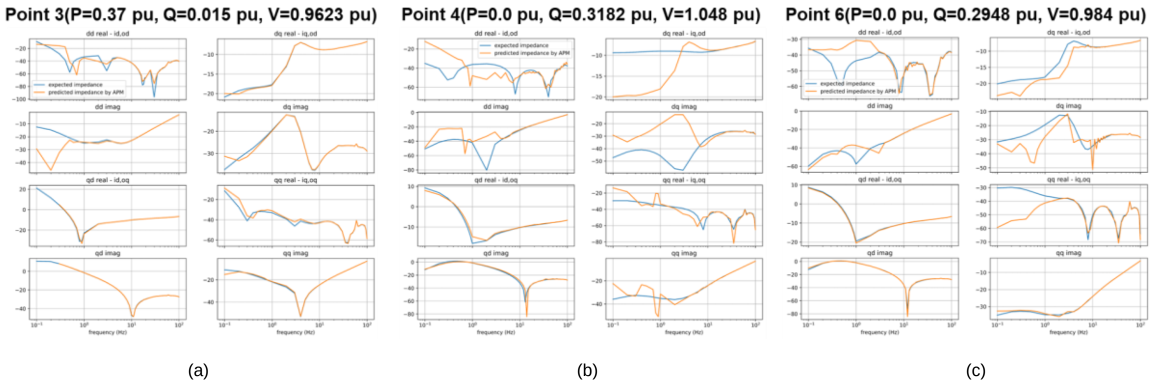

Figure 3 Comparison of expected and predicted impedance by APM for operating points 3, 4, and 6.

2.2 Admittance models of positive sequence IBRs

In the previous stages of research, it was observed that the frequency domain admittance/impedance of IBRs depends on the operating point, especially in the lower frequency ranges (less than 10 Hz).. Hence, this effort aims to assess the potential for using positive sequence models to obtain frequency domain admittance/impedance characteristics that can be further used to form state space models to be used in the small signal stability models/assessment. A key benefit of using positive sequence models for frequency scans is the comparatively less time required for performing frequency scans for the lower frequencies. Further, the aim is to find how the stability characteristics using positive sequence models compare with the characteristics obtained from EMT models and uncover the different nuances and limitations in using positive sequence models through this framework. The overall process that can be followed is shown in **Error! Reference source not found.**, and there may be different considerations in each step that need to be understood.

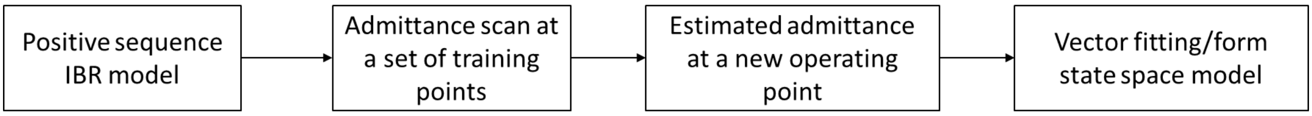

Figure 2 The procedure to use positive sequence models in small-signal assessment

Assuming a given network with positive sequence IBRs as a starting point, there are two approaches to isolate an IBR model in order to perform the impedance/admittance scan. The first approach is to connect the selected IBR, with the correct power flow and dynamic models, to a Single Machine Infinite Bus (SMIB) system. Another approach can be to disconnect the rest of the network (apart from the IBR) and connect the SMIB system to it – presently the former approach is adopted due to the comparatively lower upfront effort for setting up the test IBR models. The differences in the two approaches are in the initial starting case that is used. The first is for a new resource connecting to the network while the second is for a scenario where an existing interconnected resource is present.

One of the positive sequence IBR models from the synthetic NEM network is selected, and the procedure described in **Error! Reference source not found.** is applied to it. When choosing the training and test points for assessing the performance of the APM algorithm, the same training and test points are chosen as the ones used for the OEM models. For the test points, the “expected” admittance obtained by performing the frequency domain impedance scans at the test operating points are compared with the “predicted” frequency admittance characteristics obtained from the APM algorithm at the test points. **Error! Reference source not found.** shows this comparison for some of the illustrative operating points – in some cases (such as operating point 1) the APM algorithm is able to estimate the admittance at the test point accurately, whereas moderate or significant mismatches are observed for operating points 2 and 3.

