Power System Stabiliser Capability of Offshore Wind Power Plants

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***Abstract*—Nowadays, wind power generation is being located offshore because of its higher wind speed at lower height and larger installation zones in comparison with onshore technologies. Recently, the concept of wind power plant has been introduced as a result of the increment of wind power penetration in power systems. Transmission system operators are requiring wind power generation to help to power system with some ancillary services such as fault ride through or power system stabiliser capability. Therefore, it is important to study power system stabiliser capability of wind power plants. In this paper, a comparison of various power system stabiliser schemes is presented. The effect of the distance from the shore tie-line to the offshore wind farm on the controller response is also evaluated. These studies show that offshore wind power plants have promising power system stabiliser capability even using local input signals.**

***Index Terms*—Cable Length Influence; Offshore Wind Power Plants (OWPP); Oscillatory Stability; Power System Stabiliser (PSS)**

1 Introduction

The increment of wind power penetration in the power system has led transmission system operators (TSO) to concern about stability issues. Growing of wind power generation reduces the percentage of synchronous generation in power system, and converter based wind power plants reduce power system inertia [1].

Modern wind power plants (WPP) are expected to provide support to the grid such as reactive power regulation, keep the wind turbines online during a voltage fault [2], [3], frequency response [4] and in a near future contribute to power oscillation damping. The latter is already carried out by energy storage systems and/or flexible AC transmission systems (FACTS) [5].

Synchronous generators can exhibit rotor oscillations, such oscillations are classified as: local or intra-area modes (0.7 - 2 Hz) which are the oscillation modes among close synchronous generators, inter-area Modes (0.1 - 0.7 Hz) which are the oscillation modes appearing between various areas of generation sharing power, and there are also others such as torsional modes and control modes which exhibit higher frequencies ($>$ 2 Hz). These oscillations are commonly damped in synchronous generators with a power system stabiliser (PSS) device [6].

Wind power (including all the different electrical concepts) does not induce new oscillatory modes into power system, because the generator concepts used in wind turbines do not engage in power system oscillations. For example, fixed speed wind turbines (FSWT) has intrinsically more damped oscillation modes [7], and generators of the variable speed wind turbines (VSWT) are decoupled from the grid by a power converter [7].

The extra contribution of the FSWTs to the stability is limited, therefore it is not very effective as PSS. On the other hand, VSWTs are capable of enhance power system oscillation damping since they have a power converter delivering the desired active and reactive power to the grid. Thus, the use of variable speed wind turbine has been suggested to actively contribute the grid to damp rotor oscillations [8], [9]. This power regulation is done by the addition of a PSS scheme to the converter control, which demands to the wind turbine a variation on the power delivery [10], [11], [12]. This power variation modifies the power flow of the whole power system in order to damp the desired oscillation modes.

Offshore wind power plants (OWPP) can be far away from the main network. It implies that communications will be required if it is necessary the measurement of remote signals for the controller. On the other hand, oscillatory modes could be not observable on local signals reducing the effectiveness of the PSS. Furthermore, the offshore location implies that the system is away from synchronous generation areas, therefore OWPP only can act against inter-area oscillation modes [13], [15], [14].

The aim of this paper is to clarify the PSS capability of the OWPP to damp inter-area oscillation modes with local signal and to analyse the influence of the distance from OWPP to the main network on the controller. This paper is organized as follows. In Section 2, an overview of power system stability concepts is introduced. Power system Stabilizer design for wind power plant is presented in Section 3. Power system stabiliser capability of an offshore wind power plant is simulated and the influence of its distance from wind power plant to shore is discussed in Section 4. Finally, in Section 5, the conclusions are summarized.

2 Power System Stability Background

Power system stability can be defined as the ability to remain in equilibrium during normal operating conditions and to regain an acceptable equilibrium after being subjected to a physical disturbance with most system variables bounded [16], [17].

