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WP4 Report

SSO Identification Tool

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Contents

1 Introduction

The primary deliverable of this project is the SSO Identification Tool to study user provided converter-driven plants in PSCAD using frequency domain techniques. The tool provides a comprehensive framework to analyse the user models in frequency domain, either in isolation or connected to the transmission network. The tool comes with a browser-based user interface that offers users full control over the settings and parameters of the tool along with visualisation of results.

The development work is completed in WP3, and the tool is currently being used within the Operability Innovation team to test its compatibility with different user models. The user manual for the tool along with a step-by-step guide for setup is provided in the WP3 report.

The focus of this work package is to discuss the implementation plan so that the tool can be used by the wider team. It also highlights any further developments necessary based on feedback from the ESO to ensure that the tool meets the business requirements and can be used seamless with a wide variety of user models.

The implementation plan and further development needs are discussed in separate sections. No indication for the time and effort necessary to achieve these objectives have been included in the report. These will be calculated on a case-by-case basis if requested by ESO.

2 SSO Tool Recap

The developed framework is an end-to-end automated process, implemented as a tool with a user interface. The overall process is shown in Figure 1. It includes several important steps to process operational scenarios with the objective of eliminating scenarios that do not pose any threat of damping issues in the subsynchronous frequency range.

The first step in the process is to read the base case EMT model and provide users an interface to define several operational scenarios. These scenarios can be both topological changes in the network (such as planned outage or shunt compensation switching) and operational setpoint adjustments (such as MW and MVAr export of IBRs). Once a list of scenarios is defined, these are applied to the EMT model to create several variations of the base case model.

The next step is to create a frequency domain representation of the EMT models by injecting voltages (limited to less than 1% peak to peak for transmission connections) at certain frequencies such as 1Hz to 40Hz. Several frequency injection techniques are discussed in literature [1], [2], [3], [4] each having their strengths and weaknesses. Some techniques are based on the injection of a wide-band frequency such as white noise to capture the non-linear characteristics of IBRs while others are based on injection in bands with quadratic phase displacement. However, the most important consideration is the use of a Multi Input Multi Output (MIMO) transfer function model over a Single Input Single Output (SISO) model. If the positive and negative sequence impedances are decoupled, then the standard sequence domain impedance, calculated as per equation (1), can be used. This SISO transfer function model is valid as long as there are no active non-linear devices in the system.

$$Y_p = \frac{I_p}{V_p}, Y_n = \frac{I_n}{V_n} \tag{1}$$

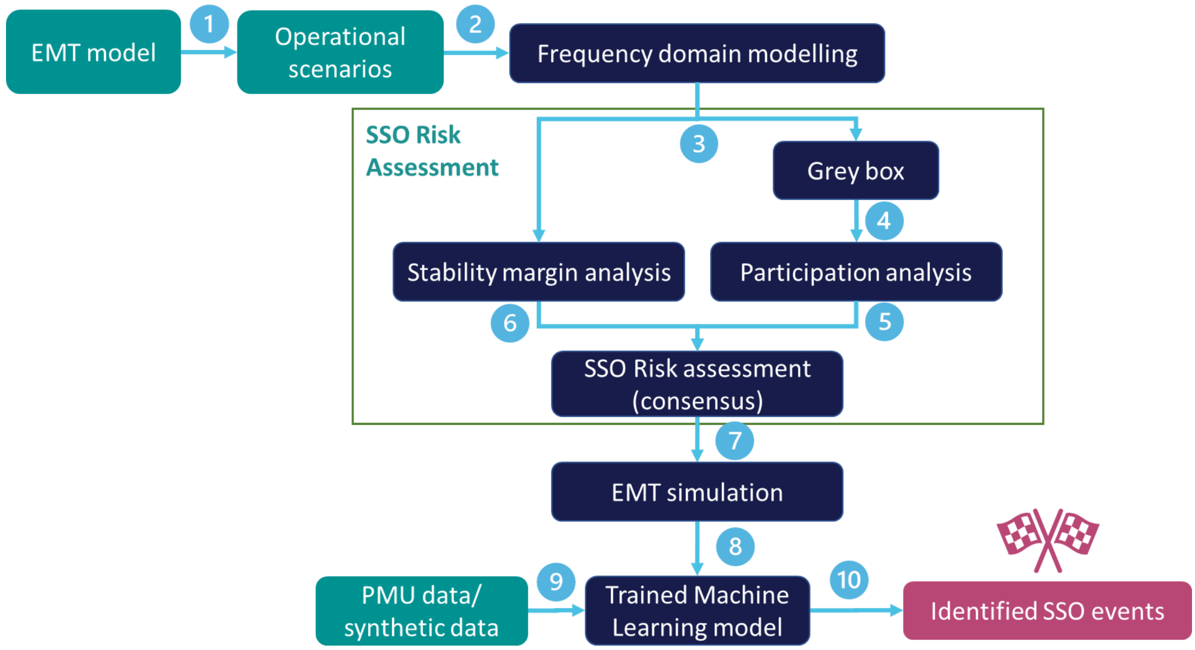


Figure 1 Overall process flow diagram of the developed framework.

The SSO tool implements both SISO and MIMO impedance calculation methods. It is up to the user to decide which impedance form is suitable for a particular network. Please refer to the WP3 report for the guidelines for selecting a particular method.

3 Implementation plan

The use of the tool in BAU requires extensive testing to ensure that the performance of the tool is robust and replicable. At the time of the handover, the tool has been tested with the following open-source models and user models by ESO. The measured impedance is compared with the MHI dynamic scanning tool, wherever appropriate, to ensure correctness of the results.

3.1 Passive network

A double circuit transmission line with an equivalent voltage source. The transmission line is series compensated and the parameters are tuned to introduce a series resonance at 30Hz. A diagram of the network in PSCAD is shown in Figure 2.

