24 August 2022

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To whom it may concern,

Re: System Strength Requirements Methodology and System Strength Impact Assessment Guidelines amendments consultation

DIgSILENT Pacific welcomes the opportunity to provide feedback to AEMO's NER S5.2.5.10 Guideline Consultation.

Please find attached a technical note detailing our feedback on the consultation.

Should you require any clarification or further information, please do not hesitate in contacting us.

Yours faithfully,

Umberto Cella
Principal Engineer
DIgSILENT Pacific

TECHNICAL NOTE

For	AEMO	**Project No.**	3877
From	DIgSILENT Pacific	**Subject**	Consultation feedback on AEMO guidelines
Date	24 August 2022	**Doc No.**	3877-ETN-03

1 Overview – S5.2.5.10 Protection to trip plant for unstable operation

The accepted protection systems to detect unstable operation for synchronous plant are well understood in terms of pole-slip protection, reverse power etc. The equivalent for asynchronous plant is not understood as deeply, and the initial summary guide produced by AEMO [1] correctly identifies a number of interpretative issues in both the working and the intent of the Clause S5.2.5.10 and particularly sub-clause (a) 2.

DIgSILENT has investigated hardware and algorithmic options that will allow generators to meet the requirements of this clause, but, as pointed out by AEMO, several clarifications are required. Importantly, it is also necessary to understand AEMO's interpretation of this Rule.

The opportunity to provide feedback on the Initial Summary Guide [1] is appreciated. Creating a set of guidelines is a positive initiative, and should be expedited to the extent reasonably possible.

2 Understanding the technical problem

The technical problem influences power system security: this technical note attempts to describe its more important aspects.

2.1 Synchronous machine and unstable operation

The synchronous machine is well understood when considering oscillatory stability. The types of protection typically accepted are generally for large instabilities, rather than small oscillations. Notably pole-slip protection and reverse power relays respond under large-signal rather than small signal conditions.

Small signal stability is dealt with at the connection stage and devices, such a power system stabilisers (PSSs), are used to achieve required damping of known oscillation modes.

2.2 Asynchronous generating systems and unstable operation

Asynchronous machines are quite different to synchronous machines in many respects and this may make detection of unstable operation more challenging than that for a synchronous machine. Specifically, we may have:

- Two or more levels of control, for example fast inverter-level controls, and slower Power-park-level controls,

- For grid-following inverter systems, there is no physical equivalent to pole slipping, were the closest phenomenon may be the loss of synchronism of phase locked loops

There are many more differences and some similarities, but the key points are:

- Protection systems for synchronous machines may not be appropriate for asynchronous generators, other than perhaps for grid-forming inverters
- As with the oscillations in a synchronous machine power system:
    - Both inverter and PPC controllers can influence the oscillation characteristics (frequency and damping)
    - An individual machine may be unstable and oscillate, which may cause other machines to respond
- The instabilities observed between inverter based generating systems tend to be related to control systems (as opposed to inertia) and have higher frequencies than electromechanical modes.

2.3 Small signal analysis

It appears that:

- For a given set of systems conditions (generation, load, network), oscillation frequencies are likely to be relatively stable and not change appreciably in frequency, magnitude and damping
- Since these oscillations are likely to be strongly related to control systems and their settings, adding a new renewable generator in the electrical vicinity of the part of the power system under investigation may change existing modes of oscillation or result in new modes developing
- If the assumption that these control oscillations are observed mainly in voltage / reactive power signals is correct, strong parts of the power system will tend to isolate oscillation modes, making them more localised.

All of the above considerations could (and should?) be **confirmed through analysis using AEMO's wide-area model**, as the outcomes are likely to affect operating and planning policies related to inverter based generating systems.

3 Detection of oscillations

Digital signal processing techniques can be used to detect oscillations in any of the generator primary quantities, with those of most interest being:

- Active power
- Voltage
- Reactive power
- Voltage phase angle.

3.1 Bandwidth for detection

The time necessary to positively detect an oscillation depends on the frequency of the oscillation. Fast oscillations (say 20 Hz) can be detected rapidly while slow oscillations (say 0.1 Hz) require at least 10 seconds of recording in order to be detected, and an even longer time to estimate their damping.