The stability responses of a power system can be classified as [18]:

- Rotor angle stability, which is concerned with the ability of each interconnected synchronous machine of the power system to maintain or restore the equilibrium between the electromagnetic torque and the mechanical torque.
- Frequency stability, it is related with the capability of a power system to restore the balance between the system generation and the load, with minimum loss of load.
- Voltage stability, which is dependent on the capability of a power system to hold on in steady state, the voltages of all buses in the system under normal operating conditions and after a disturbance.

Depending on the particular fault, rotor angle stability can be classified into two different groups such as transient stability and small signal stability. A power system under a small disturbance is considered in small signal stability. A small disturbance can be, for example, minor changes in load or in generation on the power system. This paper is interested in small signal stability analysis [19].

The study of small-signal stability may result in two different response modes such as non-oscillatory or aperiodic mode due to lack of synchronizing torque, and oscillatory mode due to lack of damping torque. The aperiodic problem has been largely solved by the use of automatic voltage regulators (AVR) into the generators. Oscillation modes are usually canceled by means of Power System Stabilizers (PSS).

Oscillatory small-signal stability problems which must be taken into account are inter-area modes with frequency ranging from 0.1 to 0.7 Hz and local modes in the range from 0.7 to 2 Hz [20], [21].

3 Power System Stabiliser for Wind Turbine

The input can be any signal affected by the oscillation to be damped. Thus, to avoid the use of wide-area communications in the control, local signals are selected as inputs to the PSS. The offshore wind power plant connection point is selected as measurement point in order to avoid the filtering effect introduced by the transformer connected between the grid and the OWPPs. Moreover, it is important to take into account that OWPPs are usually connected into the grid far from generation areas, as shown in Fig. 2. Since the proximity of OWPP to synchronous generators is an important factor, it is not possible to increase the damping of the local (or intra-area) oscillation modes with the PSS capability of OWPP. Therefore, the design of the power system stabilisers can only be focused on the damping of the inter-area oscillation modes.

The PSS control is based on the design of a conventional PSS for a synchronous generators [22]. However, in wind turbines the phase compensation is not required to produce damping torque, therefore lead/lag compensator is not necessary. According to [23], [9], the PSS control can be composed of a proportional controller, a limiter and a band pass filter (or washout filter) to limit the frequency range where the controller is acting (Fig. 1). The inputs and the outputs used in PSS for wind turbine can be different from the conventional PSS. The output can be any variable capable of varying the power delivered to the grid such as the active or reactive power, the generator slip or the excitation voltage. Actually, the PSS introduces small variations referred to the reference values of the output signals. This PSS control can be individually included in each wind turbine of the wind power plant.

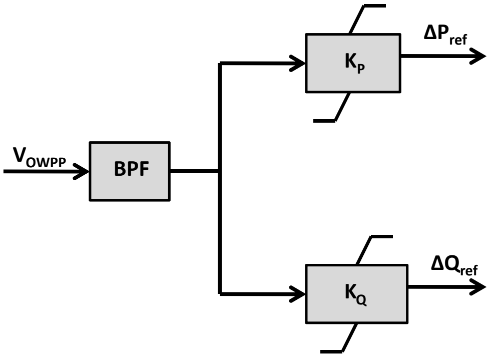

Fig. 1. Block representation of the Active and Reactive Power PSS controller

4 System Simulations

The power system under study is based on the well-known two area network described in [24], with an offshore wind power plant (OWPP) connected to the tie-line between the two areas. The OWPP is assumed as an aggregate model for simulation, therefore the PSS control is also assumed as an aggregate controller. The system appears represented in the Fig. 2. A three-phase fault is considered in the middle of the tie-line in order to excite the power system oscillation. In this study an OWPP of 50MW are assumed which is less than a 5% of wind power penetration on the system.

For the present study, the PSS controllers applied to the wind power plants are selected as input the offshore wind power plant connection point voltage and as output the active and/or power reference. The band pass frequency of the filter is between $0.08\ Hz$ and $1.5\ Hz$, since the inter-area modes are in the range from 0.1 Hz to 0.7 Hz. The active (Kp) and reactive (Kq) gains have been set in 10^4 and -10^5, respectively. The values of these gains are important they can affect the stability of the system. Finally, the output saturations were also included to limit the controller outputs between -0.15 and 0.15 in p.u., in both cases.