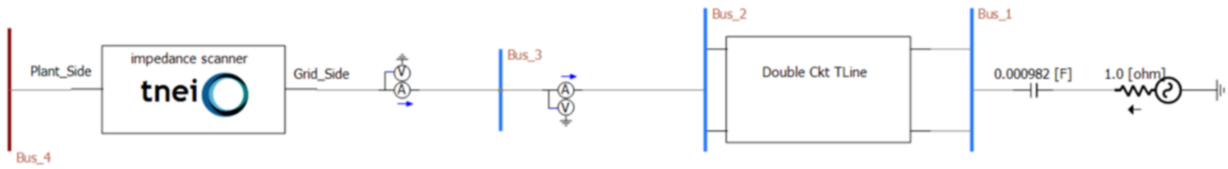
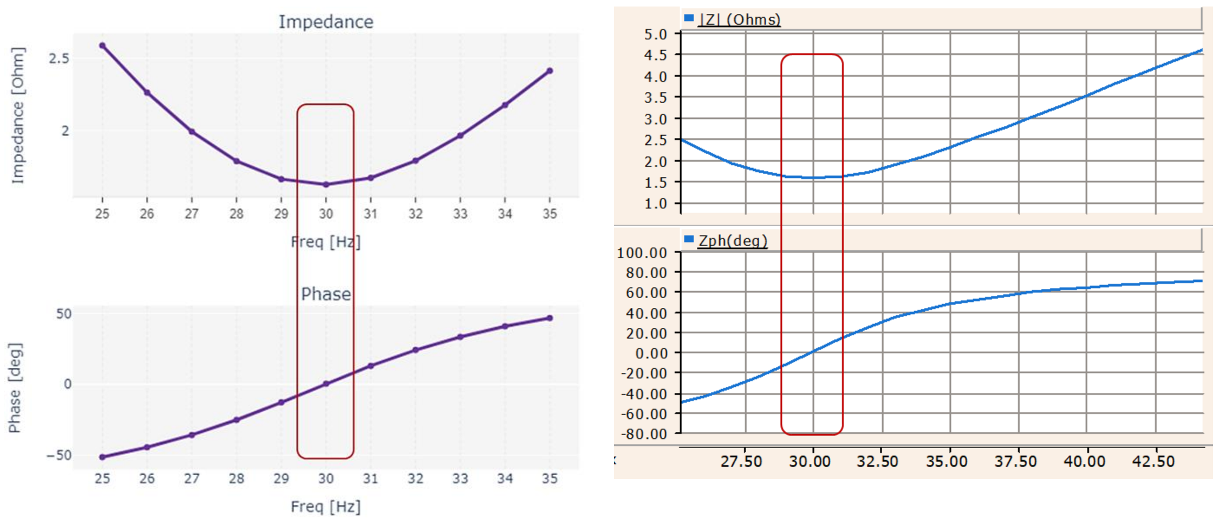


Figure 2 Passive network with a series resonance at 30Hz

This simple model is an easy test to ensure that the frequency injection method and the associated module to extract the relevant frequencies to calculate the impedance are implemented correctly. Figure 3 shows the comparison of the scan between the scanner developed as part of the SSO tool and the dynamic scanner provided by MHI. The impedances are calculated using the SISO form in both scanners.



(a) (b)

Figure 3 Impedance scan of the passive network showing resonance at 30Hz, (a) SSO Tool Scanner, (b) MHI Dynamic Scanner

3.2 Active network

3.2.1 DFIG wind farm

An average model of a DFIG wind farm is selected for this test. The wind farm is connected to a voltage source with a small internal impedance. Before scanning, the wind farm is operated at a stable point. Thereafter, a voltage perturbation of 1% peak-to-peak is introduced and the model is checked again to ensure that the small signal perturbation does not alter the operating point of the model. Figure 4 shows the diagram of the model implemented in PSCAD.

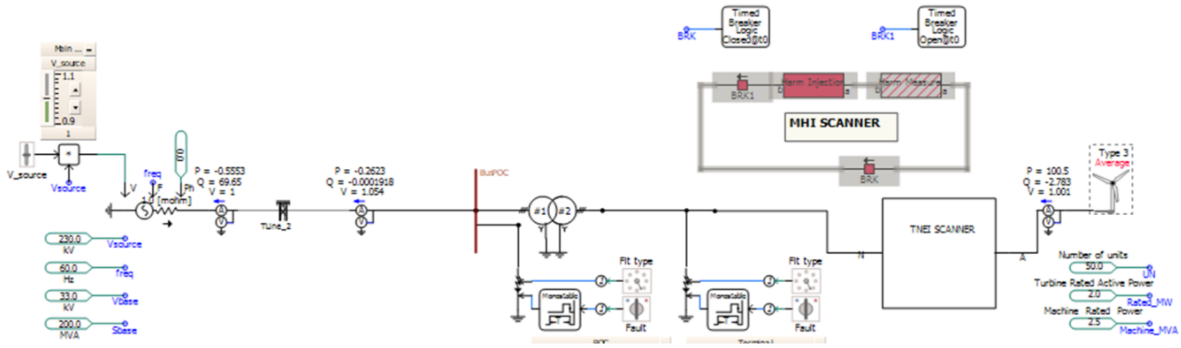
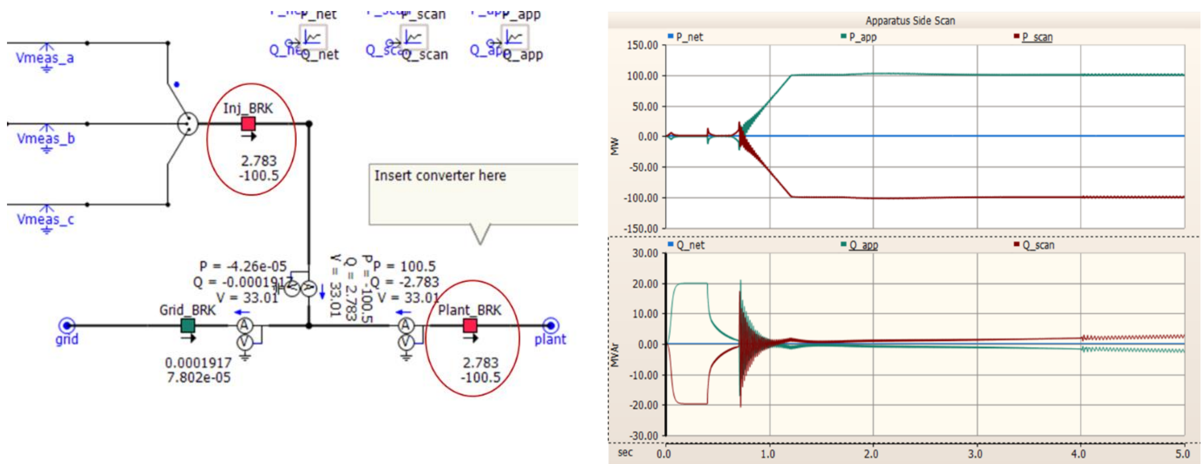


Figure 4 DFIG wind farm connected to an external voltage source

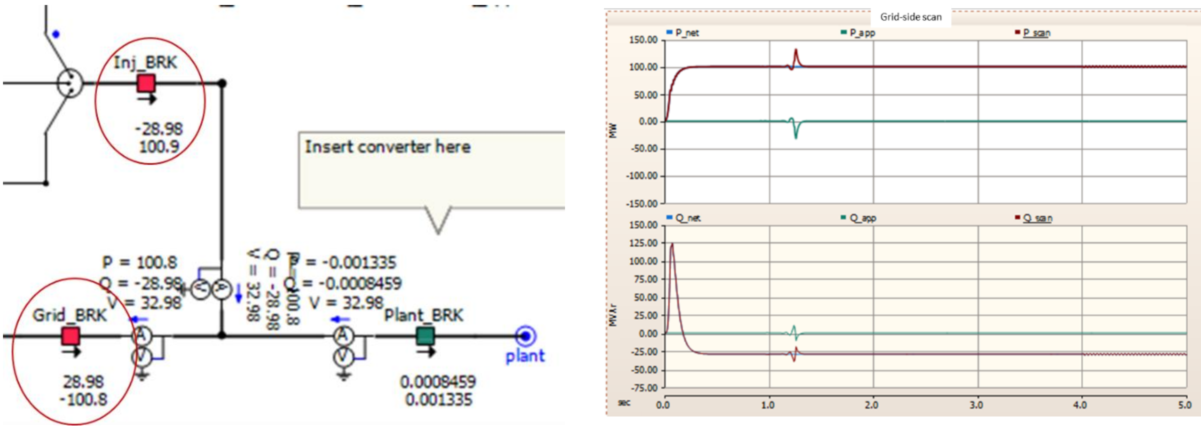
Figure 5 shows the exchange of power between the scanner and the DFIG wind farm during the apparatus side scan. The wind farm operates at a steady setpoint exporting 100MW that sinks into the voltage source within the TNEI scanner. The breaker on the grid-side (*Grid_BRK*) is kept open for this scan and no power is exchanged with the grid.