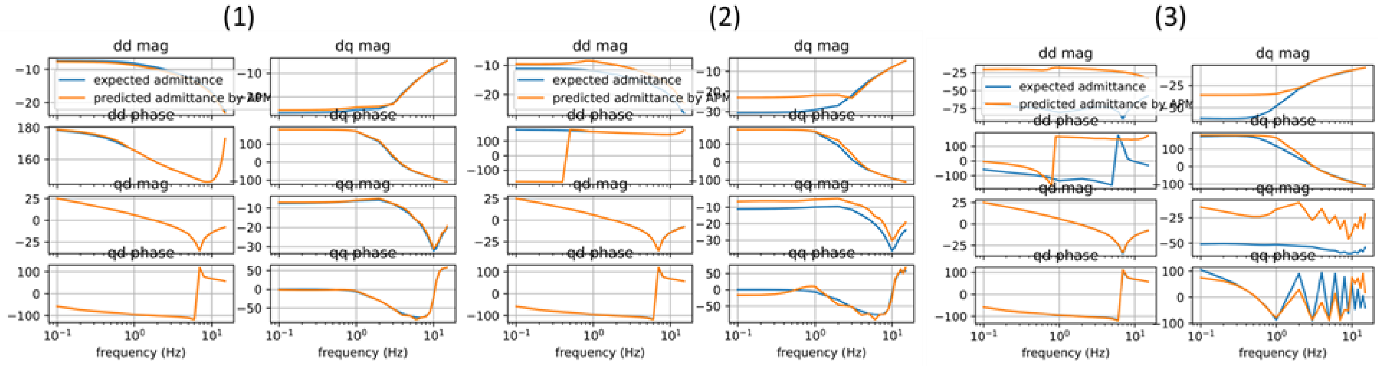

Figure 3 The expected frequency domain admittance characteristics for a positive sequence IBR model compared with the predicted admittance characteristics at the same operating point using APM algorithm for three test operating points

A key observation here is that for the test points where the predicted and expected admittance characteristics were significantly different (such as operating point 3, where the active power from the IBR was close to zero) for the positive sequence IBR model, the APM algorithm also had a poor performance for the OEM EMT models, indicating a similar trend. Further, APM had (relatively) lower mismatch for the operating point 1 for the OEM EMT model. The cases where the predicted admittance characteristics were significantly different from the expected admittance characteristics continue to be investigated further.

Once the impedance/admittance models are obtained from the APM algorithm, a vector fitting process same as the one utilized in the previous stage of research is applied to the impedance/admittance characteristics. It is observed that for certain operating points (e.g. operating point 1) the vector fitting successfully describes the impedance/admittance, however, where the APM had large errors, there may be challenges in applying the vector fit process, as shown in **Error! Reference source not found.**.

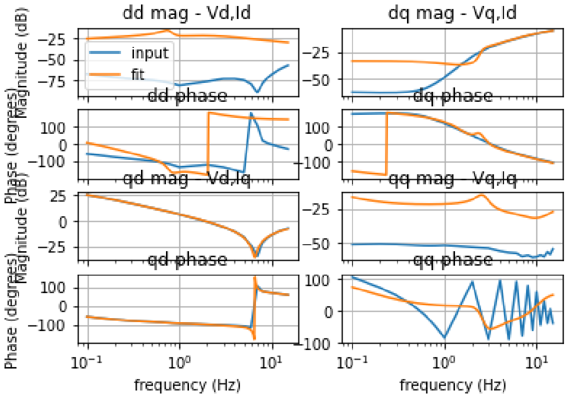

Figure 4 Vector fitting process is unsuccessful for the case where the there were large mismatches between the expected and predicted frequency domain characteristics

For the three operating points shown in **Error! Reference source not found.**, **Error! Reference source not found.** shows the open loop poles obtained from applying the vector fit process to form state space models on both expected and predicted frequency domain admittance characteristics. For operating point 1, it is observed that the poles obtained for the expected and predicted models are very close, though there are still a few differences. These differences increase as the differences between the predicted and expected frequency domain characteristics increase progressively for operating point 2 and 3. Work continues to integrate these models in a network small signal model to assess the impact on stability.

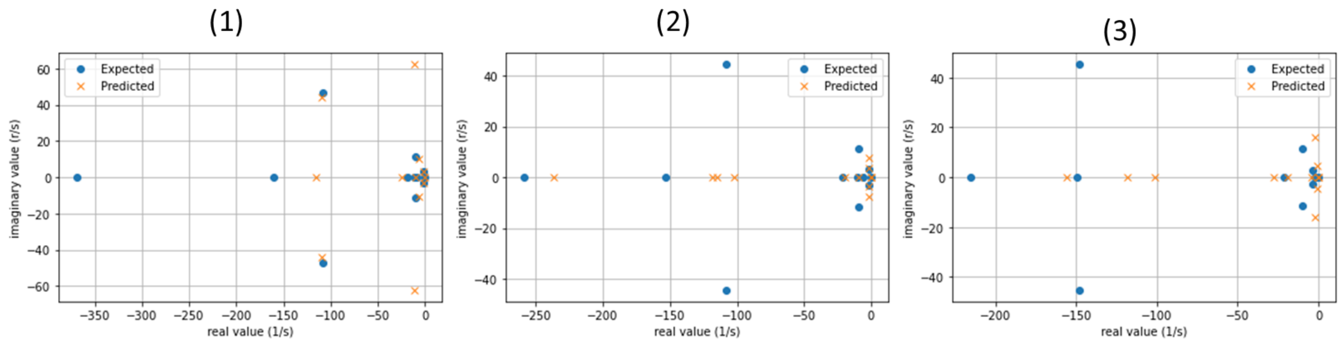

Figure 5 Open loop poles compared for the three selected test points for the state space models formed using the expected and predicted frequency domain characteristics

3. Outstanding activities

For both OEM IBR models and positive sequence models, a further investigation into the performance of APM for operating points where it currently results in large mismatches is ongoing. Factors such as the number of training operating points as well as the combinations of the active power, reactive power and voltages covered by the training points is also being examined. Two more OEM IBR configurations are also planned to be tested. For the positive sequence IBR models, the state-space models formed using the procedure described here are planned to be integrated into a network to assess their impact on small-signal stability, and the frequency domain characteristics will be compared for similar EMT and positive sequence domains to understand the limitations and similarities when using positive sequence IBR models for frequency domain admittances/impedances. In subsequent efforts, the team plans to also assess the impacts and potential benefits/trade-offs of obtaining various services from IBRs (such as voltage and/or frequency support) on small signal stability characteristics.

4. Progress against the Roadmap

The work continues to align with the roadmap. Per the initial roadmap, the third year of a total three-year effort would look towards application of the developed methods in real system environments. The work done so far in this stage of the work is on track with the roadmap. It is estimated that approximately 75% of the work to be done under the two critical relevant tasks (i.e., stability margin evaluation and small signal stability screening methods) has been carried out

5. Research relevance to Australia

The Australian power system continues to see a high penetration levels of IBRs in operation and in the planned projects. Hence, incorporating these changes into small signal stability assessment is essential. One of the aims of this research effort is to streamline the process of forming the small signal model including representation of IBRs where only blackbox model is available, and by applying the procedure to OEM models, the various practical challenges may be identified and the process may be modified to account for those, making it easier to apply the process on actual networks. The potential for the use of positive sequence models can also result in a significant reduction in the time and computational effort required for performing frequency domain impedance/admittance scans, thus potentially shortening the connection cost for a new IBR. The trade-offs and impacts identified by the planned effort of examining the relation between obtaining different services from IBRs and small signal stability may also help power system planning and operation functions. The large (and fast-growing) share of IBRs in the Australian power system makes these factors highly relevant for the Australian scenario.

6. Recommendation research priorities

In this stage of the project, the procedure to form state space models using frequency domain admittance/impedance scans for blackbox IBRs is expected to be refined and improved in terms of application to OEM IBR blackbox models and potential improvements in speed by utilizing positive sequence models. A next step of the research can be to extend this further to apply on a real system in a planning setting, as well as to explore the computational aspects further and the possibility of applying the procedure in an operational setting. Further, another facet that can be studied is utilizing multiple-frequency network equivalents to represent the far-away regions not critical to a particular analysis to further improve the application to a large network scenario.