Most DSP algorithms are configurable and can adjust relatively easily to accommodate a required frequency band. However, the output required here is a 'prompt' detection and, where appropriate, action on the plant to reduce what might be a security risk. **There is a trade-off between having a wide detection band and a prompt response.**

Based on the assumption that inverter-based generators do not materially affect low frequency electromechanical modes of oscillation, the detection range should be in the vicinity of 5 - 25 Hz, where most of the observed control modes of oscillation appear to be. It is possible AEMO has seen higher/lower frequency modes, in which case it may be necessary to extend this range to capture the observations to date.

Our experience is that is quite feasible to have good detection and reasonable response times for frequencies down to 0.5 Hz, which requires at least a two second data buffer to capture a single cycle at this frequency.

Our recommendation in relation to an appropriate detection bandwidth is to **set it to accommodate known control oscillation models and resist the temptation to specify an unnecessarily broad bandwidth** that is not based on analysis and observation.

3.2 Estimation of damping

The observed control modes of oscillation (for example, in West Murray) appear to have the characteristics of a limit cycle, with a **sustained oscillation that does not vary much in amplitude**. These oscillations would likely fail the definitions of 'adequate damping' and the requirements of the power system stability guidelines. **The oscillations detected,** rather than being damped, seem to **"fade-in" and "fade-out".**

3.2.1 Measuring damping after an incident

Data can be retained in the event an oscillation is detected. This data can be analysed afterwards to assess the damping if there is sufficient resolution of the oscillation in the presence of noise. Observations of data published by AEMO in relation to the West Murray events show a clear limit cycle oscillation.

3.2.2 Recommendations in relation to detection of damping

The near real-time estimate of oscillation damping may be beneficial, but it could be unreliable. This would mean a decision to reduce a generating system's output purely on the detected damping is undesirable. Metrics such as oscillation amplitude (and maybe frequency and relative phase angle) would be more reliable criteria on which to base decisions.

3.3 Detecting phase

The sub-synchronous oscillation manifests as amplitude modulation of quantities such as voltage, active or reactive power. The oscillatory amplitude component can be detected in these data streams: the reciprocal phase of the oscillatory component detected on these quantities can be calculated. In this way, one may be able to **estimate if the monitored generating system is contributing to (reinforcing) or damping that oscillation by looking at the phase angle between, say, the voltage and reactive power oscillations**.

Further information on the theory behind this is provided in Appendix A where the phase angle difference between voltage and reactive power oscillations is observed to be **an indicative measure only**. There are some circumstances such as a controller with a POD targeting electromechanical oscillations or a response from a generating system comparable to the oscillation magnitude, where with a phase difference of less than 90 degrees between Q and V, the generating system **still contributes to damping**.

Our experience with detection of phase angles is that noise can influence the measured phase angle, particularly where the signal amplitude is low, making the signal to noise ratio small.

Our recommendation is to therefore **not rely on phase angle as the only measurand** on which to base an executive decision, but rather to use another criterion (say amplitude) in addition to the phase angle.

As highlighted in Appendix A, these **criteria may be quite complex and require a significant amount of logic and data processing to implement**.

4 Other aspects of the oscillatory stability monitor

We have discussed with both AEMO and some NSPs what the requirements are for a device to meet the requirements of S5.2.5.10.

The following comments are made based on experience with the detection of sub-synchronous oscillations and the various topics raised by AEMO and the NSPs in our discussions.

4.1 Amplitude of detected sub-synchronous oscillations

Noise is an important factor in the reliable detection of sub-synchronous oscillations. In some discussions, number as low as 0.1% of nominal values have been suggested. **These numbers are low with respect to typical noise on the power system variables** like voltage, active and reactive power.

DIgSILENT would suggest that amplitude triggers are set to around 0.5% of nominal to provide reliable triggering. In general, **the "average" amplitude of oscillations may vary according to, for example, system strength and damping, and will be different in different areas of the network**. DIgSILENT recommends that **measurements are taken at each specific connection point**, or as close as possible to it, **before a threshold is selected**.