(a) (b)

Figure 5 Apparatus side scan

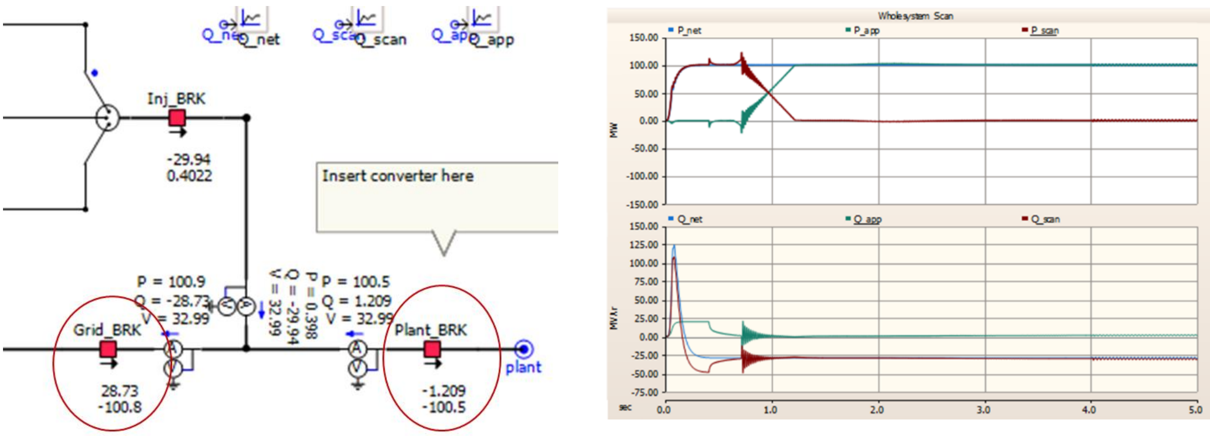
Figure 6 shows the scanner setup for the grid-side scan. The important point to note here is that the grid-side scan should be performed at the same operating point as the apparatus-side scan. This means that the power export from the wind farm should be the same as the power flowing into the grid. This is ensured in the figure below as 100MW flows from the scanner to the grid.



(a) (b)

Figure 6 Grid side scan

Figure 7 shows the scanner setup for the whole system scan. It is important to ensure in this case that no power (or very minimal power) is exchanged with the scanner and the entire export of the wind farm flows into the grid. From the figure below, we can see this condition is maintained as 100MW export from the wind farm flows into the grid will a minimal power is exchanged with the scanner.

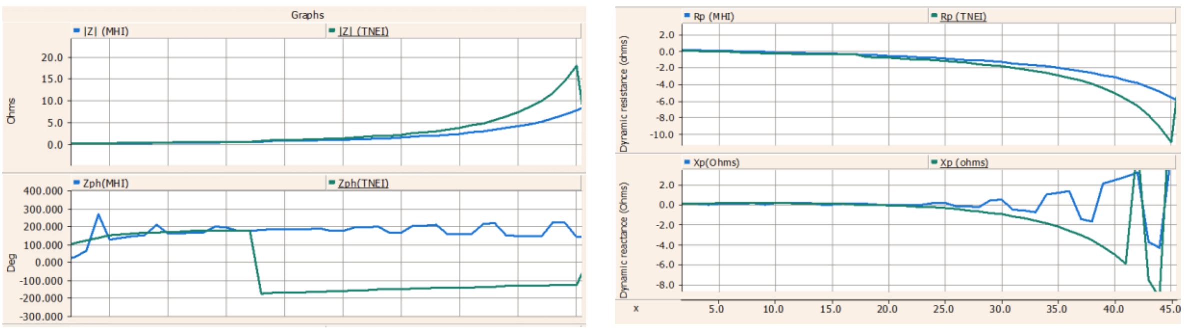


(a) (b)

Figure 7 Whole system scan

The impedance scan results from TNEI scanner and MHI scanner are compared in Figure 8. The impedance magnitude is similar in both cases up to around 25Hz. Beyond this frequency, the values start to diverge, and the difference increases with frequency.

The reactance plot (TNEI scanner – green curve) shows that around 17Hz, the value crosses over from positive to negative. This is captured in the phase plot as well where the phase changes from positive to a negative value. The reactance from the MHI scanner (blue curve), however, shows an oscillatory behaviour and the value toggles between positive and negative, although the calculated phase remains positive throughout with a small oscillatory behaviour.



(a) (b)

Figure 8 Comparison of impedance scan results between TNEI scanner (green) and MHI scanner (blue)

3.2.2 Blackbox model

A compiled model of a STATCOM is used here to test the performance of the tool in measuring impedance of blackbox user models. The STATCOM is connected to the South East Coast network model in PSCAD at Bolney 400kV substation. All other sources in the network are represented by equivalent voltage sources and no other active elements are present except the STATCOM.

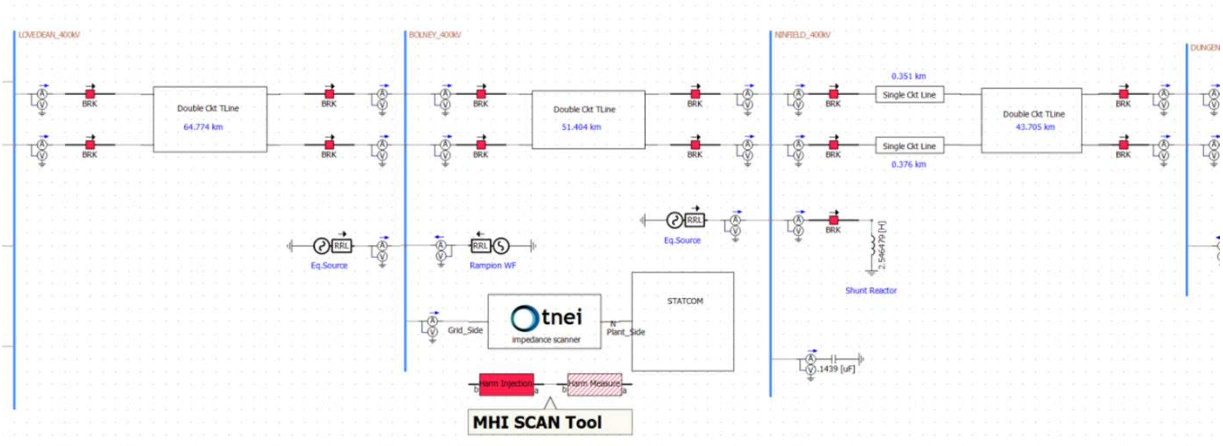
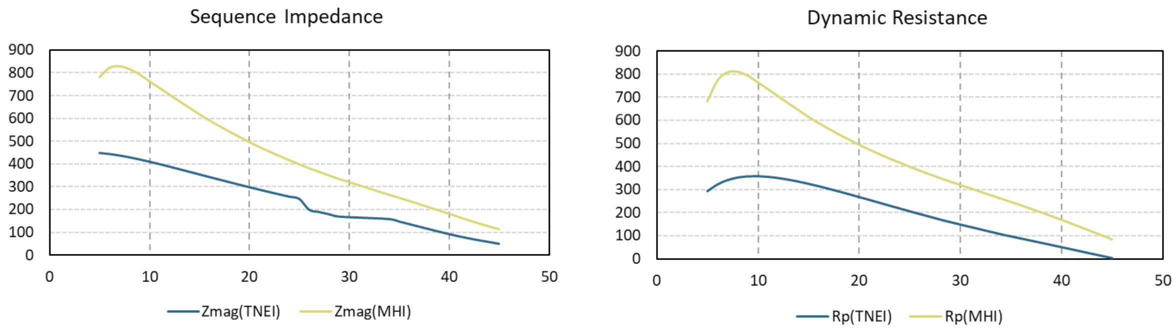