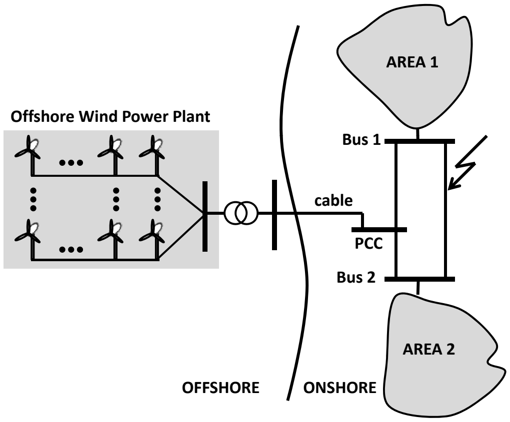

Fig. 2. Representation of the power system utilised in this study

The analysis is divided in two study cases. First, the PSS capability of the OWPP is studied by the use of different PSS control schemes. Second, the influence of the length of the cable which links the OWPP and the main network, in the PSS control response.

4.1 Case 1: Comparison of different PSS schemes

In this case a comparison between different control schemes was carried out to evaluate the PSS capability of the OWPP. The system under study is simulated in four scenarios:

- no PSS installed in the OWPP controllers (used as base case),
- OWPP with an extra active power loop to damp oscillations (P-PSS),
- OWPP with an extra reactive power loop to damp oscillations (Q-PSS),
- OWPP with both additional control loops (active and reactive power, PQ-PSS) with the same aim.

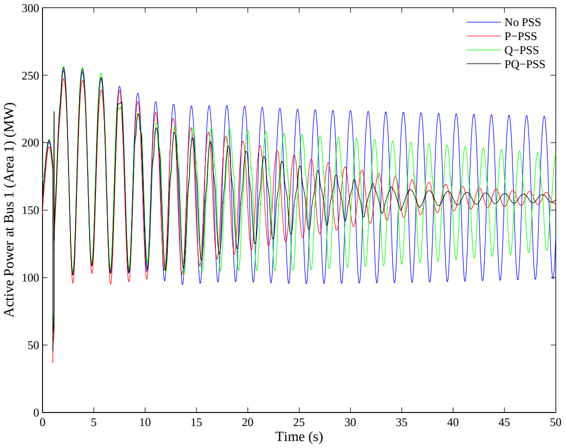

Fig. 3. Active power flowing through Bus 1, which connects Area 1 with the tie-line for different PSS schemes (Case 1)

In Fig. 3, the active power flowing through the Bus 1 which connects the Area 1 with the rest of the system is shown. Since Area 2 has larger loads than generation systems, the active power flows from Area 1 to Area 2. In this figure, it can be observed that the system without OWPP PSS compensation (no PSS) presents an almost critically stable dynamic behaviour. The inclusion of an extra Reactive power loop into the system shows slight damping improvement. On the other hand, the addition of an extra active power loop into OWPP presents an important improvement on damping oscillation modes. Finally, it can be observed that the simultaneous use of active and reactive power shows even a better damping capability. The better response obtained with P-PSS than Q-PSS is an expected result since active power affects directly mechanical dynamics, whereas reactive power affects indirectly rotor dynamics.

Fig. 4 presents the active power delivery response of the wind power plant. It can be seen that for the No-PSS and Q-PSS cases, the wind power plant is delivering a constant value of active power. On the other hand, in P-PSS and PQ-PSS cases, the OWPP is delivering a compensating signal to damp the oscillations. Moreover, it can be observed that this response reaches the saturation limits for both cases. Although in the PQ-PSS case, the active power delivered enters into the linear zone sooner than the power delivered by the P-PSS. This is a consequence of the interaction with the reactive power loop.

In Fig. 5, it is plotted the reactive power delivered by the offshore wind power plant. As occurs with the active power, in the No-PSS and P-PSS cases, the offshore wind power plant remains at their reference value (0 Mvar). The Q-PSS and PQ-PSS react against the oscillation. In both cases the reactive power reaches the saturation limits. However, the Q-PSS does not leave the saturation during all the simulation time because of its lower effect on the oscillatory mode which requires more reactive power feeding from the wind power plant.

Fig. 6 and 7 show the voltage magnitude and a zoom of it at Bus 1, respectively. As happens with the active power at the same bus, the active and reactive power PSS provides better damping capability on the voltage than other controllers. Although P-PSS loop also obtains promising results.

The magnitude and the corresponding zoom of the voltage at point of connection of the offshore wind power plant with

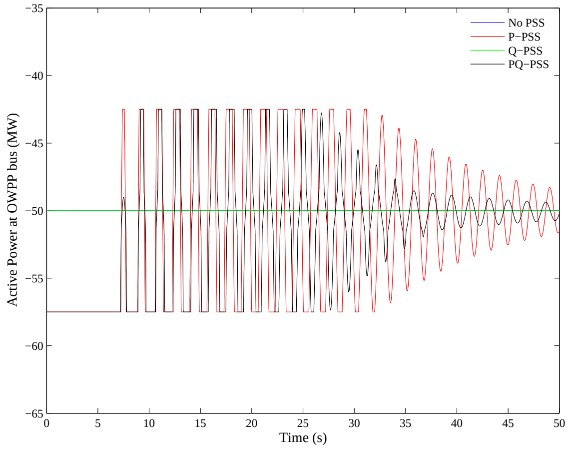

Fig. 4. Active power delivered by the wind power plant for different PSS schemes (Case 1)

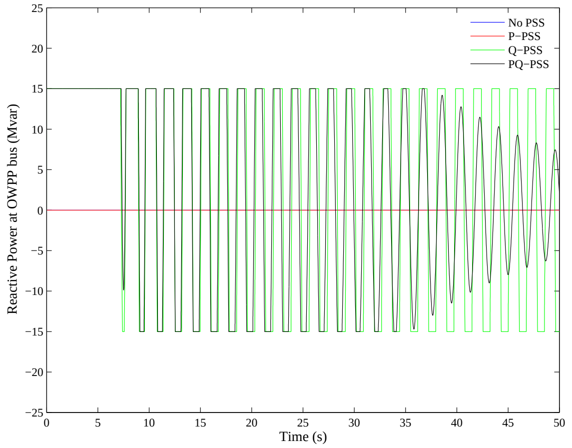

Fig. 5. Reactive power delivered by the wind power plant for different PSS schemes (Case 1)

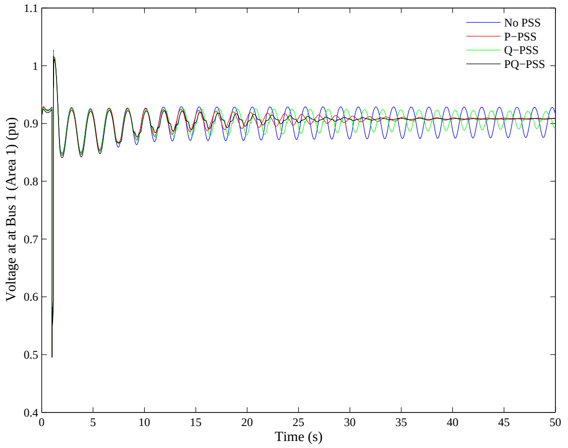

Fig. 6. Voltage Magnitude at Bus 1 for different PSS schemes (Case 1)

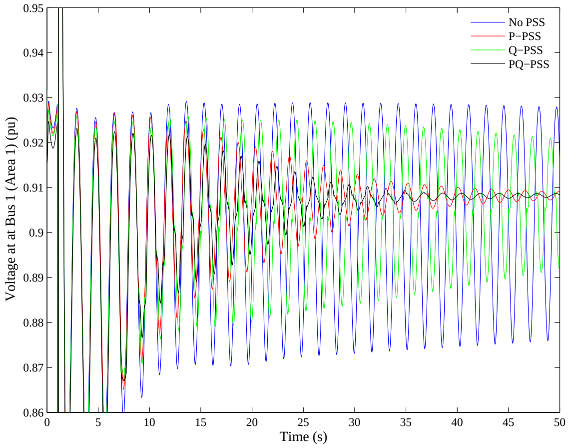

Fig. 7. Zoom of Voltage Magnitude at Bus 1 for different PSS schemes (Case 1)

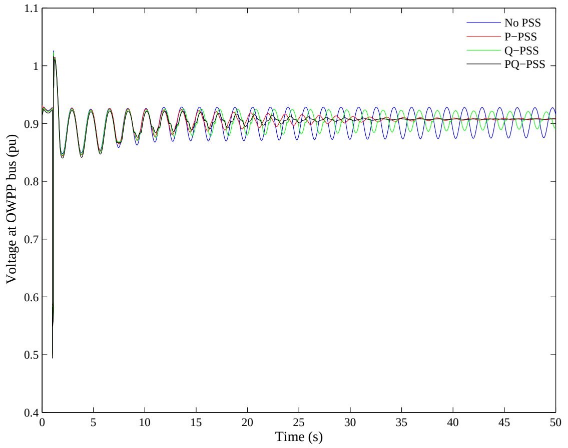

Fig. 8. Voltage Magnitude at OWPP connection Bus for different PSS schemes (Case 1)

the grid are presented in Fig. 8 and 9, respectively. In this case, it can be observed that as happens in the voltage magnitude at Bus 1, the PQ-PSS and P-PSS rapidly stabilise the oscillation. The voltage at OWPP bus is the input signal for the PSS controllers, therefore rapid stabilisation of this signal implies less actuation time of this controllers.

4.2 Case 2: Effect of the cable length on the PSS capability

In this case, the effect of the cable length on the PSS capability is analysed. Since only local variables are used in the PSS, the length of the cable may have marked effect on its damping capability. To this end, the system is simulated under four different cable length: 10, 30, 50 and 70 km, respectively. In order to evaluate all the length under the same case, the active and reactive PSS controller is connected for all the

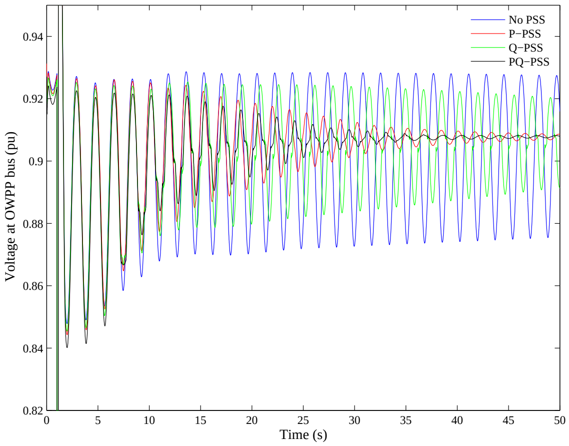

Fig. 9. Zoom of Voltage Magnitude at OWPP connection Bus for different PSS schemes (Case 1)

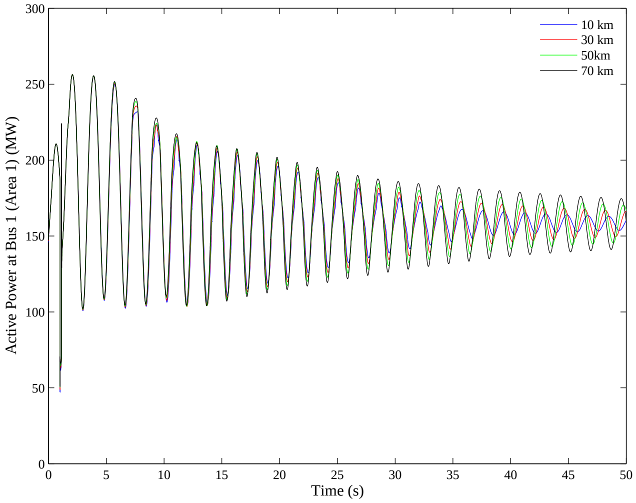

Fig. 10. Active Power flowing through Bus 1 which connects Area 1 with the tie-line for different cable length (Case 2)

simulations. Active and reactive PSS (PQ-PSS) was selected since it presented the best damping behaviour in the previous subsection.

Fig. 10 presents the active power flowing through the Bus 1. It can be observed a reduction in the PSS damping capability for longer cable length. This is an expected result because the observability of the oscillation is lower when the cable length increases. However, the oscillation damping achieved by the PSS controller is still quite important. The system is still better damped at 70 km with active and reactive PSS controller, than the same system with shorter line using only reactive PSS controller.

In Fig. 11 and 12, the active and reactive power delivered by the wind power plant is presented. It can be observer that for long cables the compensation signals are smaller. This is a consequence of the observability of the oscillation in the measurement point. Clearly, the PSS must delivers large active and reactive power to achieve the same damping. However, in Fig. 11 and 12, the compensation signals are smaller for long cables because of the PSS parameters were not optimised for each length. Fig. 13 and 14 show the voltage magnitude and a zoom of it at Bus 1, respectively. Again, the damping contribution is greater for short cable lengths.

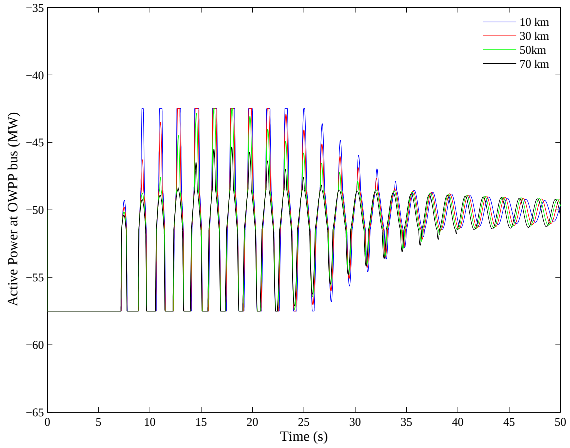

Fig. 11. Active power delivered by the wind power plant for different cable length (Case 2)

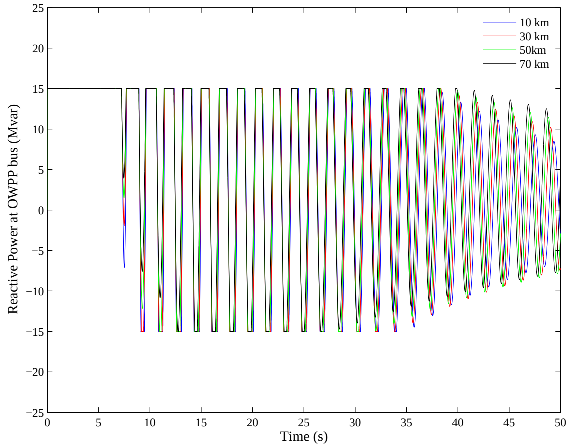

Fig. 12. Reactive power delivered by the wind power plant for different cable length (Case 2)

The voltage magnitude and a zoom of it at the connection point of the offshore wind power plant with the grid are presented in Fig. 15 and 16, respectively. In this case, it can be observed that longer cable lengths imply larger voltage decays. This is a consequence of the OWPP controls, which has been designed to deliver a fixed active and reactive power values without voltage regulation.

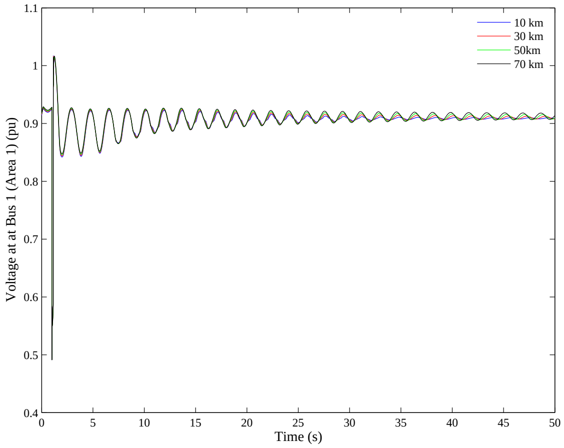

Fig. 13. Voltage Magnitude at Bus 1 for different cable length (Case 2)

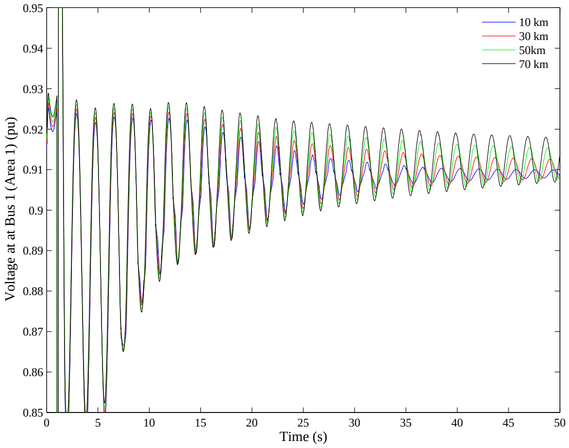

Fig. 14. Zoom of Voltage Magnitude at Bus 1 for different cable length (Case 2)

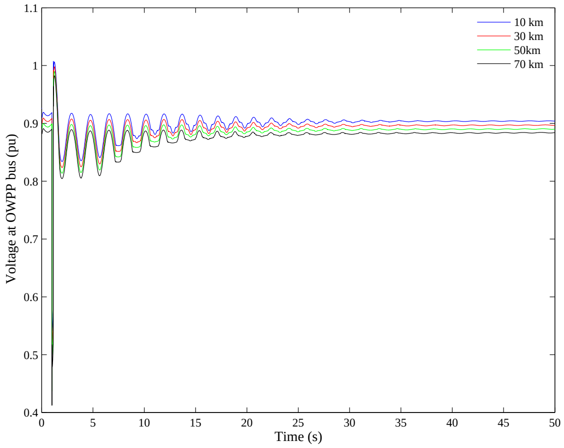

Fig. 15. Voltage Magnitude at OWPP connection Bus for different cable length (Case 2)

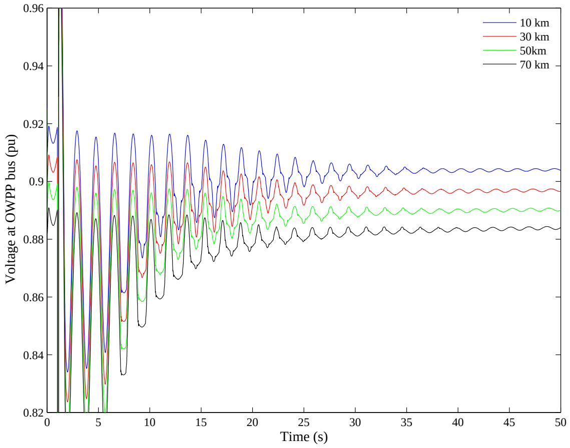

Fig. 16. Zoom of Voltage Magnitude at OWPP connection Bus for different cable length (Case 2)

5 Conclusions

The PSS capability of OWPP has been analysed in different scenarios. First, a comparison of several PSS schemes such as the use of only active power as compensation signal (P-PSS), the use of only reactive power (Q-PSS) and the use of active and reactive power simultaneously (PQ-PSS). In all cases, the PSSs have been designed as a simplified conventional PSS for synchronous generators considering the OWPP voltage (local signal) as input. The response obtained with the three PSS schemes has been compared with an OWPP connected into the power systems without any PSS. The PSS controllers for wind turbines have shown promising damping properties. The best damping behaviour has been observed in the case of the controller with active and reactive power PSS. The controller acting only on the active power has shown also good performance on damping inter-area oscillations.

The influence of the cable length connecting the OWPP to the power system on the damping capability has been also analysed. Since only local signals can be used to compute the compensation signals in PSS without communications, the distance between the OWPP and the PCC has strong effect on the damping capability. The observability of the oscillations is lower for long distances. Nevertheless, simulation results have shown that for significant distances the OWPP still provides a satisfactory damping capability. Therefore, PSS schemes without communications are capable of damping oscillation even being far away from the PCC.

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