4.2 Protection or monitoring system

A protection relay has a certain meaning according to the Standards. DIgSILENT recommends that the detection of small oscillation, and the associated operational algorithms, are kept separated from a protection function. Namely:

- If **the control system of the plant fails**, and the output swings are a material and immediate **danger** to equipment and power system security, a **relay shall be the device that trips the plant immediately**
- Any protection device must have an algorithm that is both highly reliable (will trip when required) and highly secure (not trip when not required to do so). For instance, given that the results of **the phase angle difference between Q and V method for oscillations is only indicative**, this method **should not be implemented within protection until it is proven**.
- If an **oscillation** is detected, whose amplitude causes a non-compliance **but not an immediate threat**, shall be handled by a separate sophisticated and flexible algorithm, which runs on a separate signal processing system, and raises alarms for operators' attention

4.3 Interlocks with system frequency

From discussions, there appears to be a requirement to interlock the operation of the device with frequency, such that the device executive action is disabled/inhibited if frequency goes outside the normal frequency operating band.

It is not difficult to provide such an interlock but it may prevent executive action when it is required, with the system in an unusual or stressed operating condition or configuration.

It will be very helpful if the rationale for inhibiting executive action under certain circumstances can be explained and demonstrated via studies, which show the responses that are being managed.

4.4 Multiple trigger thresholds

It makes sense to have a low-level alarm threshold where no executive action is taken. For higher level amplitudes, potentially in combination with other signal logic, a second threshold could be used to identify a potentially greater threat to system security and hence a need for some form of executive action.

4.5 Requirement for redundant devices

Discussions indicate a requirement for duplicate devices. This is good for manufacturers of the devices, but it is perhaps not necessary, because the device is not a protection relay.

DIgSILENT proposes that the device shall alarm to operators that it is not functioning, given that its primary function is to monitor events that cause non-compliance but not an immediate power system security and/or integrity threat. The latter events shall be handled by protection relays in a fully redundant X/Y scheme.

4.6 Manual inhibit

Discussions indicated a potential requirement to inhibit the operation of the device. If there is a requirement to inhibit with a manual control, this is probably best delivered in SCADA where the inhibit signal originates (presumably from the power system operator).

4.7 Clock synchronization

From AEMO's perspective as power system operator, having an accurate clock will allow comparing the data form monitors located at various buses and, potentially, provide some insight into the source of an oscillation. The cost of providing a GPS synchronised clock is not prohibitive and is justified on the basis of potential system benefits.

4.8 Multiple frequency tracking

As with electromechanical modes of oscillation, it is possible for multiple sub-synchronous oscillation modes to exist simultaneously. This is less likely in parts of the network with only a few inverter-based generating systems but may have a higher probability of occurrence where there is a higher density.

Given that a period of sub-synchronous oscillation may be triggered by a single event (system fault, frequency decline), the probability of multiple modes existing at the same time is probably not negligible. Therefore, the device shall be capable to detect several sub-synchronous oscillation frequencies.

5 Summary and recommendations

We support AEMO for consulting on these guidelines and providing us an opportunity to provide comments.

1. **Control system modes of oscillations:** The primary focus should be on control system modes of oscillation and not the electromechanical modes dealt with using other processes and systems that are already established and tested
2. **Separation between small oscillation monitoring and action against control system malfunctioning**: DIgSILENT recommends that both a monitor and a protection relays are installed, because a monitoring system is not as dependable as a relay, and a relay is not as algorithmically advanced as a monitoring system. Algorithms applied to protection relay must be proven to be extremely reliable and secure (i.e. novel methods must be validated with thorough wide area modelling and hardware testing).
3. **Complexity:** DIgSILENT recommend a simple configuration of the device initially – probably based on one or two amplitude thresholds – while system events are measured and analysed, and responses better understood.
4. **Confirm effectiveness of executive actions (e.g. ramp down) through wide area model**: oscillations measured in the field shall be replicated in AEMO's wide-area model, so that they can be better understood, and the least invasive strategy to control them is devised
5. **Fade-in and out as opposed to damping**: the oscillations that are being targeted here are not damped ones, but they rather fade-in and fade-out after a while, while maintaining reasonably constant amplitude. The same criteria of damping used so far should not be applied to these oscillations
6. **DIgSILENT recommend measurements**: more data in order to investigate the phenomenon are required. DIgSILENT recommends that synchronized measurements of oscillations are taken in critical areas, and are analysed in depth, in order to develop an informed and substantiated guideline, given that economical consequences (ramp-down of plants) may occur.
7. **Customizable and flexible device:** Given the large uncertainty on this matter at the moment, DIgSILENT proposed that guidelines recommend a device that can be re-configured to implement different/more complex algorithms than the one currently being proposed. In this way, any future developments in the understanding of these oscillation will not require generators to substantially replace/integrate their existing systems