Figure 9 South East Coast model with the STATCOM connected at Bolney 400kV substation

The impedance scan response of the MHI scanner is compared with the TNEI scanner in the subsynchronous range. The MHI scanner uses a Single Input Single Output (SISO) implementation to calculate the impedance while the TNEI scanner uses a Multi Input Multi Output (MIMO) approach.

Figure 10 compares the impedance scan for the black box STATCOM model between TNEI and MHI scanners. The impedance measured using MIMO method (TNEI scanner) is found to be lower than the impedance based on SISO method (MHI scanner). The difference between the two impedances becomes smaller with increase in frequency. This trend aligns with the findings from literatures i.e., the MIMO results approach SISO values as the frequency goes beyond ≈500Hz.

The fact that MIMO results are lower than SISO measurements in the subsynchronous range is very important. A higher value of the apparatus impedance means that even when the grid is weak (high impedance), no intersection of the impedances can be observed in the frequency domain. This gives a false sense of security that the system is stable and there is no risk of controller interactions when perturbed from the steady operating point.



(a) (b)

Figure 10 Impedance scan results from TNEI and MHI scanners for a STATCOM user model

3.2.3 Benchmark system

The CIGRE benchmark system is the primary model used in the project to develop and test the SSO tool. The benchmark system was originally developed by the CIGRE WG C4.49 in MATLAB Simulink and TNEI replicated the model in PSCAD. A diagram of the model from PSCAD is shown in Figure 11.

The model has two wind farms connected by AC exports to a 220kV substation. Both wind farms are grid following but have minor differences in their controller implementation. The external grid is modelled by a voltage source in series with a variable impedance to modify the fault level.

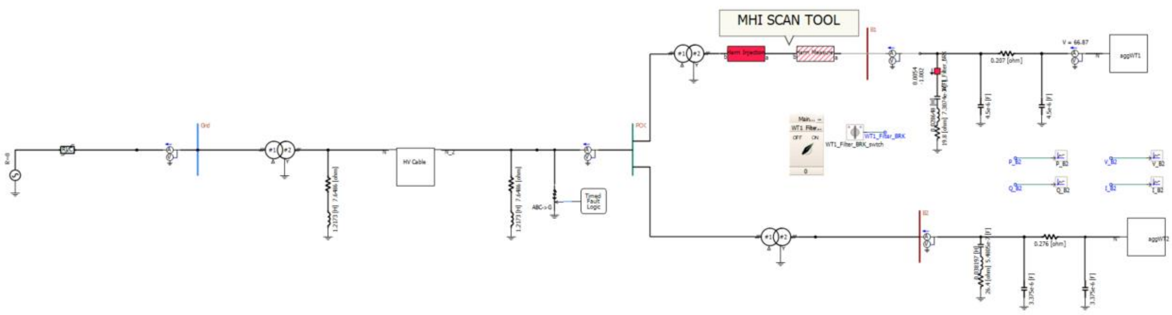


Figure 11 CIGRE Benchmark system for SSO analysis

In this case study, the impedance scan response of the MHI scanner (SISO) is compared with the SISO implementation of the TNEI scanner (SISO). There are two purposes of this comparison, (a) to show that the SISO impedances from the two scanners are similar and the results can be reproduced by different scanners as long as the same operating point is maintained for the scans, and (b) the SISO scans are unable to detect SSO in the frequency domain, but an EMT study shows clear oscillations after a fault event.

Figure 12 shows the apparatus side scan for WF1 from both scanners. The impedance values are not identical but very close to each other. However, the reactance and phase plots are significantly different between the scanners. While TNEI scanner shows a change in reactance from a capacitive to an inductive value and a corresponding change in the phase angle, the MHI scanner estimates inductive behaviour of the wind farm controller for the entire subsynchronous range.

