This paper was presented at the 14th Wind Integration Workshop and published in the workshop's proceedings.

Wind Power Plant Control Optimisation with Incorporation of Wind Turbines and STATCOMs

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***Abstract*—This paper addresses a detailed design and tuning of a wind power plant slope voltage control with reactive power contribution of wind turbines and STATCOMs. First, small-signal models of a single wind turbine and the whole wind power plant are developed, being appropriate for voltage control assessment. An exemplary wind power plant located in the United Kingdom and the corresponding grid code requirements are used as a base case. The final design and tuning process of the voltage controller results in a guidance, proposed for this particular control architecture. It provides qualitative outcomes regarding the impact of system delays, grid conditions and various operating conditions of the wind power plant, with and without incorporation of STATCOMs.**

***Index Terms*—Wind turbine, Offshore wind power plant, Power system, Voltage control, State-space model, Grid codes.**

I. Introduction

THE increasing amount of wind power generation in both transmission and distribution grids has forced the wind power plants (WPPs) to take over the past responsibility of conventional generation to control the node voltages adequately. This has also engaged different countries to tighten their grid codes requirements in this regard. Nowadays, voltage control at the point of common coupling (PCC) of a WPP is realized by an overall controller which provides voltage or reactive power reference signals to the wind turbines (WTs). However, their contribution is limited due to reactive power capability limit. Moreover, the tendency of increasing distances of HVAC cable connections in offshore WPPs (up to more than 150 km) will challenge voltage control at the PCC. A way of dealing with this issue is by integrating fast acting devices such as STATCOMs, which are capable of supporting the voltage with fast dynamic responses.

Such sophisticated approach for voltage control requires high-performance and robust solutions, smoothly incorporating all plant controllers, as large WPPs are not characterized by simple Single-Input-Single-Output (SISO) systems. It is important to investigate how the involved grid connected converters can be included to provide a stable control solution for different operational scenarios in order to fulfill the dynamic requirements. This aspect even reinforces the need of investigating the final tuning process and control philosophy adjustment, as the implementation of STATCOMs has not yet been investigated thoroughly in previous control studies regarding WPPs.

Hence, the focus of this project is placed on the development of a WPP model for control analysis as well as the design and tuning process of one selected voltage control architecture. An exemplary WPP located in the United Kingdom (UK) and the corresponding grid code requirements are used as a base case. In order to obtain qualitative outcomes by means of frequency-domain analysis, small-signal models of a single full-scale converter (type-4) WT and the whole WPP are developed, being appropriate for voltage control assessment without usage of already built-in models. Finally, a guideline is provided for the control design and tuning process, regarding the impact of system delays, grid conditions and various operating conditions of the WPP, with and without incorporation of STATCOMs.

The rest of this paper is organized as follows: Section II describes the composition of the applied benchmark WPP and the relevant grid code requirements for this study. Section III describes the modelling of WPP components for small-signal analysis. Sections IV and V focus on the design and tuning process for a plant voltage controller, which leads to some proposed guidelines to be used for parametrizing the overall controller in Section VI. The conclusion of this study is given in Section VII.

II. System Description and Requirements

A. System Characterization of the Benchmark Wind Power Plant Network

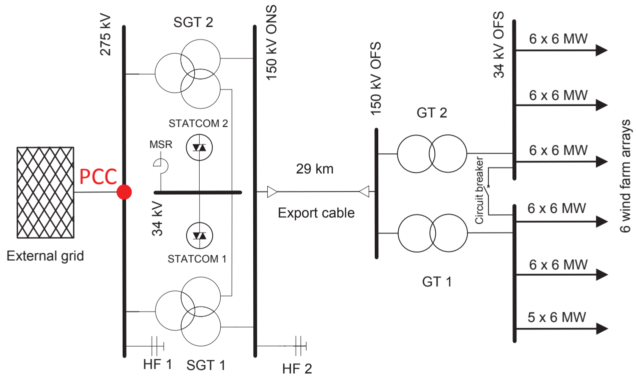

Figure 1. Single line diagram of benchmark offshore wind power plant

A benchmark WPP located in the UK is used as a base case for this study. Therefore, the WPP takes into account the requirements for transmission systems in the UK and general engineering rules for WPP topologies. The single line diagram of the WPP topology is presented in Fig. 1. It comprises 35 WTs of variable speed, full-scale power conversion and a rated power of 6 MW. Moreover, two STATCOMs with an MVA rating of $\pm 25\,\mathrm{Mvar}$ respectively are connected together with a mechanically switched reactor (MSR) which expands the STATCOM operating range while all the time keeping smooth reactive power control [1, p. 45]. The WPP power is transferred to the onshore grid by an export cable, where the PCC is defined.

B. Grid Code Requirements

The UK *Grid Code* [2] sets out the operating procedures and principles of power plants and also determines the relationship between the *National Grid Electricity Transmission* (NGET) and the users of the *National Electricity Transmission System* (NETS). According to the *Grid Code* a WPP controller has to be able to perform a continuously automatic voltage control of the WPP without introducing any instability over the entire operation range. Lately NGET has prepared a guidance note with some specific requirements regarding voltage control requirements of a WPP [3]. The specific requirements are given in Tab. I. The relevant parameters are given by rise time (t_r), settling time (t_s) and delay time (t_d). The controller shall response within 0.2 seconds and reach 90 % of the set point in a linear way within 1 seconds. The settling time shall not exceed 2 seconds, where the peak-to-peak amplitude of any oscillations (OS) shall be less than 15 % of the steady-state value. Moreover, the bandwidth of interest in this study is 5 Hz.

Table I
DESIGN REQUIREMENTS FOR VOLTAGE CONTROL

Parameter	Value	Unit
t_d	0.2	[s]
t_r	1.0	[s]
t_s	2.0	[s]
OS	15	[%]

III. MODELLING OF WIND POWER PLANT COMPONENTS

In order to analyze voltage control during normal operation, the occurrence of small-signal changes may be assumed. Then, the models are able to be linearized around a certain operation point for the purpose of this analysis. For this WPP system the state-space approach is applied, as it offers the possibility of separating plant- and controller components enabling the user to apply generic tools for analyzing typical feedback control systems. [4]

A. Wind Turbine Generators and STATCOMs

The topology of nowadays' widely used full-scale converter WTs are characterized by decoupling the two AC circuits on the machine and grid side respectively by the converter's DC-link. When the focus of analysis is laid on reactive power and voltage control, the WT system can be reduced to its grid-side converter as depicted by the schematics in Fig. 2.

The reduced electrical model is represented in dq-reference frame and its linearized mathematical expressions are outlined in [5]. The relevant dynamics in the system are analyzed

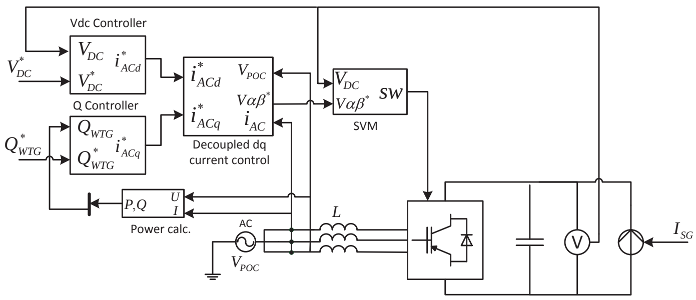

Figure 2. Schematic diagram of grid-side converter and its controller for a type-4 WT.

by computing the Eigenvalue spectrum of the Multiple-Input-Multiple-Output (MIMO) system in Fig. 3. It shows that the dynamics of the outer control loops (DC-link voltage and reactive power control) exhibit frequencies around 2 Hz, hence being highly relevant for the overall voltage control of the WPP. The remaining dynamics exceed the system bandwidth of 5 Hz and will not affect the relevant WPP control dynamics. [5]

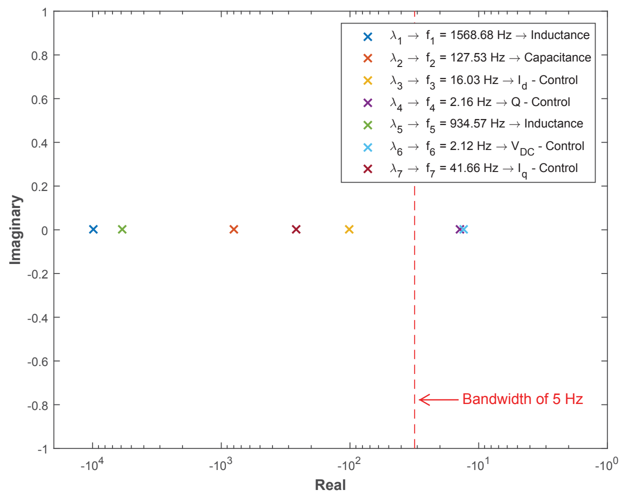

Figure 3. Eigenvalue spectrum for the WT state-space model.

The STATCOM features the same topology of a grid-connected converter, just without active power production, represented by the constant DC current source in Fig. 2. Hence, the complete state-space model of the STATCOM is developed according to the considerations and derivations for the WT model [5].

The model functionality is successfully validated against a numerical EMT model, with the outcome that the linearized state-space model provides adequate results, even in the case of larger reactive power changes [5].

B. Wind Power Plant Network

The WPP network, namely an interconnected set of electrical lines and transformers both onshore and offshore, transfers the power generated by the WTs to the PCC, where the interface of WPP network and external grid is defined. Due to the low frequency area to be regarded, for these components similar model considerations as for power flow studies are applied.

Thus, cables are represented by the classical RLC π-model, while transformers and external grid are expressed by an equivalent series RL impedance. Both mechanically switched reactor (MSR) and C-type harmonic filters (HFs) are modelled by shunt admittances. [6]

All network components and the individual state-space models of WT and STATCOM are connected by a set of algebraic, complex equations according to Kirchhoff's law in a common synchronous reference frame with RMS phasor variables. The functional diagram of the WPP network model is depicted in Fig. 4. The state-space representation of the network is achieved by linking current injections and bus voltages by the network impedances and admittances. [5]

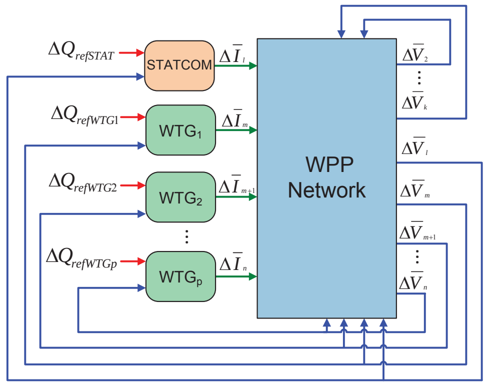

Figure 4. Functional diagram of wind power plant model used for the state-space representation.

The resulting MIMO system of the whole WPP with $\mathbf{\Delta Q_{ref}}$ as input signals and $\mathbf{\Delta V}$ is successfully validated by means of load flow simulations, thus it delivers satisfying outcomes regarding the voltage states of the whole network [5]. In this way, the dynamic behaviour within the WPP is assessable with respect to voltage control, which enables to check the voltage limits within the MV network as well as reactive power capability limits by the individual WTs and STATCOMs.

C. Wind Power Plant Controller

The WPP controller receives reference and measured feedback signals and provides set-points to the individual WTs and STATCOMs as depicted in Fig. 5. The feedback loops of both

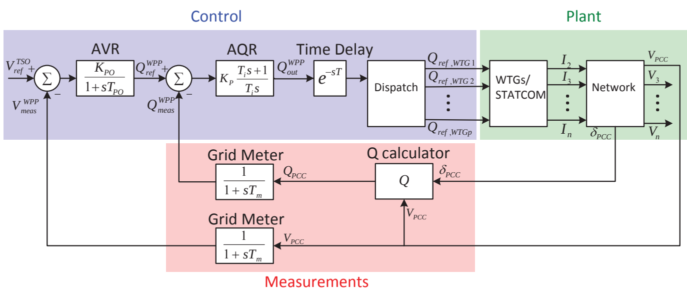

Figure 5. System representation for the overall wind power plant voltage control

voltage V_{PCC} and reactive power Q_{PCC} include meters, which sense the voltages and currents. Their sampling process is described by a first-order time response with T_m.

On the control level the outer loop (AVR) is characterized by slope control according to the *Grid Code* requirements with its slope gain K_{PO} and time constant T_{PO}. The inner loop (AQR) takes into account the internal reactive power losses within the WPP before initiating the reference signals Q_{out}^{WPP} to the individual units. There are several control strategies available for the inner control loop, e.g. by adding feed-foward signals to accelerate the response [1]. However, in this study PI control serves as a base case strategy, since it is commonly used in today's WPPs.

Control application is realized by signal discretization which exhibits a sampling time T_s. Moreover, the WPP control also contains a processor, that computes the control and dispatcher algorithms, as well as a communication hub. This whole process introduces a time delay T_{com}, which is grouped together with the sampling delay leading to a total system delay expressed by e^{-sT}. [1]

The dispatch function handles the distribution of reactive power signals to the individual WTs and STATCOMs. Its level of sophistication is mainly related to optimization algorithms, as for instance regarding the voltage levels within the WPP to remain within normal operating range or to minimize active power losses in the collector system [5]. As a base case in this study, the simplest dispatch method by sending equal reference points to all individual units is applied.

IV. Design of Plant Voltage Controller

The design process for the superior voltage controller should take into account the whole operational range of a WPP and different grid conditions regarding the short-circuit ratio (SCR) of the connected WPP. Moreover, a focus is laid on the incorporation of STATCOMs for reactive power contribution. Describing the whole WPP model by SISO systems enables a stepwise design of AQR and AVR.

A. Design of AQR

In order to prevent fast transients in the system, the reactive power control is normally limited by ramp-rates which lowers the demand of fast response times. In this case, the *Symmetrical Optimum* (SO) method is known to be a feasible solution for parametrizing PI controllers, such as the inner loop AQR of the overall voltage control [7]. The transfer function $G_{Q_{out}^{WPP} Q_{PCC}}(s)$, describing all the dynamics within the WPP without possible system time delays, can be reduced to a second-order system with equal frequency characteristic in the relevant low frequency area. With T_1, T_2, K_{plant} and Eq. 1 the PI control parameters are determined. [5]

$$
\begin{aligned}
T_i &= 4k_1T_2 \qquad & k_1 &= \frac{1+\left(\frac{T_2}{T_1}\right)^2}{\left(1+\frac{T_2}{T_1}\right)^3} \\
K_p &= k_2\frac{T_1}{2K_{plant}T_2} \qquad & k_1 &= \frac{1+\left(\frac{T_2}{T_1}\right)^2}{\left(1+\frac{T_2}{T_1}\right)^3}
\end{aligned}
\tag{1}
$$

Then, in the presence of system time delays the designed AQR will perform with increased overshoot and settling time. A common approach to overcome process dead times is to use a so called *Smith Predictor*, a type of predictive controllers [8]. As shown in Fig. 6 the AQR is extended by an internal plant model G_p, representing the delay-free response, and a delay estimate e^{-sT}, thus taking into account the dead time in order to compute the output setpoint Q_{out}^{WPP}.

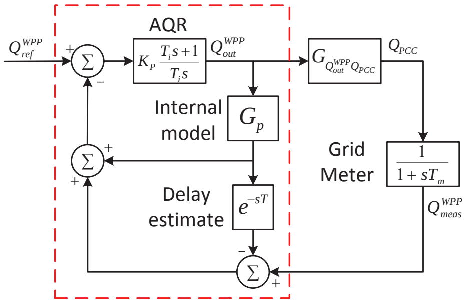

Figure 6. Extended control structure of wind power plant AQR with *Smith Predictor*

The impact of the *Smith Predictor* on the system performance is illustrated by an exemplary reactive power step response in Fig. 7, where an overshoot of 10 % is eliminated and the settling time reduced by 0.2 seconds.

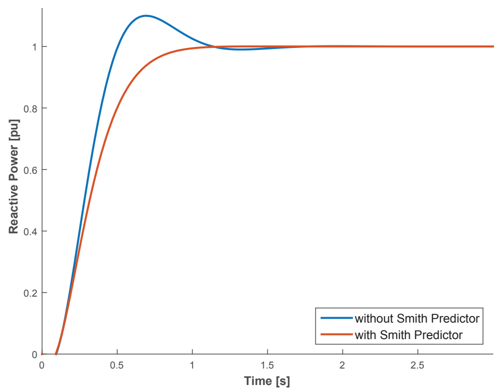

Figure 7. Reactive power step response of closed-loop system with wind power plant AQR with and without *Smith Predictor* for $t_d = 0.1\,\mathrm{s}$

However, one might claim that using a *Smith Predictor* requires a set of internal plant models representing various WPP configurations and operating conditions. Hence, it is worth analyzing whether one particular internal model can be applied for different actual plant behaviours. In Fig. 8 step responses of 6 test cases are depicted, representing different active power production levels of the WTs (cut-in, average and rated wind speed) at two different SCRs (strong grid: $SCR_{max} = 100$, weak grid: $SCR_{min} = 11$). The internal model of the *Smith Predictor* is developed for SCR_{max} and $P_{WTG,0} = 0.5\,\mathrm{pu}$ without STATCOM contribution. Nonetheless, the results imply a similar system performance for deviant operational points and grid conditions. However, a 7th test case regards the implementation of the STATCOMs, which changes the AQR performance significantly by an increased overshoot of 6.5 %. Hence, an unique internal plant model is not sufficient in this case and the incorporation of STATCOMs should be regarded for designing the AQR.

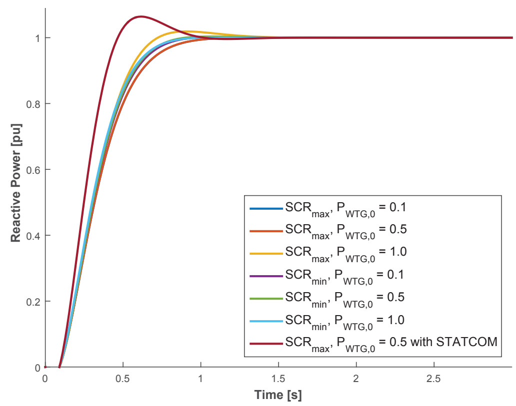

Figure 8. Reactive power step response of closed-loop system with wind power plant AQR including *Smith Predictor* for $t_d = 0.1\,\mathrm{s}$ and various test cases

B. Design of AVR

As the system delays constitute a crucial variable for voltage control performance, the AVR is designed by regarding an extreme case value of $t_d = 0.2\,s$, which might be present in the WPP without violating the delay time requirement stipulated by the *Grid Code* (Tab. I). Then the time constant T_{PO} should be used to respect the bandwidth ω_b of the inner loop controllers [1], what can be simply accomplished by using Eq. 2. The value of $T_{PO} = 0.22\,s$ is obtained based on one design test case.

$$T_{PO} = \frac{1}{\omega_b} \tag{2}$$

The slope gain K_{PO} of the outer loop AVR is imposed by the TSO and can vary depending on the WPP location and grid conditions. A default slope setting of 4 % is defined by the *Grid Code* and applied for an exemplary tuning process of the voltage controller.

V. Tuning of Plant Voltage Controller

A. Tuning of AVR

In the next stage the design specifications of Tab. I are considered for evaluating the dynamic performance of the system. As the performance of voltage control is highly dependent on the grid conditions, the tuning process is accomplished for both SCRs ($SCR_{max} = 100$ and $SCR_{min} = 11$) [5]. The default control architecture to be used in decent software tools for control analysis (e.g. *Mathworks SISO Design Tool*) is shown in Fig. 9.

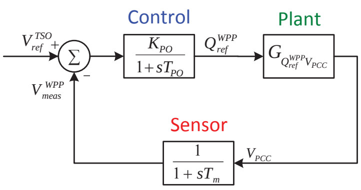

Figure 9. Control architecure used for AVR tuning

The high-order plant transfer function $G_{Q_{ref}^{WPP}V_{PCC}}(s)$ is approximated by a third-order system by implicit balancing techniques [9]. It exhibits equal frequency characteristic within the bandwidth of interest (5 Hz), taking into account a first-order behaviour of the WTs and considering one pole introduced by the AQR and the time delay respectively [5].
Now, the closed-loop poles of the system are analyzed by plotting the root locus of the open-loop system. In Fig. 10 the colored areas delimit the forbidden area for placing the poles of the system in order to fulfill the design criteria.

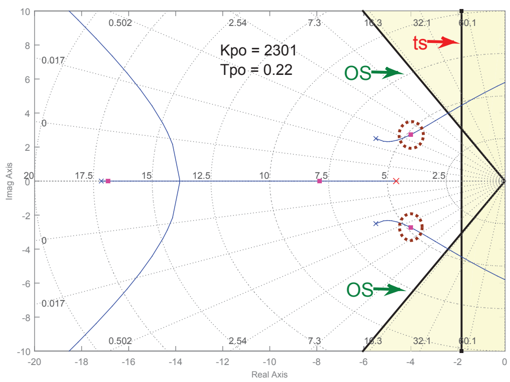

Figure 10. Root locus plot of AVR open-loop system with SCR_{max} and slope of 4 %

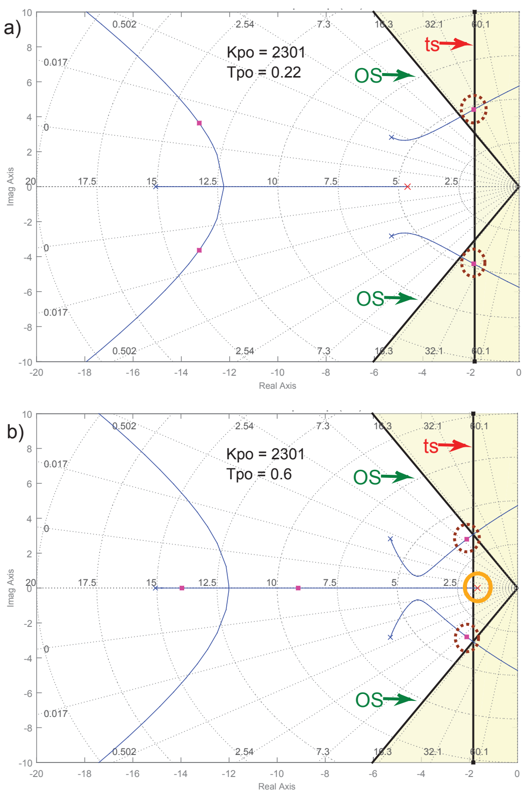

Figure 11. Root locus plots of AVR open-loop system with SCR_{min} and slope of 4 %: a) with $T_{PO} = 0.22\,\mathrm{s}$, b) with $T_{PO} = 0.6\,\mathrm{s}$

The vertical line is associated with the settling time value t_s provided. The two rays, starting at the root locus origin, specify the allowed percent of overshoot (OS). For the case with SCR_{max} it can be seen that the requirements can be fulfilled for a default slope of 4 %, when observing the encircled closed-loop poles.
For the case with SCR_{min} it is observed in Fig. 11a. that the design criteria are violated. While the settling time constraint is just fulfilled, the system response will show too large overshoot, which is due to a high open-loop gain of the system, introduced by a relatively large grid impedance in weak grids [5]. The open-loop gain can be reduced by selecting steeper slope values (up to 7 %). However, depending on the connection agreements with the TSO slope gain adjustment is not a solution, as the WPP operator must be able to control the PCC voltage just as with relatively flat slope characteristics (down to 2 %). In this case it is ascertained that voltage control performance can be improved, if the time response of the AVR is prolonged. Fig. 11b. depicts such a case for a slope of 4 %, where the time constant is increased to $T_{PO} = 0.6\,\mathrm{s}$. Moving the corresponding open-loop pole (encircled in yellow) to the right modifies the root locus, so that the closed-loop poles is kept inside the permitted area.

B. Verification of Tuning Process

To verify the tuning process and to show the impact of different operating conditions of the WPP, step responses for a PCC voltage change of $\Delta V_{PCC} = -5\,\%$ are performed. Fig. 12a. shows the system response for various initial active power values of the WTs. A small difference in overshoot ($\Delta OS = 1.4\,\%$) compared to the base design case leads to the conclusion that voltage control performance changes slightly for other wind conditions. In this way, it seems reasonable to include some margins in the tuning process to fulfill the requirements for all operating conditions.
However, the base design case disregards possible reactive power contribution by STATCOMs. Their activation leads to a more significant change in overshoot ($\Delta OS = 3.7\,\%$), which is illustrated in Fig. 12b. Thus, for the most suitable control design it is recommended to regard whether the WPP will incorporate the STATCOMs into voltage control permanently or not. Depending on this decision, the parameters of both AQR and AVR should be selected during the design process.

VI. Proposed Guidelines for Design and Tuning

Based on the results some guidelines regarding the design and tuning of the voltage controller of a WPP can be provided. Prior to setting up the individual design and tuning steps, following information is required for the particular WPP under consideration:

- As it is crucial for the slope control performance, the stiffness of the external grid should be provided in terms of a minimum and maximum short-circuit ratio SCR_{min} and SCR_{max} for the particular point of connection. Moreover, for the voltage controller a fixed slope setting or an adjustable range is defined by the TSO.
- As it constitutes a major concern for the control performance, the system delays (controller sampling and communication delays) need to be obtained.

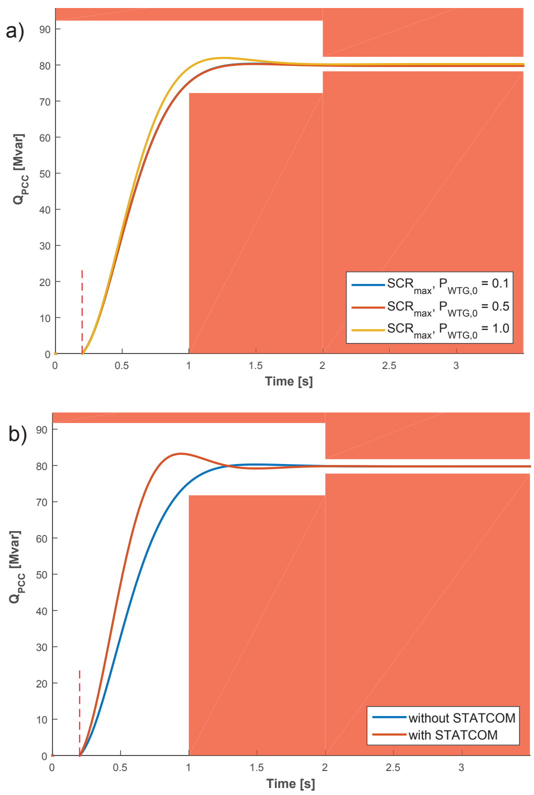

Figure 12. System step response ($\Delta V_{PCC} = 5\,\%$) for a slope of 4 % and SCR_{max}: a) with various operating conditions of the WTs, b) with and without implementation of STATCOM

- It has been ascertained that the presence of STATCOMs affects the voltage control performance significantly. Hence, it needs to be known for the design process whether STATCOMs are incorporated permanently for reactive power contribution or not.

A linearized model of the WPP system needs to be developed in order to obtain the plant transfer functions. Then, the following design and tuning steps are proposed:

a) Design of inner control loop (AQR)::

1) The *Symmetrical Optimum* method is applied to parametrize the PI components of the AQR.
2) A *Smith Predictor* is implemented by using the plant function $G_{Q^{WPP}_{out}Q_{PCC}}(s)$ and the estimated time delays to enhance the AQR performance with due regard to present system delays.

b) Design of outer control loop (AVR)::

3) The time constant of the slope control (AVR) is obtained by considering the bandwidth of the upstream system, which is defined by AQR, system delays and WPP network.
4) The gain of the slope control (AVR) is calculated by the predefined slope setting and the maximum reactive power capability of the WPP.

c) Tuning of outer control loop (AVR)::

5) Root locus analysis is applicable in order evaluate the control performance according to the grid code requirements, for the demanded slope values and the grid parameters SCR_{max} and SCR_{min}.
6) In case of non-compliance for any of those cases in step 5., the AVR time constant is adjusted to enhance the control performance. The tuning process should account for some margins regarding the fulfillment of overshoot, rise and settling time requirement, since the system behaviour varies for different operating conditions.

VII. Conclusion

By using a linearized small-signal model of the whole WPP system being applicable for voltage control analysis, this paper has presented a method to design and tune the WPP voltage controller taking into account factors such as system delays, grid conditions and possible implementation of STATCOMs for the purpose of voltage support.

Initially, a small-signal model of the whole WPP is constructed and the system dynamics being relevant for the overall voltage control are determined by Eigenvalue analysis. The resulting state-space model enables to analyze the full dynamic behaviour of the WPP as well as to investigate possible dispatch strategies for sending the reactive power signals to the individual WTs and STATCOMs.

The final design and tuning process of the WPP voltage controller provides qualitative outcomes regarding the impact of system delays, grid conditions and various operating conditions of the WPP. The formulated guidelines have summarized the aspects and steps to be considered for one particular voltage control architecture in WPPs, including the impact of reactive power contribution by STATCOMs.

Acknowlegment

This paper is part of the final MSc thesis, a project proposed by DONG Energy. The authors would like to thank Florin Iov from Aalborg University as well as Lukasz Hubert Kocewiak and Mikkel Peter Sidoroff Gryning from DONG Energy for all their support. The presented work will be used in the PSO-forskel *RePlan* project “Ancillary Services from Renewable Power Plants”.

References

[1] Jorge Martinez Garcia. *Voltage control in wind power plants with doubly fed generators.* Aalborg University, The Faculty of Engineering and Science, Department of Energy Technology, 2010.

[2] National Grid Electricity Transmission The Grid Code. Issue 5. Revision 13 2015.

[3] National Grid - Guidance Notes - Power Park Modules, 2012.

[4] Jian Sun. Small-signal methods for ac distributed power systems–a review. *Power Electronics, IEEE Transactions on*, 24(11):2545–2554, 2009.

[5] Fitim Kryezi Lennart Petersen. *Wind Power Plant Control Optimisation with Embedded Application of Wind Turbines and STATCOMs.* Aalborg University, Department of Energy Technology, 2015.

[6] Prabha Kundur, Neal J Balu, and Mark G Lauby. *Power system stability and control*, volume 7. McGraw-hill New York, 1994.

[7] E Ceanga, C Nichita, L Protin, and N Antonio Cutululis. Theorie de la commande des systemes. *Ed. Tehnica, Bucuresti*, 2001.

[8] Ari Ingimundarson and Tore Hägglund. Robust tuning procedures of dead-time compensating controllers. *Control Engineering Practice*, 9(11):1195–1208, 2001.

[9] A Varga. Balancing free square-root algorithm for computing singular perturbation approximations. In *Decision and Control, 1991., Proceedings of the 30th IEEE Conference on*, pages 1062–1065. IEEE, 1991.