Appendix A Consideration of sub-synchronous oscillations and the phase angle between signals

This section provides commentary on the Q and V phase angle difference methodology presented in AEMO's "S5.2.5.10 Consultation Technical Note" where the following points are raised:

- It is important to define clear objectives
- The phase angle difference between plant Q and V oscillations could provide some indication of poor control performance for an inverter base system.
- The precise value of the phase angle difference between Q and V oscillations may not always be a good measure for how bad the performance is:
  - Oscillation frequency phasor based analysis shows that with Q and V oscillation phase difference less than 90 degree attenuation of an oscillation may still occur.
  - An example of an inverter based system with a POD is provided which actively modules its voltage to dampen existing electromechanical modes yet the Q and V for this device are nearly in phase. Such controls could be installed on future plant for added stabilisation.
- The methodology uses simplifying assumptions and therefore may not be applicable under all circumstances.

The above points are further elaborated below.

A.1 Simplified methodology analysis

This section shows that for some circumstances, phase angle differences less than 90 between plant Q and POC V can still yield an attenuation of the oscillation. A similar approach to AEMO's technical note is adopted with difference that a graphical (phasor based) method is used.

For clarity in this section complex quantities are written in **bold** and oscillation quantities are prefixed with a Δ to emphasise the fact that the focus is on the oscillatory component only. Otherwise, the same names are used as in the AEMO technical note to avoid confusion.

A.1.1 Objective

The purpose of AEMO's methodology is determining whether a plant improves or exacerbates a voltage oscillation. Though a specific measure for this objective is not defined, a reasonable metric (M) is the amplification of a voltage oscillation's magnitude with and without the presence of the plant:

$$M = \frac{V_{with\ plant}}{V_{without\ plant}}$$

A.1.2 Measurement quantities

We must recognise that the measurements which are available for any real system which must perform an assessment of a plant's contribution to oscillations are necessarily limited. Under practical circumstances, it is only possible to measure the final resultant POC voltage oscillation ($\boldsymbol{\Delta V}$) and the plant reactive power response ($\boldsymbol{\Delta Q}$). The external oscillation which may be emanating from the grid ($\boldsymbol{\Delta D}$) and the relative impact of the plant's reactive power response output on the voltage (K) are unknown quantities.

A.1.3 Oscillation frequency phasor based analysis

We assume that all oscillation quantities (voltages and reactive power) are sinusoidal when considering one frequency at a time. In this case these quantities can be expressed as oscillation frequency phasors (one for each oscillation frequency), which are complex numbers which possesses magnitude and phase.

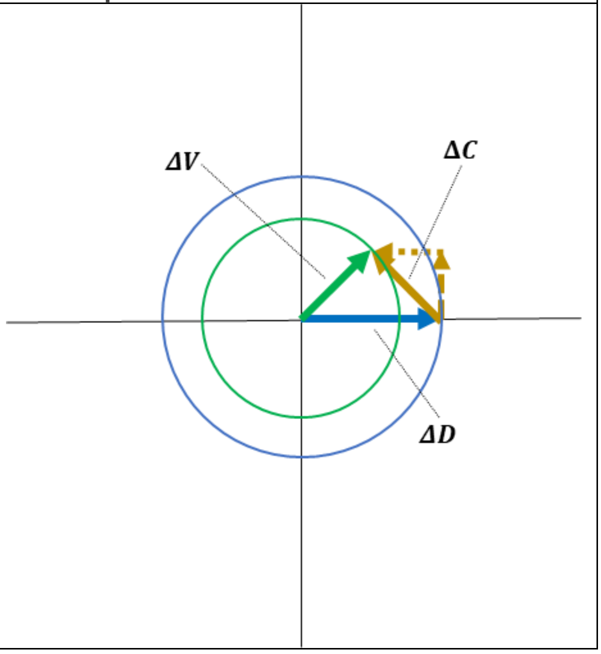
Following the approach in AEMO’s technical note, with the plant out of service the resultant oscillation voltage at the POC is equal to the external oscillation ($\boldsymbol{\Delta D}$). With the plant in service, the influence of its reactive power output on voltage ($\boldsymbol{\Delta C}$) yields a total POC voltage oscillation ($\boldsymbol{\Delta V}$) given by:

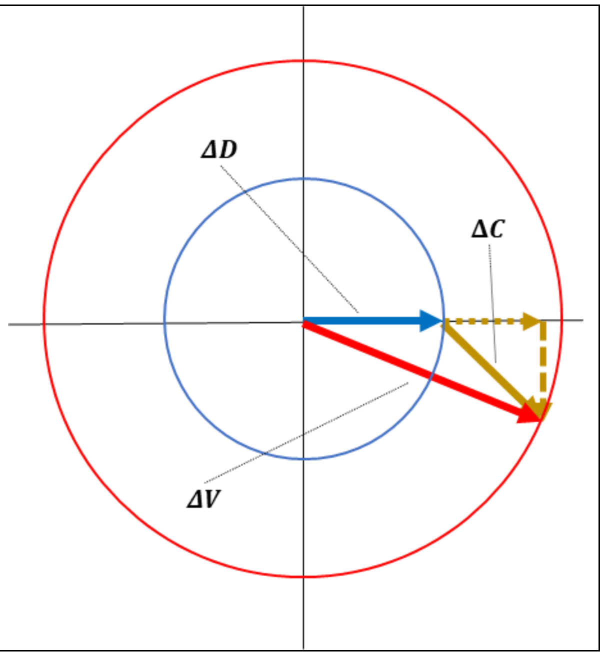
$$\boldsymbol{\Delta V} = \boldsymbol{\Delta D} + \boldsymbol{\Delta C}$$

The resulting POC voltage oscillation is shown graphically considering several possible cases in Table 1. The following conclusions are drawn:

- The resultant POC voltage oscillation magnitude is generally reduced when the plant response ($\boldsymbol{\Delta C}$) is counter phase to the external oscillation ($\boldsymbol{\Delta D}$).
- However it is possible for the phase angle difference between the plant response ($\boldsymbol{\Delta C}$) and the POC voltage oscillation ($\boldsymbol{\Delta V}$) be close to 90 degrees and yet some attenuation is still achieved. This is elaborated upon in a more systematic fashion in the next section.

Table 1: Graphical representation examples of AEMO's simplified system setup.

Case	**Phasor plot**
A - Example showing attenuation in the final voltage (ΔV) oscillation with the plant in service compared to case without it (ΔD) **Note: the phasors represent the voltage amplitude and phase disturbances at the detected oscillation frequency**	

B - Example showing amplification in the final voltage (ΔV) oscillation when the plant is in service compared to a case without it (ΔD) **Note: the phasors represent the voltage amplitude and phase disturbances at the detected oscillation frequency**	

A.1.4 Oscillation amplification and V and Q phase angle difference

Let us consider an oscillation at a frequency of interest and let the resultant measured POC voltage oscillation phasor be $\boldsymbol{\Delta V} = \Delta V \angle 0° = \Delta V$. Let the transfer function from the measured POC voltage ($\boldsymbol{\Delta V}$) to the plant induced voltage change ($\boldsymbol{\Delta C}$) take the value $\boldsymbol{A} = A\angle\phi$. The magnitude A includes both effects of the gain of the controller and the source reactance and hence is generally not precisely known. ϕ depends on the phase between the voltage change introduced by the controller and can be measured by comparing the relative phase angles of known quantities $\boldsymbol{\Delta V}$ and $\boldsymbol{\Delta Q}$ (which will be in phase with $\boldsymbol{\Delta C}$).