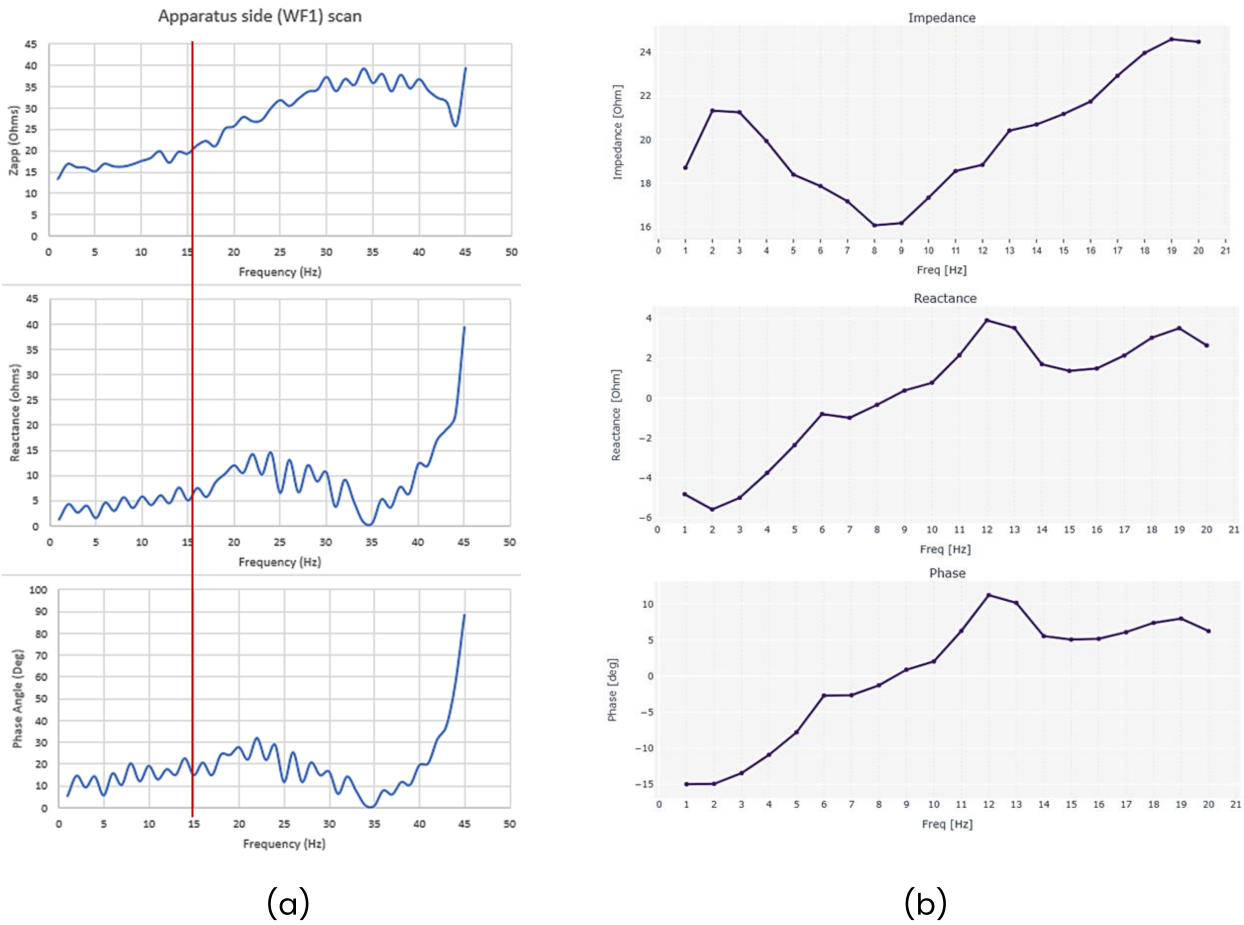
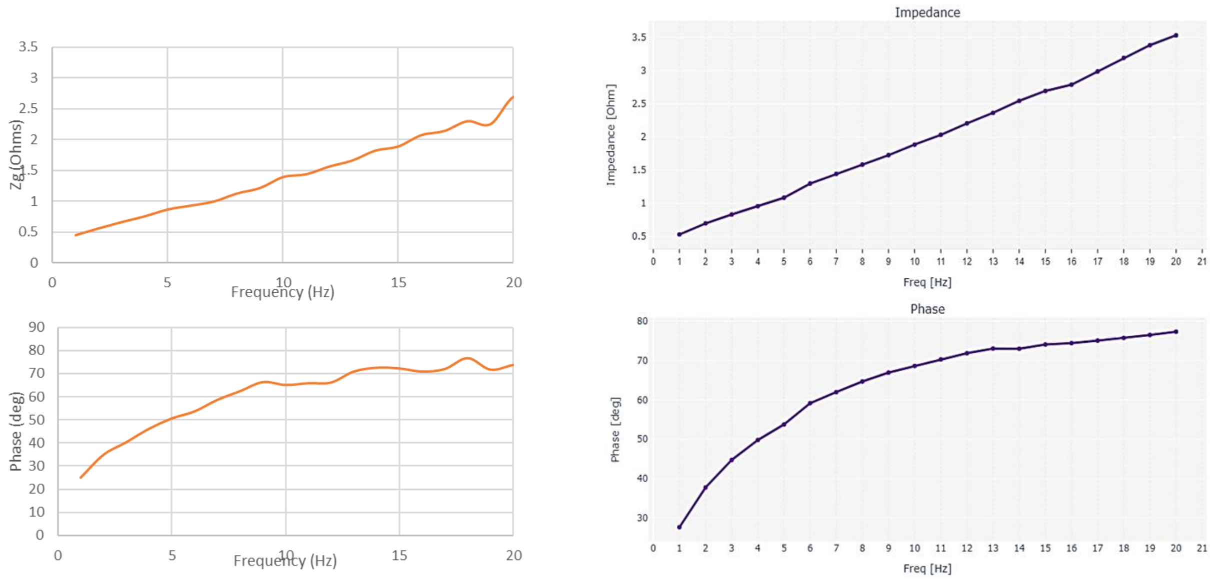


Figure 12 Apparatus-side scan of the CIGRE system using, (a) MHI scanner, and (b) TNEI scanner

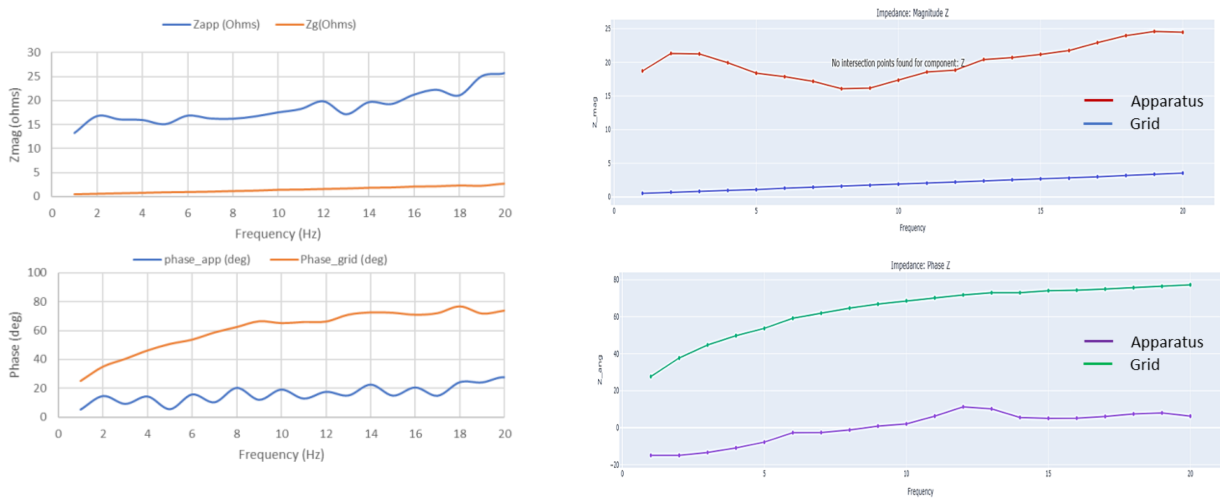
Figure 13 presents the grid-side scan from the two scanners. In grid-side scan, the external grid is in parallel to WF2. So, the grid is not entirely a passive network and there is expected to be some degree of sequence coupling present. As both scanners are using SISO method, the effect of the sequence coupling is not captured in the results. The impedance and phase values are similar for both scanners with some minor undulations seen in MHI results.



(a) (b)

Figure 13 Grid-side scan of the CIGRE system using, (a) MHI scanner and (b) TNEI scanner

The apparatus and grid side scans from the two scanners are used in Figure 14 for an impedance intersection analysis. As evident, both scanners report the same conclusion that the apparatus impedance is much greater than the grid impedance in the range 1Hz to 20Hz and therefore there is no risk of unwanted oscillations in this range.



