

2025-05-16

INFORMATION

Compliance testing for POD

Introduction

This document includes Svenska kraftnäts general requirements regarding Power Oscillation Damping (POD) as well as an update and replacement of the POD related articles 4.5 and 4.6 in

- > SvK 2021/5426, “Kraftparksmodul: Bilaga 5”, (Nätanslutning av generatorer (RfG), September 2024)

and article 2.16 in

- > SvK 2021/5426, “Kraftparksmodul: Bilaga 6”, (Nätanslutning av generatorer (RfG), September 2024).

For the time being, this document will remain stand-alone until it can be incorporated into future updates to the appendices listed above.

For power park modules, the POD requirements are separated into two categories:

- > POD-Q, modulation of reactive power based on local voltage amplitude.
- > POD-P, modulation of active power injections based on local voltage frequency.

This document will only focus on compliance testing of the POD-Q function.

For questions regarding this document or exchange of digital models please turn to anslutningskoder@svk.se, or NDB@svk.se regarding specific modeling questions.

This is a translation of a Swedish document. If there are any discrepancies between the two versions of this same document, the Swedish version shall have precedent.

**RfG**

Artikel 21.3. Kraftparksmoduler av typ C ska uppfylla följande ytterligare krav avseende spänningsstabilitet:

f) När det gäller dämpningsreglering av effektpendlingar ska en kraftparksmodul kunna bidra till att dämpa effektpendlingar om detta anges av den berörda systemansvarige för överföringssystemet. Kraftparksmodulens reglerenskaper när det gäller spänningen och reaktiv effekt får inte inverka negativt på dämpningen av effektpendlingar

RfG, ACER Recommendation 2023

Article 21.2. Type C power park modules shall fulfil the following additional requirements in relation to voltage stability:

f) with regard to power oscillations damping control, if specified by the relevant TSO a power park module shall have a power oscillation damping function which, through the control of the active power, reactive power, or both, helps to attenuate the power oscillations. The power oscillation damping shall be able to damp inter-area oscillations in the range of, at least, 0,1 Hz – 1,0 Hz. The voltage and reactive power control characteristics of power park modules must not adversely affect the damping of power oscillations.

Article 22.2. With regard to power oscillations damping control, type D power park modules shall have a power oscillation damping function which helps to attenuate the power oscillations through the control of the active power, reactive power, or both. The power oscillation damping shall be able to damp inter-area oscillations in the range of, at least, 0,1 Hz – 1,0 Hz. The relevant TSO in co-ordination with the relevant system operator shall have the right to request and approve the tuning of the power oscillation damping by the power-generating facility owner to damp the inter-area oscillation mode based on frequency ranges specified by the relevant TSO in coordination with adjacent TSO or TSOs. The relevant TSO shall have the right to request the tuning of the power oscillation damping by power-generating facility owner to damp the local oscillation mode, in which the power park modules is oscillating against the network.

The proposed power oscillation damping control shall be approved by the relevant TSO.

Svenska kraftnät general requirements

With reference to RfG article 14.5.a, with regard to control schemes and settings, Svenska kraftnät requires the following regarding POD:

Power park modules of types C and D shall be equipped with POD for damping of power oscillations. The POD-function shall be active according to EIFS 2018:2 5 kap 7 §. The POD-function shall be stable and actively damp power oscillations with frequencies in the range 0,25-1 Hz.

The POD-function shall be implemented as control of active power through feedback of the local frequency (POD-P), or as control of reactive power through feedback of local positive sequence voltage (POD-Q).

The owner of the power park module shall agree with Svenska kraftnät all signals for measurements, as well as the control design and parameters for the POD-function. Svenska kraftnät requests, if possible, that POD-P is implemented. Implementation of POD-Q is acceptable if the power park module owner is able to clearly show that implementation of POD-P is impossible on technical grounds.

- > POD-Q shall have the ability to dampen power oscillations within the frequency range 0,25-1 Hz while measured voltage is within 95-105 % of its reference value, unless otherwise agreed with Svenska kraftnät. The damping contribution of the POD-Q-function shall be continuously available within the required voltage range.