The plant induced change is then related to the measured POC voltage by $\boldsymbol{\Delta C} = \boldsymbol{A}\boldsymbol{\Delta V}$.

$$\boldsymbol{\Delta V} = \boldsymbol{\Delta D} + \boldsymbol{\Delta C} = \boldsymbol{\Delta D} + \boldsymbol{A}\boldsymbol{\Delta V}$$

The above equation can be rearranged to yield:

$$\frac{\boldsymbol{\Delta V}}{\boldsymbol{\Delta D}} = \frac{1}{1 - \boldsymbol{A}}$$

The measured amplification M because of the plant response can be calculated from the above as follows:

$$M = \frac{V_{with\ plant}}{V_{without\ plant}} = \left|\frac{\boldsymbol{\Delta V}}{\boldsymbol{\Delta D}}\right| = \left|\frac{1}{1 - A[\cos(\phi) + j\sin(\phi)]}\right|$$

$$= \frac{1}{\sqrt{[1 - A\cos(\phi)]^2 + [A\sin(\phi)]^2}}$$

$$= \frac{1}{\sqrt{1 - 2A\cos(\phi) + [A\cos(\phi)]^2 + [A\sin(\phi)]^2}}$$

$$= \frac{1}{\sqrt{1 + A^2 - 2A\cos(\phi)}}$$

The amplification that results for a range of $A\angle\phi$ values is shown in Figure 1. Negative dB values indicate attenuation and positive dB values indicate exacerbation. These results show that depending on the value of A, there may be some circumstances where the phase angle difference between $\boldsymbol{\Delta V}$ and $\boldsymbol{\Delta Q}$ is less than 90 degrees and voltage oscillation attenuation still occurs.

This analysis assumes that a steady state operating condition is achievable and that the plant response is dynamically stable (does not grow exponentially).

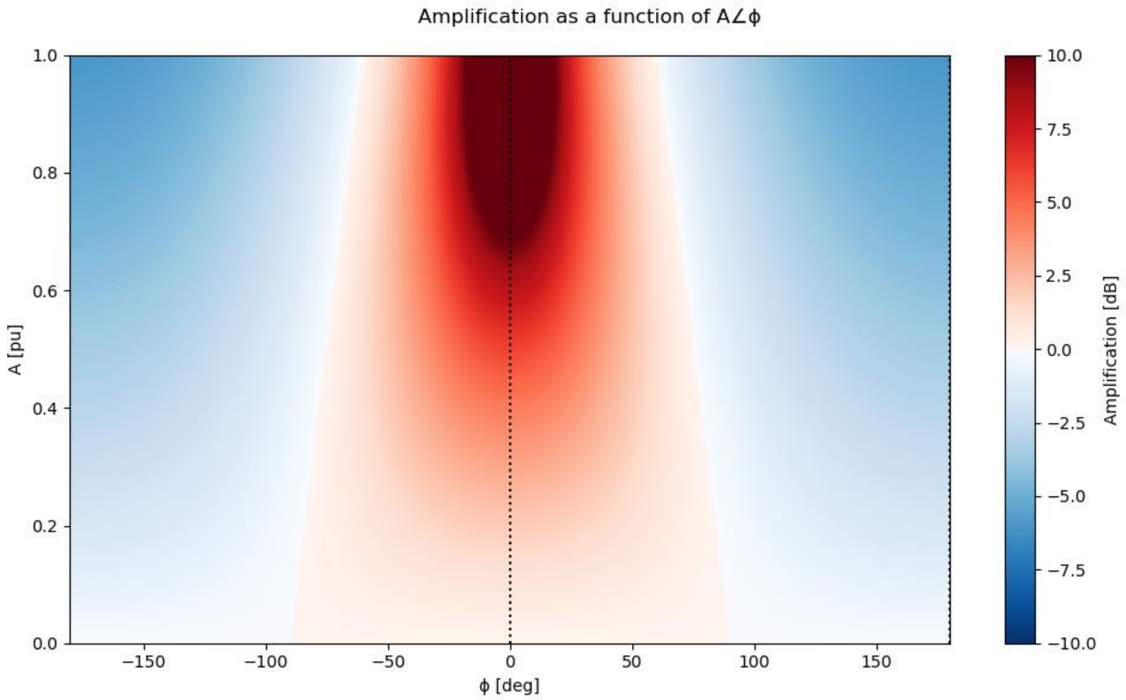


Figure 1: Amplification (in dB) resulting from various values of A∠ϕ. Values beyond ±10 dB are not shown with unique colours.

A.2 Example of an IBR system with POD

A Dual Machine Infinite Bus (DMIB) model of a synchronous generator in parallel with an IBR plant is used to show that under some circumstance, a plant's Q and V oscillation phase angle difference less than 90 degrees still results in positive damping of oscillation modes.