(a) (b)

Figure 14 Impedance intersection results for the CIGRE system based on scans from (a) MHI scanner and (b) TNEI scanner

To verify the conclusions from frequency domain analyses, we performed an EMT study. The CIGRE benchmark model at the same operating point as before is subjected to a three-phase to ground fault near the export cable at 275 kV for 60 ms. Figure 15 shows the voltage, active and reactive power responses measured at the POC. The system had a stable operation before the fault was applied at around 6 seconds and thereafter a sustained oscillation of around 20Hz appeared in the system variables. This is in clear contradiction to the conclusion from the frequency domain method in Figure 14. This case study reaffirms the

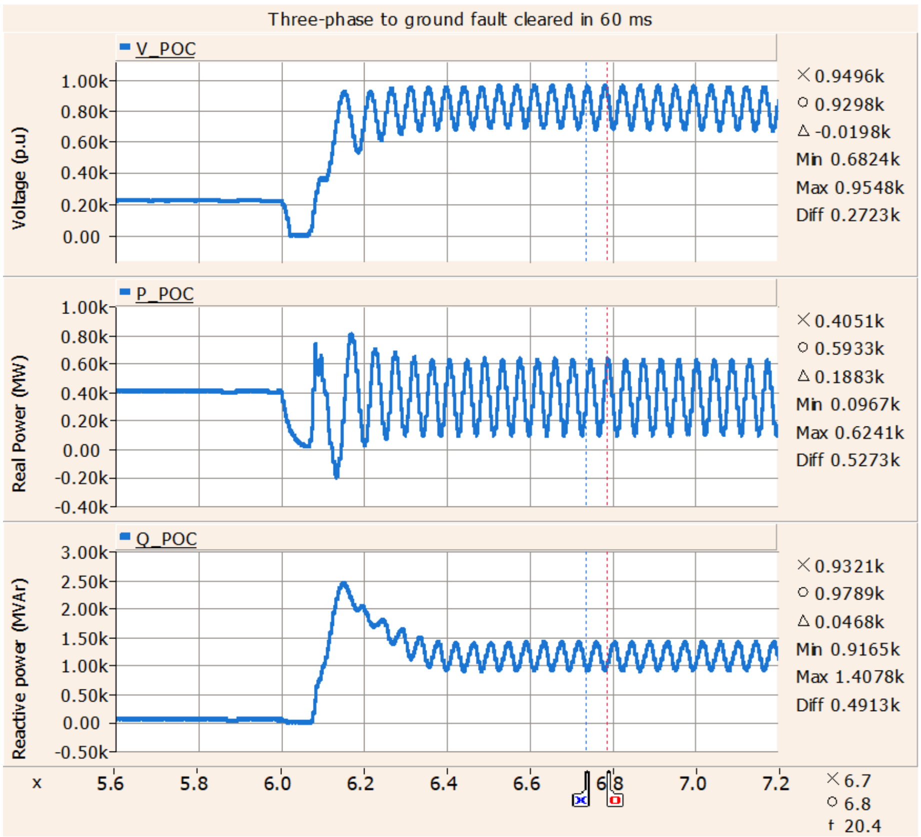


Figure 15 Variables monitored at the POC shows oscillations after a 60ms 3-phase to ground fault

3.3 Next steps in the implementation plan

The initial validation of the results from the SSO tool with MHI scanner and PSCAD EMT simulations have been promising. As a next step, the tool should be tested with several other user models and the conclusions drawn from the frequency domain methods compared with time domain simulations. Currently, the tests are limited to wind farm models and STATCOM. This should be extended to include other technology types such as VSC HVDC links, SVC, BESS, Solar PV inverters etc.

The CIGRE benchmark system is the primary PSCAD model used to test the SSO code during its development. The benchmark system is in a single project file and does not require any external library or .dll files to compile the model. This is however not the case with user provided models that usually have a complex set up process and sometimes require the model to be split into several projects, connected by power network interface feature of PSCAD. The SSO tool in its current form does not work with every type of user models and as part of the implementation plan, one of the important enhancements would be to modify the source code to work with a wider variety of user models provided to the ESO during connections applications.

PSCAD model initialisation is another important requirement that is currently not addressed by the SSO tool. As PSCAD does not offer an in-built solution to initialise machine models for studying different operational scenarios, this needs to be done outside of PSCAD using a load flow solver. This involves replicating the PSCAD model either in a commercial load flow package or an open-source python package. An API will need to be developed to exchange information between the two packages to ensure that the correct voltage and internal angle of the machines are calculated for each operational scenario studied in PSCAD.

The purpose of using frequency domain methods is to reduce the computational time for studying large volumes of scenarios. As PSCAD does not have an in-built network initialiser, for every frequency scan, the model starts from zero and depending on the size of the network, the model can take up a significant time to reach a steady state before frequency scan can be performed. This negates the advantage of using frequency domain methods to filter out high risk scenarios. The use of PSCAD's snapshot feature is useful in this case as the model is initialised based on state variables saved at a stable operating point. This feature is currently not supported by the SSO tool. The implementation plan should consider including this to speed up the frequency scan process.

There are several other enhancements that can add value to the SSO tool such as wider network analysis, root cause identification etc. These enhancements will require more effort than the ones discussed above and therefore they are included in Section 4 as part of future works. To summarise the implementation plan, the key points are listed below. These developments can be achieved within a period of 6 months.

3.3.1 Key points

1. Validate the SSO tool with time domain simulations for different technology types such as VSC HVDC links, SVC, BESS, Solar PV inverters etc. In addition, the tool can be tested with future offshore network configurations such as multi-infeed multi-vendor DC topology, multi-terminal multi-vendor DC topology, general ring topology, star topology, star with central switching topology etc.
2. Update the source code of the tool to work with a wider variety of user models, especially models split into several projects or requiring external compiled library files.
3. Develop an API to interface with a load flow solver to initialise PSCAD models under different operational scenarios.
4. Update the SSO tool to use PSCAD's snapshot feature to reduce the time taken for each frequency scan study.

4 Future work

This section covers all improvements that can increase the value of the tool for day-to-day application within the ESO teams. These enhancements can be further prioritised depending on the long-term objectives of the tool and building in-house capabilities around controller interaction studies.

4.1 Multi set run

The current implementation is restricted to a single set having several projects. These projects are considered to be independent of each other i.e., the network model is contained in its entirety in a single project file. This file is replicated several times to reflect different scenarios and these scenarios are studied in parallel by allocating them to a set.

However, larger projects will usually have several linked project files, each modelling a part of the network. In this case, the group of files that constitute a single project will need to be allocated to a set. To study several scenarios, multiple sets need to be created, and launched in parallel to speed up the computation time.

The SSO tool automation module will need to be updated to work with multi set runs for projects split across several files.

4.2 Vector fitting

The accuracy of the vector fitting algorithm in the Grey Box method is pivotal to recreating the small signal model of the network. The vector fitting is applied to the whole system impedance to calculate a Multi Input Multi Output transfer function model of the entire system. This process captures the system modes that are poorly damped and are at risk of causing instability.

The vector fitting algorithm is based on an iterative approach that tries to estimate the poles and zeros of a transfer function whose response closely matches the measured response. This is achieved by defining a loss function and monitoring the pole zero values that minimise this loss. Currently, the loss function *Least Square Error (LSE)* is calculated across all locations where the whole system impedances are calculated. This means that the objective is to minimise the overall value of LSE even if that leads to a higher LSE in some locations.