- > Voltage control and fast fault current injection shall be implemented such that they do not negatively affect the POD-Q-function within the required voltage range.
- > POD-P shall have the ability to dampen power oscillations within the frequency range 0,25-1 Hz. Frequency control functions, such as FSM, LFSM, and synthetic inertia, shall be designed such that they contribute to damping power oscillations within the frequency range 0,25-1 Hz. The damping contribution from POD-P shall be continuously available.
- > Both POD-P and POD-Q shall be able to be activated or deactivated as per instructions from Svenska kraftnät (for example during grid restoration or island operation).
- > Both POD-P and POD-Q shall be implemented as linear control. Non-linear elements such as saturation or ramp limiters may be implemented for the purpose of protecting the power park module hardware. Usage of non-linear control elements shall nevertheless be motivated and subject to approval from Svenska kraftnät. If a non-linear control design is implemented for the purpose of improving the damping functionality of the POD-function the motivation shall include an analysis of the impact of the non-linearity on performance and robustness of the POD-function.
- > *Continuously available* means the POD-function shall be designed and implemented such that it is active continuously during normal operation. The POD-function may have to be limited during extreme operating conditions, for example for the physical protection of the power park module. Such limitations should be implemented in such a way that no risk of inducing power oscillations occur.
- > The POD-function should preferably be implemented as a combination of POD-P and POD-Q.
- > It shall be possible to, as per instructions from Svenska kraftnät, the relevant system operator, or the power park owner's control room, activate or deactivate the PSS or POD-function. Such instructions shall be realized within 15 minutes.



POD-Q – Reactive Power Oscillation Damping

Reference to existing grid code

- > RfG: Section 2, chapter 3, article 21.3.f
- > EIFS 2018:2: 5 kap, 7 §

Background

Power park modules (PPMs) have an impact on the dynamics of the power system. Whereas the dynamics of synchronous machines are largely bound by the laws of physics, much of the dynamic of power park modules is dictated by control design choices. At the same time, intellectual property (IP) rights protect the control design. This makes predicting the effects of PPMs on grid dynamics challenging. The procedure in this document is used to test the dynamic properties of the PPM's voltage/reactive power control to ensure that it has a stabilizing effect on power oscillations in the frequency range of 0.25 to 1.0 Hz.

The simulation study is divided into two main parts.

- > Part one consists of a simulation of POD-Q and different reactive control modes (voltage/reactive power/constant power factor) in an undamped test system.
- > Part two consists of an open-loop frequency response test of the POD-Q control function.
 - Part two (i.e. open-loop frequency response test) will be replicated in a physical on-site test for the final operational notification (FON).

Part one: Simulation in an undamped test system

Purpose of simulation study

The purpose of the simulations is to show that the PPM is equipped with a POD control function that contributes to positive damping, for oscillations with an eigenfrequency of 0.25 to 1.0 Hz (period time of 4.0 to 1.0 seconds). The main purpose of the POD-Q control function is to compensate for the destabilizing effect that voltage control may have on interarea modes, in particular the voltage control from the PPM itself. The PPM is also required to contribute with a net improvement of overall POD, therefore the POD-Q should be available regardless of reactive power or voltage control mode.

- ## Instructions for simulation study

system impact study. A connection to a strong enough grid for the connection level and a high X/R ratio is therefore sufficient for this test.

In the test system, generators 1 and 2 have equal power rating and inertia. This simulation study is intended to illustrate the damping effect of the PPMs voltage/reactive power control. Bus 3 should therefore be placed in the electrical center between generator buses 1 and 2, since this maximizes the observability and controllability of the V-Q paired POD-Q control scheme. Note that both observability and the controllability of the V-Q paired POD-Q is proportional to the power flow between buses 1 and 2. A higher power flow will therefore give more visible results in the simulated model. If needed (e.g., to speed up simulation time) the power flow can be increased by modifying the power settings of generators 1 and 2, while keeping them equal.

An undamped oscillation is created by simultaneously disconnecting the loads from bus 1 and 2. The eigenfrequency (or period time) of the oscillation can be changed by varying the inertia constant of the two generators.



- > Simulations shall be performed in systems with interarea mode eigenfrequency of 0.25 and 1.0 Hz (period times 4 and 1 s).
- > Simulations shall be performed with and without the PPM connected to the grid to demonstrate the damping improvement of the PPM.
- > Simulations shall be performed with all of the implemented reactive power control modes.
- > Changes to the simulation model need to be documented.

Result of simulation study

The simulation should be considered approved if:

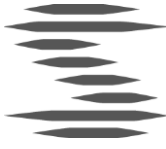
- > The PPM actively improves damping of interarea modes with eigenfrequencies in the interval 0.25-1.0 Hz (at least for the control modes where the POD-Q function is activated). Fulfillment of the conditions is determined by measuring the rotor angle difference between generators at buses 1 and 2, the voltage at bus 4 as well as the active and reactive power injected by the PPM.
- > When simulating the system, the damping shall be improved when the POD-Q function is activated compared to simulations with a deactivated POD-Q function.

Part two: Open-loop frequency response test

Purpose of test and simulation study

The purpose of this testing procedure, with accompanying simulation study, is to show that the modelled POD-Q control fulfills the phase shift requirements of POD-Q and that the simulated results correspond to the measured response of the POD-Q control function. This testing procedure assumes that the PPM is designed such that the voltage and POD-Q control functions can be tested in open loop. The PPM is equipped with a fast internal current controller that lets the PPM track reactive power reference changes with sufficiently high bandwidth, for small changes around the operating point. The voltage and POD-Q controller then modulates the reactive power reference.

- > Simulations should be performed before the ION with the power levels that are planned to be used during the testing procedure. The result from the initial simulation study is used as a basis for the testing procedure. For the FON, the POD-Q control is tested on site following the same procedure as the simulation study performed for the ION.
- > Qualitative model validation shall demonstrate a reasonable visual match between the simulated and measured test results. The simulation therefore



needs to be performed under similar operating conditions as the corresponding test.

Instructions for test and simulation study

These instructions describe an open-loop frequency response test of the POD-Q control functionality. An example of the open-loop test setup is illustrated in the block diagram in Figure 2 below.

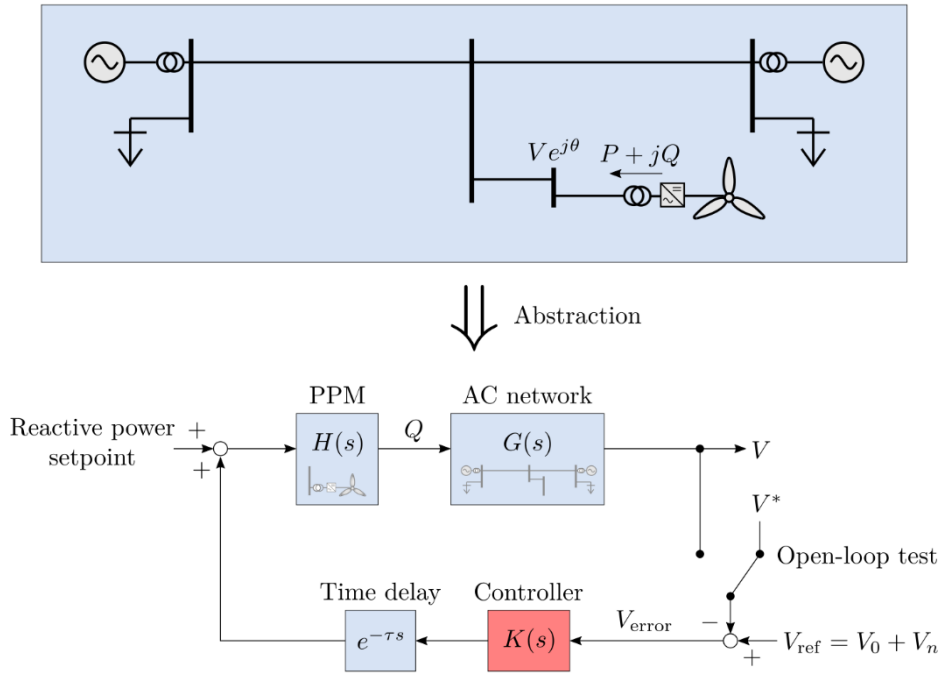


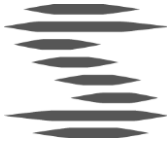
Figure 2 Block diagram illustrating the open-loop testing procedure. This illustration shows the test signal V_n applied to the reference. Other implementations are allowed, as long as it is clear how the test signal affects the voltage input error V_{error} .

The purpose of the test is to determine the small-signal response characteristic of the PPM's voltage and POD-Q control by testing its frequency response characteristic. In the setup shown in Figure 2, the open-loop plant of interest is

$$H(s)e^{-\tau s}K(s) \quad (1)$$

Where the transfer function $H(s)$ represents the dynamics of the PPM (its ability to track a reactive power reference), $e^{-\tau s}$ represents the sum of all time delays in the control loop and $K(s)$ is the voltage and/or POD-Q controller to be tuned and tested.

Since this is an open-loop test the AC network, $G(s)$, has little impact on the result. The result from the simulation and testing procedure can therefore be compared without the need for a detailed and accurate network model. For continuity, it is



recommended to use the same system used in “Part one: Simulation in an undamped test system”.

Simulations are performed on the open-loop system by applying a sinusoidal signal

$$V_n(t) = 0.02 \times \sin\left(\frac{2\pi}{T_n} \times t\right)$$

to modulate the input error $V_{\text{error}}(t)$. The voltage error seen by the voltage and POD-Q regulator then becomes

$$V_{\text{error}}(t) = -V^* + V_0 + V_n(t)$$

where V^* is the measured voltage at the initial time when the loop is broken and V_0 is the voltage reference value at the initiation point.

- > The sinusoidal test signal, $V_n(t)$, can be applied to the measurement or to the reference as long as it is clear how the applied test signal affects the voltage error. In the description of the testing procedure, it needs to be clear if the positive or negative feedback is assumed.
- > Filtering dynamics and any eventual time delays associated with measurement and communication must be included in the test.



The reactive power shall be measured and plotted against the voltage reference, as shown in Figure 3. The sinusoidal variations $V_n(t)$ shall have an amplitude of 0.02 pu. The period time T_n shall be varied so that the frequency response at least covers one decade below and one decade above the intended POD frequency range. As an example, if the intended POD frequency range is 0.25-1.0 Hz (period times 4 – 1 s), the frequency sweep should cover frequencies in the range 0.025-10 Hz (period times 40 – 0.1 s).

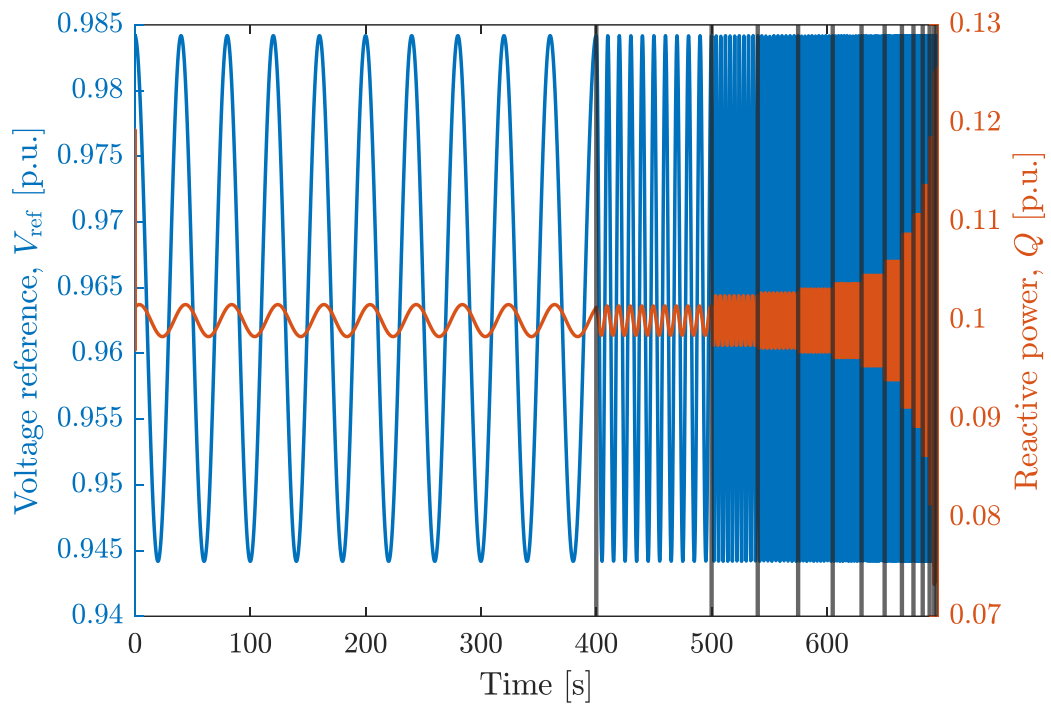


Figure 3 Open-loop frequency response of the PPM in voltage and POD-Q control mode. A sinusoidal variation is applied to the voltage reference as described in Table 1.

Table 1 Sinusoidal variation of voltage reference value added to the PPM.

Step	Sinusoidal variation of reference voltage
Step 1	Add a sinusoidal variation to the voltage reference with an amplitude of 0.02 pu and a period time of 40 s. The sinusoidal signal should be active until a stationary condition has been obtained, i.e., the realized reactive power is varying as a sinusoid with constant amplitude.
Step 2	Change the period time to 10 s. The sinusoidal signal should be active until a stationary condition has been obtained.
Step 3	Change the period times in the same way as in step 2 for period times: 4, 3.5, 3, 2.5, 2, 1.5, 1.0, 0.8, 0.6, 0.4, 0.2, 0.1. Before changing the period time, a stationary condition should be obtained.



- > If the simulation for the ION shows that an amplitude of 0.02 pu is too big, the simulations should be performed with an amplitude that corresponds to the amplitude that is deemed safe for the testing procedure. If the amplitude is reduced, then the reason shall be motivated.
- > For the FON, the simulation should be performed with the same amplitude as the test.
- > Simulations should be performed with all of the implemented reactive power and voltage control modes.
- > Simulations shall be performed for the ION as well as for the FON.

Result of test and simulation study

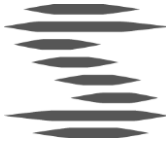
A description of the testing procedure and the applied control configuration should be included in the report describing the testing result. The result from the frequency response test shall be presented in the form of a Bode diagram.

The test and simulation shall be considered approved if:

- > The voltage reference and the reactive power is plotted to show the simulated and measured frequency response test.
- > The result of the open-loop frequency test is presented in a Bode diagram showing reactive power as a function of the voltage (QfV), with gain and phase shift achieved at each sinusoidal frequency.
- > The open-loop phase shift in the QfV response is between 0 and +90 degrees (assuming a convention of negative feedback) in the frequency range 0.25 to 1.0 Hz.
- > If the phase shift reaches below -180 degrees, the gain needs to be adjusted so that the gain margin is at least 2 if no other stability consideration requires the margin to be higher. Assuming that the open-loop plant (1) is given in p.u. power/p.u. voltage, where the power base is the nominal apparent power of the PPM. The gain of the AC network can be assumed to be $1/S_{SCR}$, where S_{SCR} (p.u. power/p.u. voltage) is the lowest short circuit ratio expected at the POC.
- > Simulations for both the ION and FON have been performed with the power levels that are planned to be used during the testing procedure.
- > Simulations and tests have been performed for the FON. A reasonable visual match between the simulated and measured test results have been shown.

Example

Figure 4 shows the QfV frequency response of the PPM simulated in Figure 3. The region shaded green covers the frequency range 0.25 to 1.0 Hz and the phase



range 0 to +90 degrees. The frequency response of the PPM lies inside the green region and thus passes the test.

- > Note that the linearized model (continuous blue/red lines in Figure 4) shows a resonance around 0.33 Hz. The reason for this is that the two-machine system is marginally damped (0.0 % damping). The interarea mode therefore also shows up in the PPM function ($H(s)$ in Figure 2) since the internal current controller is interacting with the AC network. This shows that the PPM's current controller will also have a small impact on the POD. But this has little impact on the test result. In the end, this effect is negligible compared to the voltage and POD-Q control. Note that this picture only illustrates that the internal current controller will have an effect on the POD. This effect is however very marginal. It is unlikely to see this resonance in practice if the AC network has a damping ratio above 0.0% prior to connecting the PPM.
- > The POD-Q gain is tuned such that the QfV gain has a magnitude below $S_{SCR}/2$ for angular frequencies $\omega > 0.25$ Hz (or $\omega > 1.57$ rad/s). Assuming that the gain of the AC network $|G(j\omega)| \approx 1/S_{SCR}$, this results in a gain margin of around 2 if we model a PPM with 75 ms time delay in the QfV control (red line in Figure 4).
- > Time delays will manifest as a declining phase at higher angular frequencies since the phase shift of a time delay $\angle e^{-j\omega\tau} = -\omega\tau$. In Figure 4 this is manifested as the saw-tooth pattern in the phase plot for angular frequencies $\omega > 30$ rad/s. To be able to improve stability of interarea modes up to 1.0 Hz, the maximum feasible time delay is

$$\tau < \frac{1}{1.0 \text{ Hz} \times 2\pi} < 160 \text{ ms}.$$

To have some stability margin, the time delay needs to be significantly lower than this limit. For this simulation example, a 75 ms time delay was chosen. This provides a reasonable stability margin for interarea modes up to 1.0 Hz. The Bode diagram obtained from the experimental frequency response, exemplified in Figure 4, will show if the PPM control (including any time delays) is acceptable or not. The relevant property of the time delay (the phase shifting property) is tested experimentally. Time delays impose a fundamental limitation on the achievable control performance. To some extent, it is possible to compensate for the time delay phase lag using phase advancing lead filters. This will however increase the gain at higher frequencies and make it harder to achieve the gain margin requirement.

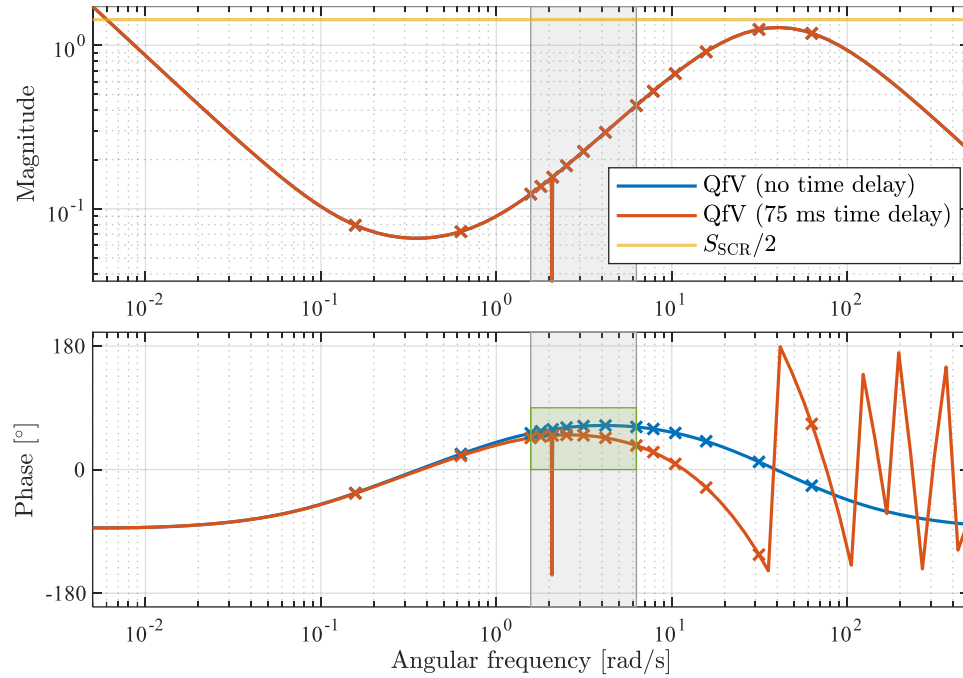
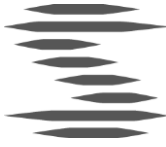


Figure 4 Bode diagram showing the open-loop, QfV, frequency response of the PPM. The continuous lines show the Bode diagram of the linearized plant with time delay (red) and without time delay (blue). The discrete x's show the result from the corresponding experimental frequency response. The simulated frequency response of the QfV function with 75 ms time delay is shown in Figure 3. The gain and phase shift are calculated using a fast Fourier transform (FFT) algorithm.



Changelog

Change date	Change
2025-04-18	First publication
2025-05-16	Svk's general requirements translated and introduced while remaining functionally unchanged from previous handling within the compliance process. Reference to bilaga 6 kap 2.17 corrected to bilaga 6 kap 2.16 in introduction.
2025-10-27	Correction of the angular frequencies