In the DMIB model the synchronous generator has a mode of oscillation involving swinging of its rotor angle against the grid. The IBR plant is configured with to control the grid bus voltage but also has a Power Oscillation Damper (POD) which acts to improve the damping of the synchronous generator's mechanical mode of oscillation. This control intentionally modulates the voltage of the grid bus to increase damping of the synchronous generator mode.

A comparison of the results with and without the IBR plant with POD show that:

- The presence of the IBR plant improves the oscillation mode damping resulting in faster settling (from -0.439 neper/s to -0.812 neper/s).
- Oscillations in the IBR plant's Q response are nearly in phase (approximately 35 degrees difference) with oscillations in its voltage.

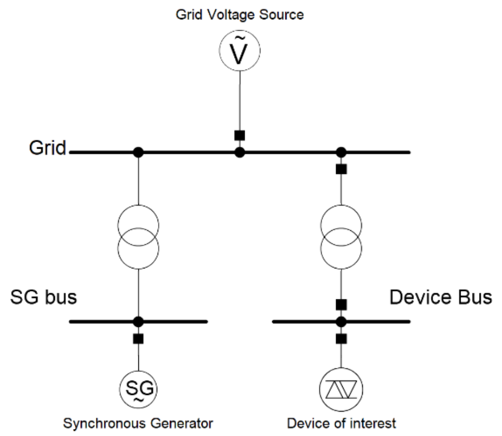


Figure 2: DMIB setup with synchronous generator and IBR with POD operating in parallel.

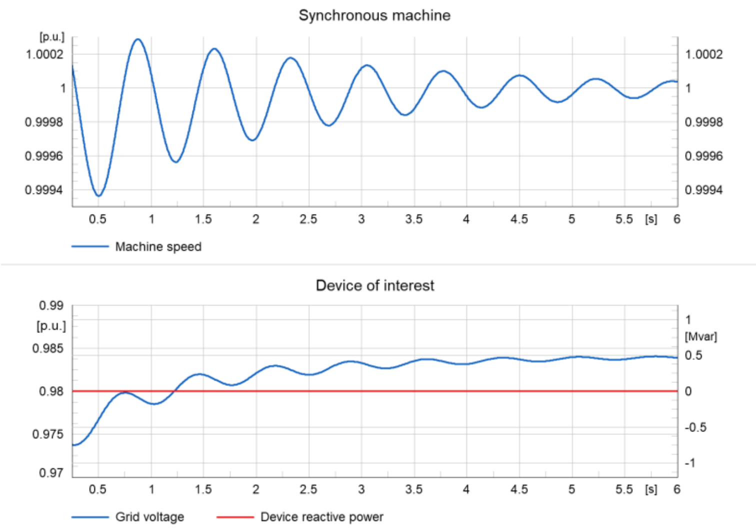


Figure 3: System response to a disturbance without the IBR with POD.

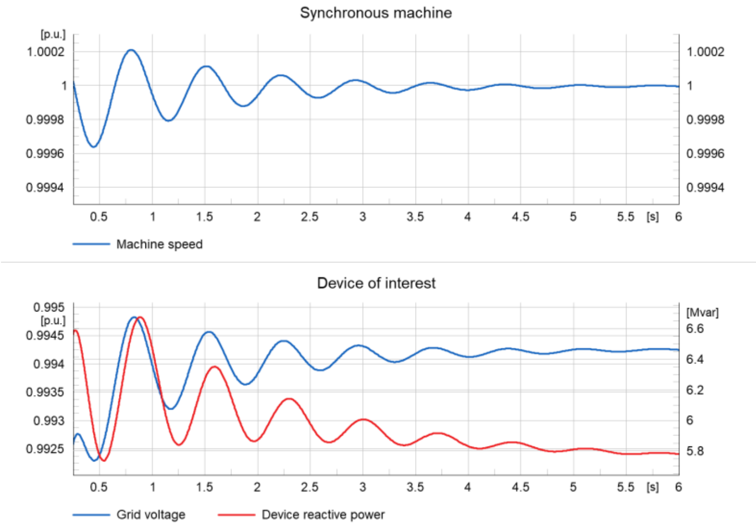


Figure 4: System response to a disturbance with the IBR with POD.