For application in large networks, this approach may lead to inferior fits resulting in estimating modes that do not actually exist in the network. To improve the accuracy of the algorithm, one approach could be to define cut sets in the network based on zone of influence or sensitivity to reduce the problem into smaller MIMO models each decoupled from the other. This will enable the tool to apply the vector fitting process to smaller areas thus avoiding the problem of global loss minimisation leading to local inaccuracies.

Another approach could be to implement the vector fitting as a two-step process. In the first pass, the estimates approximate frequencies of interest (mode) that may not match exactly with time domain results. Once the modes are identified, then the vector fitting process is repeated by changing the weights for the frequencies that are outside the area of interest to give them less priority and identify the optimal fit order that leads to minimum LSE across several epochs.

Figure 16 shows the impedance in DQ domain for the whole system measured at WF1 and WF2 in the CIGRE benchmark model. The vector fitting algorithm fits these impedance responses to transfer functions to estimate the poles of the system. It is evident from the figure that the measured impedance and the fitted value are not exactly equal, and the fit order depends on the overall error across all locations. In this example there are two locations, and each location has four impedance values. So, the error is minimised across 8 channels.

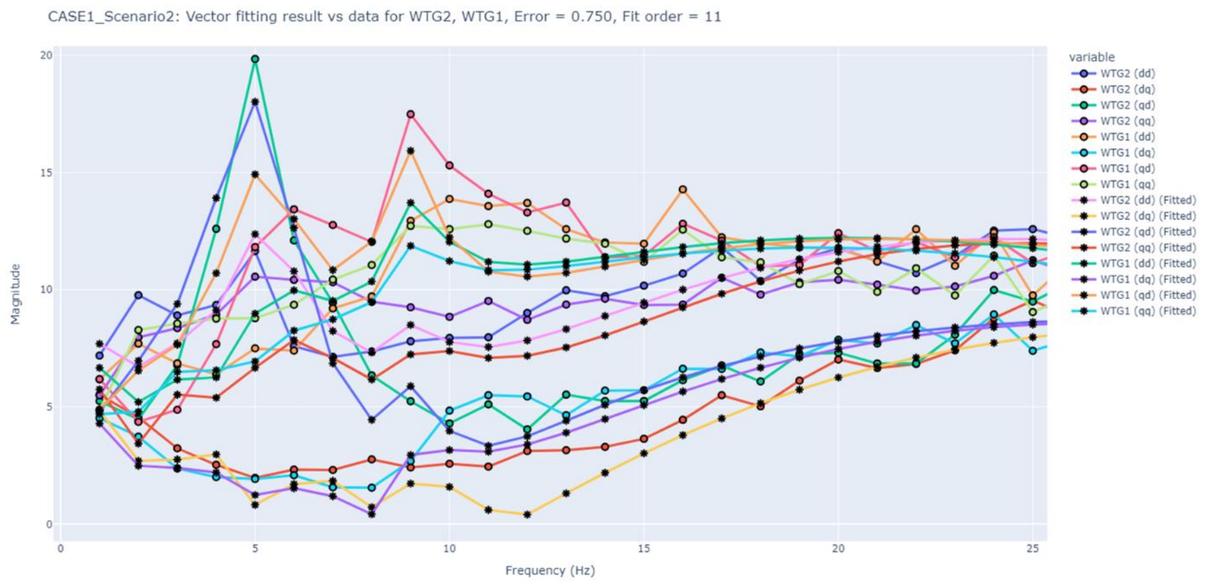


Figure 16 Measured impedance of wind farms and corresponding response from vector fitted transfer functions.

4.3 Root cause analysis

Root cause analysis of oscillation events require modal information of the system and the participation of system variables in each mode. The Grey Box algorithm is a unique approach that allows system modes identification without developing the system 'A' matrix analytically. This is particularly useful for practical studies as user models for converters are always 'Blackbox' to protect trade secrets.

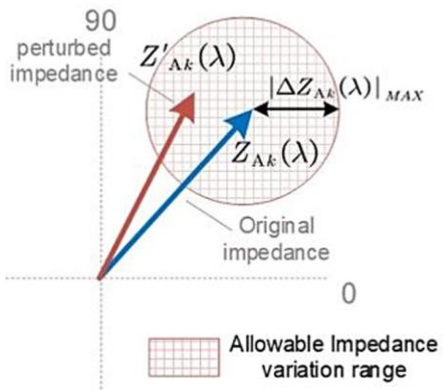
The current implementation of the Grey Box algorithm in the SSO tool is restricted to Layer 1 i.e., the participation factors for different plants are calculated but not their control parameters. The Grey Box method can be extended to Layer 2, where the participation of controller parameters is calculated for each model. However, the number of parameters considered depends on the level of protection of the user model i.e., how many parameters are available to the user to modify the behaviour of the converter.

4.4 Wider network analysis

The SSO tool is developed primarily for connection compliance studies i.e., testing the compliance of a plant connected in parallel to the national transmission system. In this case, the studied plant is modelled in detail and the remaining network is represented by an equivalent voltage source. The frequency domain analysis is performed by doing three separate scans, grid-side, apparatus-side and whole system at the point of coupling of the connection site.

Extending the method to wider network analysis involves two challenges – (a) the frequency scanning takes longer as the network model is larger, and (b) the frequency scanning needs to be undertaken at several locations. To resolve these challenges, a combination of the following approaches can be adopted -

- Split the network into areas that are electrically distant and perform the frequency scanning, particularly the whole system scan, in parallel at several locations. The current implementation allows scanning each location, one at a time. This will need to be extended to scan several locations in parallel.
- The Grey box method can be extended to calculate Impedance Margin Ratio to estimate the strength of the system under different scenarios at different parts of the network. Based on a defined threshold for weak systems, further frequency domain analysis can be restricted to parts of the network that are prone to instability.



$$IMR = \frac{|\Delta Z_{Ak}(\lambda)|_{MAX}}{\Delta Z_{Ak}(\lambda)}$$

- **A large IMR** would mean the mode is relatively insensitive to the connected apparatus, so the system is **strong.**
- **A small IMR** would mean that the system is prone to be unstable when the IBR at the location is varied, so the system is **weak.**
- This analysis is only valid around a stable operating point.

Figure 17 The concept of Impedance Margin Ratio and its relation with the sytem strength

4.5 Harmonic interaction analysis

The current implementation of the SSO tool is restricted to oscillations in the sub synchronous range only primarily because the focus of the analysis is to study controller interactions at frequencies below the fundamental. However, the analysis can be extended to the harmonic range without any significant changes to the underlying code as the principles of analysis remains broadly the same. At higher frequencies beyond 500Hz, the SISO form of impedance can be used as the sequence coupling is no longer relevant. This reduces the impedance computation time as a single injection is sufficient to calculate the frequency domain impedance.

However, at harmonic frequencies, the AC-DC coupling becomes important, and the effect of DC side on AC network interaction needs to be considered, especially for HVDC links. Figure 18 shows an example of AC-DC coupling where oscillations in DC link voltage results in oscillations in phase currents on the AC side of the convertor.

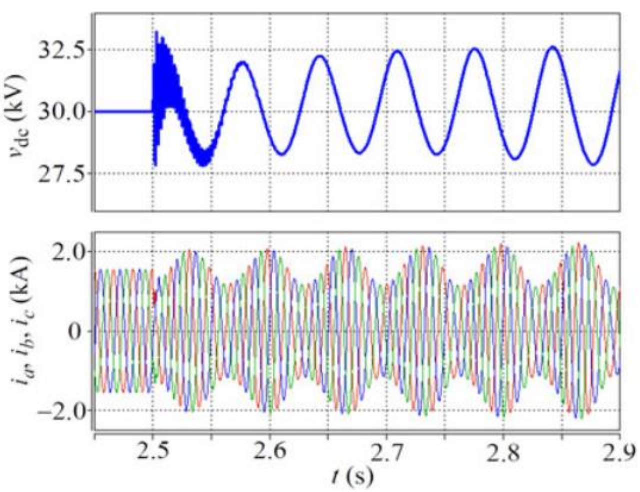


Figure 18 DC side harmonics due to oscillations in the AC network

4.6 Impedance scan of LCC converters

The SSO tool is tested with VSC converters only as most of the grid-connected converters in recent years are of this type such as BESS sites, PV sites, new wind farms and interconnectors. However, there are still some of the older interconnectors such as IFA1 and IFA2, and Western Link HVDC that have the LCC technology. The SSO tool needs to be tested for impedance scan of LCC converters and compared with EMT simulation results to identify if the same conclusions can be reached through linear model analysis. A fundamental difference between LCC and VSC converters is the commutation of the semiconductor switches. While VSC converters have gate-controlled switches, LCC converters rely on line commutation. Since impedance scan requires injection of voltage or current signals, this can interfere with the operation of LCC converters. The optimal level of injection magnitude that does not interfere with steady state operation but sufficient enough to calculate the converter impedance will need to be studied. It is likely that the frequency injection method will be different for VSC and LCC converters. Once the exact requirements are established, the SSO tool can be extended to enable scanning of LCC converters.

4.7 Impedance scan of GFM converters

The impedance scan of GFM converters is not considered in this project as connection requests are mostly for GFL converters. As more grid connected batteries offer GFM capability, it is necessary to extend the analysis of the SSO tool to cover both converter control types as well as a combination of converter types. Unlike GFL converters, a GFM converter behaves like a voltage source. It is not clear if the impedance estimation method implemented in the SSO tool can be used for GFM converters as well. Further tests are necessary to understand the behaviour of GFM converters when subjected to frequency injection and based on that the current process will need to be adjusted.

4.8 AI model for real-time oscillation detection

The SSO detector module is currently developed for offline detection. The purpose of the module is to isolate scenarios studied in PSCAD showing oscillatory behaviour, as shown in Figure 19. Instead of manually sifting through hundreds of results, the machine learning model can quickly identify SSO in system variables such as voltage, currents, and power. The model is implemented as a binary classifier to detect the presence of subsynchronous frequencies. This process can be improved to enable multi-class classification such as 'No oscillation', 'SSO oscillation', 'Harmonic oscillation' etc. A further improvement could be to model it as a continuous process i.e., to provide the frequency content of the signal as an output.

For real-time application, deep neural network architectures such as Long-short term memory (LSTM), Gated Recurrent unit (GRU) and other Recurrent Neural Network (RNN) forms can be used instead of machine learning classifiers. The advantage of the neural network approach over machine learning models is that the feature engineering process can be completely removed saving valuable seconds. Also, deep learning models are better at capturing more complex non-linear relationships.

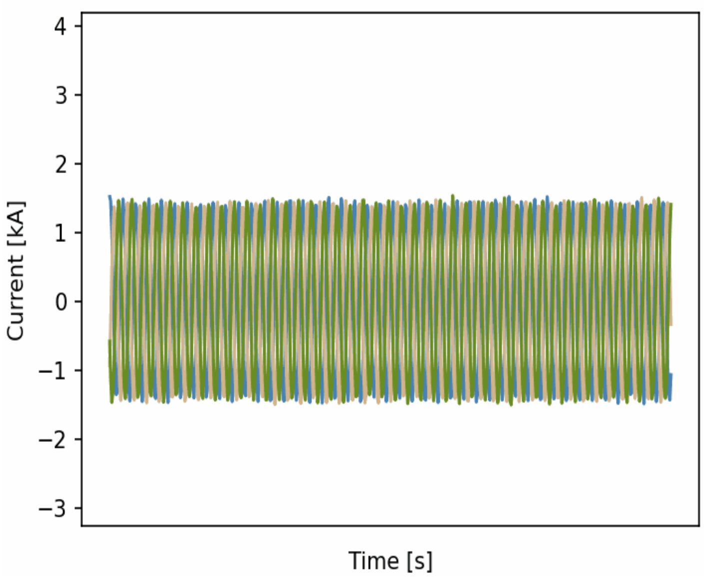


Figure 19 Real-time detection of oscillations in measured signal

4.9 Analysis in the presence of nearby IBRs

The SSO tool is tested with a single IBR connected to a substation. In reality, there could be more than one IBR connected to a substation, each having their own power park controller, similar to the schematic in Figure 20. To perform analysis in the presence of nearby IBRs, an optimal value of injection needs to be calculated that does not lead to unwanted perturbation of all IBR operating points. As an example, to measure the grid impedance from WF1, the injection should be applied before the breaker B1 (on the side of the transformer). This means that WF2 and WF3 are in parallel with the grid. For a valid measurement, these wind farms should be operating at a steady export value before and after the injection at WF1. The same applies to injections from WF2 and WF3. The grid-side scan will be dominated by the grid impedance, as the output impedance of all parallel converters should be much higher. If the grid is represented by only passive elements, then the impedance will have a monotonically increasing trend with the frequency. This rule of thumb can be used as a measure to ensure that all wind farms are operating as expected and the injections does not perturb their steady operating points.

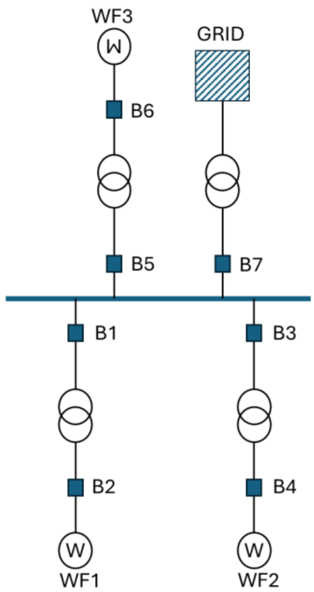


Figure 20 Impedance estimation in the presence of nearby IBRs

4.10 Additional UI features

Since no load flow initialisation feature is implemented in the current version of the tool, the UI does not have the option to import machine initialisation data from a load flow solver. A new analysis option can be added to the UI to interface and import load flow data from a separate solver such as power factory and apply the values to initialise different scenarios in PSCAD.

The current version of the UI has significant data visualization options including comparing results of different scenarios. These features can be improved further based on user feedback.

Appendix A: