Assessment of Interactions Involving Wind Farms in Large-Scale Grids

A. S. Trevisan, A. Mendonça, R. Gagnon, M. Fecteau, J. Mahseredjian

***Abstract* - Recently, field events involving adverse interactions between grid-connected inverters (GCIs) and existing power system infrastructures have been reported. Differently than conventional synchronous generating units, GCIs have a wider control bandwidth. Consequently, dynamic interactions among such units and the grid may cause oscillations in wide frequency ranges, revealing, thus, the need for detailed EMT-type models. Screening out potentially critical scenarios in EMT-type large-scale grids is non-trivial and, typically, resource demanding. This works outlines a methodology, namely, the DQ-Scanning technique, which aims at efficiently identifying critical scenarios for new interconnections. The technique is based on the extraction of input admittances and impedances for GCIs and grids, as seen from their point-of-connection, in the *dq*-frame. It is shown how the resulting admittances and impedances can be used to assess the interconnection stability. The effectiveness of the methodology is demonstrated for the interconnection of a new wind farm to a realistic multi-converter large-scale grid and validated by detailed simulations in EMTP.**

***Keywords:* Wind turbines, stability, SSR, SSCI, interaction.**

I. Introduction

THE ever increasing integration of grid-connected inverters (GCIs), mostly resulting from the large-scale integration of wind and solar plants, and integration of high-voltage direct current (HVDC) transmission systems, is posing new challenges to the study and operation of power systems. Although GCIs are capable of providing advanced grid services, recent events have been reported indicating the possibility of these devices interacting adversely with the grid [1]–[6].

GCIs are known to have a wider control bandwidth if compared, for instance, to conventional generating units. For this reason, dynamic interactions can take place in a wider frequency range. Consequently, electromagnetic transient (EMT) type studies are also becoming a necessity for the further integration of GCIs [7], [8].

A. S. Trevisan is with the Dpt. of Electrical Engineering, Polytechnique Montreal, QC H3T 1J4, Canada and with WRD GmbH (ENERCON R&D) in Aurich, D-26607, Germany (e-mail: aramis.schwanka.trevisan@enercon.de).
A. Mendonça is with WRD GmbH (ENERCON R&D) in Aurich, D-26607, Germany (e-mail: angelo.mendonca@enercon.de).
R. Gagnon is with the Hydro-Quebec Research Institute (IREQ), Varennes, QC J3X 1S1, Canada (email: gagnon.richard@ireq.ca).
M. Fecteau is with the System Studies, Hydro-Québec TransEnergie, Montreal QC H5B 1H7, Canada (e-mail: fecteau.martin@hydro.qc.ca).
J. Mahseredjian is with Polytechnique Montreal, QC H3T 1J4, Canada (e-mail: jean.mahseredjian@polymtl.ca).

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Nevertheless, consideration of large-scale multi-converter system in conjunction with all possible operation scenarios imposed by the intermittency of renewable generation and contingencies leads to a huge computational effort to address all cases [9]. There is an increasing need, therefore, for more efficient screening techniques capable of quickly identifying potentially critical scenarios, which are then verified by detailed EMT simulation. Recently, dedicated working groups and tasks forces, which are characterized by strong industry representation, were created to address this need [10], [11].

Modal analysis applied to linearized system state-space representations has long been regarded as a powerful technique for addressing power system stability, notably with regards to low-frequency phenomena [12]–[17]. It has the advantage of providing good insight into system dynamics through eigenvalue analysis and their respective frequency and damping characteristics. On the other hand, the widespread use of modal analysis in industrial applications is hindered by its intrinsic requirement for rigorously analytical development and linearization of system equations, which is not always possible. For instance, black-box (i.e., protected) models of GCI equipment are typically used in interconnection studies due to intellectual property concerns.

Due to these reasons, recently, the impedance-based stability assessment has gained ground in industry applications. It was originally proposed for the study of dc regulators in [18], but has been extended to address three-phase ac systems [19]–[26]. Contrary to the classical modal analysis, the impedance-based stability assessment is not necessarily based on the development of analytical equations, since adequate frequency scanning techniques, or measurements, can be used to extract the frequency dependent impedance characteristics of devices.

Recent works have demonstrated, however, that the presence of GCIs yields the need for a multivariable framework for impedance representation in order to capture couplings, which usually result from asymmetrical control structures, such as the phase-locked loop (PLL) [25], [27]. Additionally, it has been demonstrated in [28] that the consideration of realistic GCIs and grid equipment requires as well care in the application of techniques to extract input impedance frequency dependent characteristics.

The approach proposed in [28] indicates that, for low frequency applications, variations in the amplitude and type of perturbations applied can help extracting input admittances and impedances of GCIs and grids. Its effectiveness has been demonstrated for a realistic wind farm connected to a radial series-compensated grid.

This work, however, aims at verifying the feasibility and efficacy of the approach proposed in [28], namely, the DQ-Scanning technique, in the context of large-scale grids. For this, the large-scale EMT-type benchmark grid published as “SSCI Benchmark-I” in [29] is used. It is noted that this grid is inspired by an actual system and contains realistic topology, components, and parameters.

More specifically, the stability of a wind farm interconnection is investigated. By varying the assumed wind speed, it is demonstrated that operating dependent characteristics of wind farms are important for stability assessment and should be considered in interconnection studies.

This paper is structured as follows. In Section II, a large-scale investigation benchmark grid is introduced. In Section III, a review of stability assessment techniques is provided and a recently published technique [28] is outlined to assess the small-signal stability of power systems in the *dq*-frame. In Section IV, the technique is applied to investigate the stability of the interconnection of a new wind farm to a large scale grid.

II. Multi-converter Grid

Investigations in this work are carried out in the SSCI-Benchmark I, which was published in [29]. It is a large-scale generic EMT-type grid, however it is emphasized that its structure, components, and parameters are inspired by an actual system. The EMTP detailed model representation of the benchmark is given in Fig. 1.

(indicated by green rectangles in Fig. 1). The main upstream grid is a 315 kV grid and is connected to the rest of the system through three series compensated transmission lines.

Additionally, it is important to highlight that the SSCI-Benchmark I is a multi-converter system. It contains 5 wind power plants (WPPs) connected at different parts of the grid (indicated by blue circles in Fig. 1). Additionally, a back-to-back HVDC system is also considered (red box in Fig. 1).

To support voltage, two synchronous condensers are as well taken into account. One of them is connected close to the HVDC terminals and the other close to the far end of the grid, where grid strength is compromised.

Finally, it is emphasized that all transmission lines are modelled with distributed constant parameters and transformers as well as surge arresters havfe their nonlinear characteristics included. Further details can be extracted from [29].

III. Stability Assessment in Large-scale Grids

The complexity and multi-converter nature of nowadays grids are yielding the need for effective stability assessment techniques capable of screening out potentially critical scenarios in new interconnection projects.

Additionally, as highlighted in Section I, the use of black-box models hinders significantly the application of analytical linear control theory, for instance, modal analysis. So, any proposed methodology to address stability of modern power systems should as well cope with this fundamental constraint.

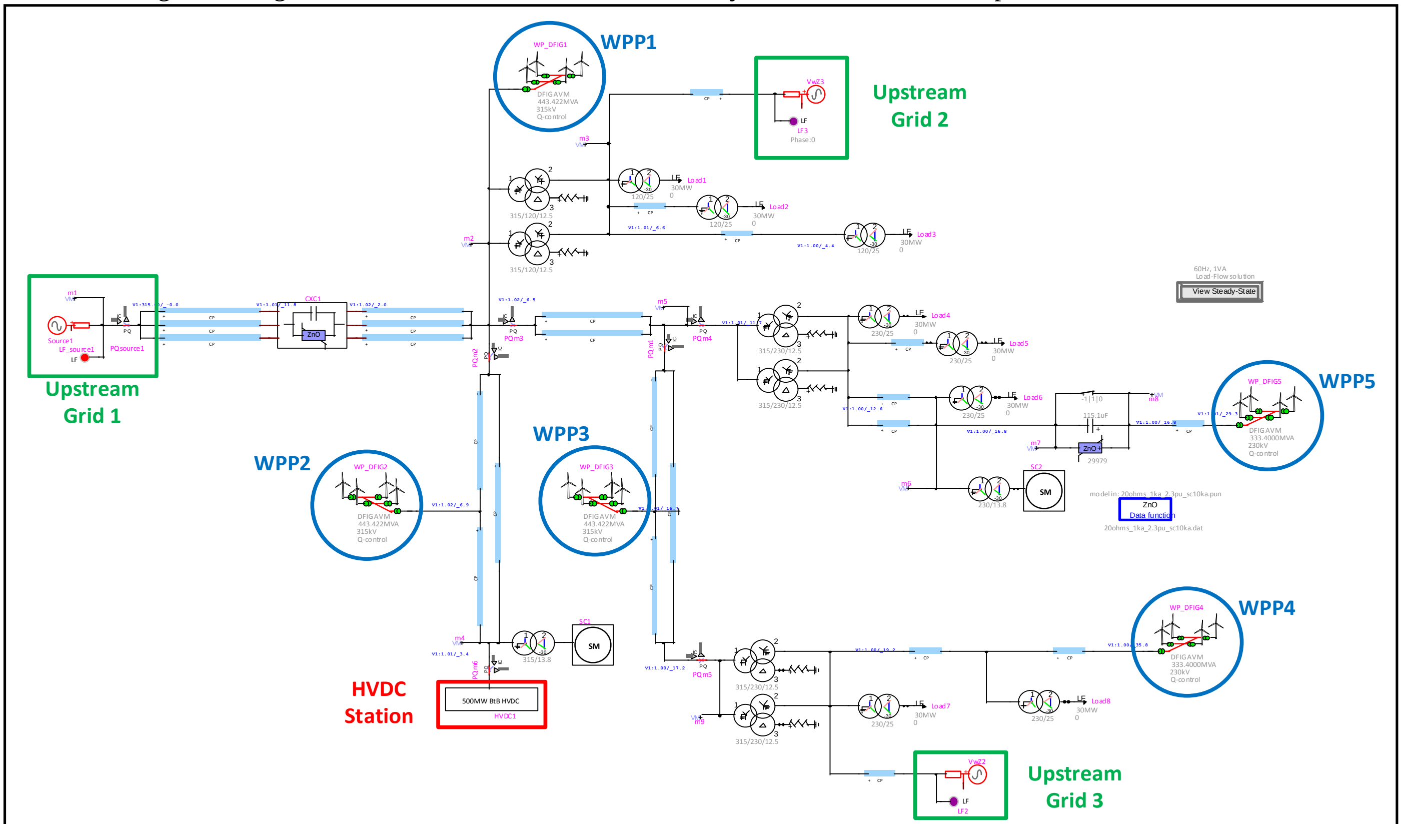

Fig. 1. EMTP Model of SSCI-Benchmark I [29].

The SSCI-Benchmark I model represents a large grid portion of a system that is connected to three other upstream grids, which are represented by their Thevenin equivalents

In an attempt to address this urgent power industry need, several screening techniques have been proposed in recent years aiming at the identification of interaction risks of new interconnections in the frequency domain. Notably, the methodologies outlined in [21], [22], [26] offer a framework for the small-signal stability assessment based on the impedance-based theory applied to positive sequence impedance (or admittance) representations of grid and grid-connected inverters (GCIs). Recent work [28] has demonstrated the advantages of DQ-Scanning. This method will be used in this work to investigate small-signal stability of the benchmark system of Fig. 1.

A. The DQ-Scanning Technique

The technique published in [28] (DQ-Scanning) is briefly recalled here for convenience. First, it is highlighted that the method does not differentiate between small and large-scale networks. It is based a two-port input impedance and admittance representations for grid and GCIs, respectively, no matter their size or complexity. This avoids, among others, the need for estimating the number of states of an investigated system for matrix-fitting algorithms, which is not always possible, as in case of black-box models.

The DQ-Scanning technique deals with the input impedances and admittances of grid and GCIs directly in the *dq*-frame. Its effectiveness in properly extracting the right input admittances has been demonstrated for field validated EMT-type type-III and type-IV wind turbine models and their rigorously developed analytical representations in [28].

Initially, a partition point of the complete system under investigation is chosen. In practical cases, the point-of-common-coupling (PCC) of new interconnection projects is a natural choice for partition. The system is then divided into two subsystems, the grid and the new to be connected GCIs, for instance, a wind farm consisting of several wind turbines. This is illustrated in Fig. 2.

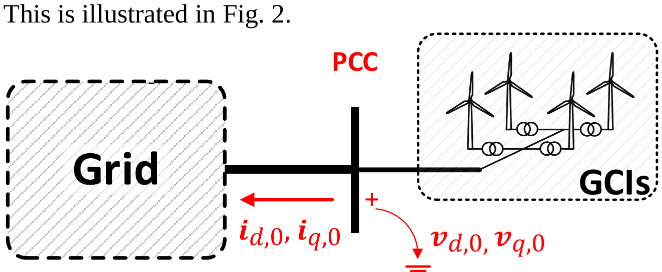

Fig. 2 System partition for the DQ-Scanning technique.

In the DQ-Scanning methodology, small-signal stability is assessed for a chosen operating condition. In practical cases, input admittance of GCIs should be extracted at least for their rated operating conditions. In case of wind farms, as illustrated in Fig. 2, this is done by assuming nominal wind speed at the turbines. Moreover, it is strongly suggested that other operating points be taken into account as well, since, as it will be demonstrated in this work, small-signal input admittances may considerably differ from one condition to another and affect system stability accordingly.

For the chosen operating points, a time-domain steady-state condition is firstly obtained in an EMT-simulation considering the detailed model representations of grid and GCIs. In this simulation, the PCC voltages and currents flowing into the grid should be monitored. The *dq*-transformed values of the steady-state currents and voltages at the PCC are then stored.

To assess the input impedances of the grid, a separate simulation is performed. In this step, only the grid as seen from the partition point, i.e., the PCC, is considered. Controlled current sources are used to inject *dq*-transformed currents. The $i_{d,0}$ and $i_{q,0}$ values extracted from the steady-state are used and single-tone perturbations are added on top of their values as outlined in [28]. This is shown in Fig. 3.

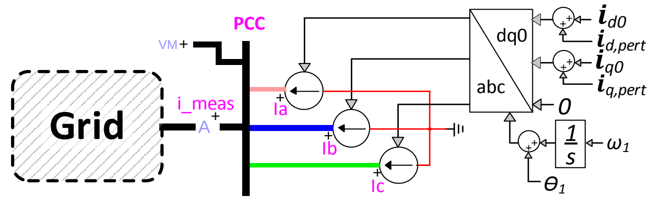

Fig. 3 DQ-Scanning of grid input *dq*-impedances.

In the case of GCIs, the DQ-Scanning is modified to assess the input *dq*-admittances. For this controlled voltage sources are used instead of current sources. The steady-state *dq*-values of the voltages at the PCC are applied and small-signal perturbations are introduced separately in the *dq*-channels. This is illustrated in Fig. 4.

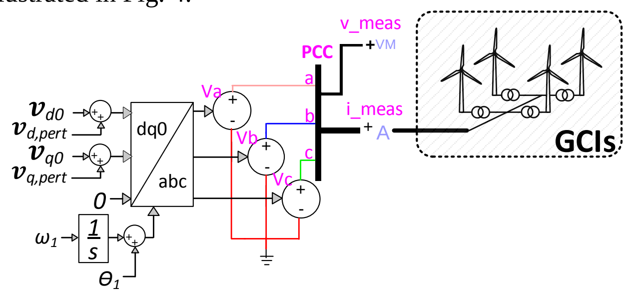

Fig. 4 DQ-Scanning of input *dq*-admittances of GCIs.

During the application of small-signal perturbations in both grid and GCIs, as illustrated in Fig. 3 and Fig. 4, respectively, the PCC voltages and currents are monitored. For each perturbation frequency f_i, a discrete Fourier transform (DFT) is used to extract the corresponding values for the measured $v_d(f_i)$, $v_q(f_i)$, $i_d(f_i)$ and $i_q(f_i)$. Then, the input impedances are calculated as given in

$$\begin{aligned} Z_{dd}(f_i) &= v_d^d(f_i)/i_d^d(f_i) \quad & Z_{dq}(f_i) &= v_d^q(f_i)/i_q^q(f_i) \\ Z_{qd}(f_i) &= v_q^d(f_i)/i_d^d(f_i) \quad & Z_{qq}(f_i) &= v_q^q(f_i)/i_q^q(f_i) \end{aligned} \tag{III.1}$$

and the input admittances as shown in

$$\begin{aligned} Y_{dd}(f_i) &= i_d^d(f_i)/v_d^d(f_i) \quad & Y_{dq}(f_i) &= i_d^q(f_i)/v_q^q(f_i) \\ Y_{qd}(f_i) &= i_q^d(f_i)/v_d^d(f_i) \quad & Y_{qq}(f_i) &= i_q^q(f_i)/v_q^q(f_i) \end{aligned} \tag{III.2}$$

respectively, where superscripts *d* and *q* indicate which of the *d*- or *q*-axes were perturbed for the evaluation.

It is noted that the application of the DQ-Scanning technique to the grid and GCIs subsystems, as seen from their PCC, results in numerical complex-valued 2x2 matrices for each assessed perturbation frequency f_i.

To address the small-signal stability of the interconnection for the evaluated operating condition, the impedance based stability assessment (IBSA) theory is applied and a source-load representation is obtained [30], however in the *dq*-frame.

For stability assessment, it suffices to understand the connection of grid and the GCIs as a closed-loop system. Based on this, it is straightforward to demonstrate that the circuit equations resulting from the source-load representation of the interconnection [30] can be rearranged to allow the block-diagram representation illustrated in Fig. 5.

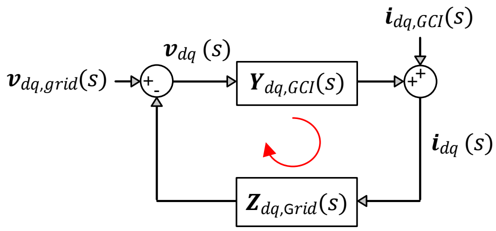

Fig. 5 Block-diagram representation of IBSA in dq-frame.

With the typical closed-loop linear control structure a possible to assess the small-signal stability. For this, the Generalized Nyquist Stability Criterion (GNC) is used. The GNC is applied to the system return ratio $\boldsymbol{L}(s)$, which is defined as:

$$\boldsymbol{L}(s) = \boldsymbol{Z}_{dq,grid}(s)\boldsymbol{Y}_{dq,GCI}(s) \qquad \text{(III.3)}$$

As outlined in [28], if the application of the DQ-Scanning technique with its intrinsic small-signal perturbation was possible, i.e., did not trigger any instabilities in the investigated systems, then it can be assumed that both systems $\boldsymbol{Z}_{dq,Grid}(s)$ and $\boldsymbol{Y}_{dq,GCI}(s)$, corresponding to the *dq*-input impedances and admittances of grid and GCIs, respectively, are open-loop stable and, thus, do not contain right-half plane (RHP) poles. In such case, it can be stated that the closed-loop system shown in Fig. 5 is stable if and only if the Nyquist contour resulting from the characteristic loci of $\boldsymbol{L}(s)$ does not encircle the critical point in the counter-clockwise direction.

IV. DQ-Scanning Applied to Large-Scale Grid

In this section the DQ-Scanning technique outlined in Section III is applied to a multi-converter large-scale grid with the aim of verifying its effectiveness under such circumstances.

For this, the large-scale grid introduced in Section II shall be used. It is assumed that the interconnection of wind farm WPP5 (see Fig. 1) is under consideration. A zoom in the grid area of WPP5 is illustrated in Fig. 6, from which it can be seen that series compensation and a synchronous condenser are connected in the vicinity of the PCC.

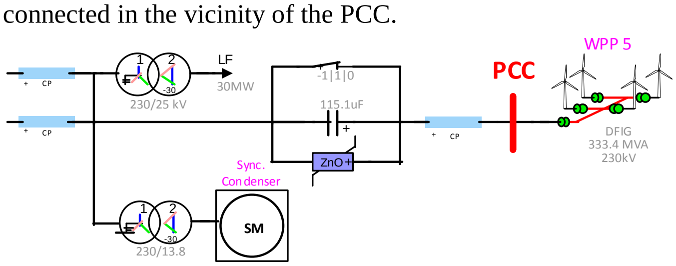

Fig. 6 Zoom in the area of WPP5 (named WP_DFIG5 in the EMTP model).

At this point, it is emphasized that input admittances may considerably change depending on the operating conditions, and, in the context of large-scale networks, these may be many. It is therefore suggested that, besides the rated operating condition, input admittances of GCIs be as well investigated for different operating conditions to better understand how sensitive these changes are and how they may impact stability. In practical cases, a good trade-off between resources for such analysis and acceptable risks should be found.

For the integration of WPP5 in this work, two operating conditions are considered, namely a first case in which nominal wind speed (11.24 m/s) is assumed for all wind turbines and, thus, the wind farm WPP5 injects nominal power, and a second case for which the wind speed is reduced to 8 m/s.

Reason for the consideration of two distinct operation conditions is the fact that GCIs may present different input admittance characteristics depending on its condition. This should be taken into account by considering the two very different wind speeds. It is reminded here that the power extracted from the wind is proportional to the cube of the wind speed [31], thus, although the wind speed is reduced by “only” 3 m/s in the second case, it is expected that the injected power is reduced by more than 50 % of the nominal power.

It is noted at this point that one of the advantages of the DQ-Scanning technique is that its application can be assigned to different stakeholders of an interconnection project. For instance, the extraction of the grid input *dq*-impedances can remain in the responsibility of the concerned system operator, whereas the extraction of the GCIs input *dq*-admittances can be assigned to the manufacturer of the GCIs or project developers. It is expected that the exchange of the DQ-Scanning results is less affected by intellectual property concerns if compared with the exchange of detailed models between project stakeholders and, thus, its application in practical projects may allow stability assessment in very early project stages.

By means of the DQ-Scanning, input *dq*-admittances of the wind farm WPP5 were assessed for the frequency region ranging from 1 to 100 Hz, in steps of 1 Hz. Their resulting magnitude and phase are shown for the two operating conditions in Fig. 7 and Fig. 8.

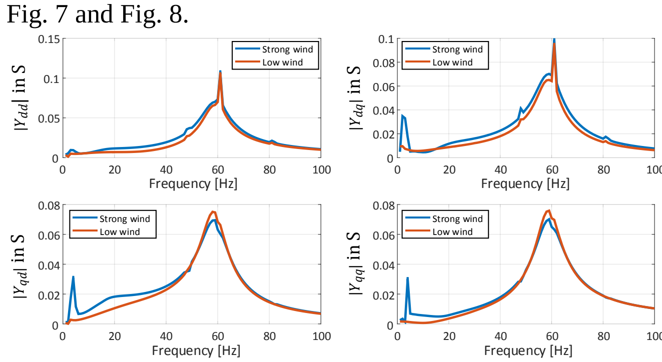

Fig. 7 Amplitude of WPP5 input *dq*-admittances for strong and low wind.

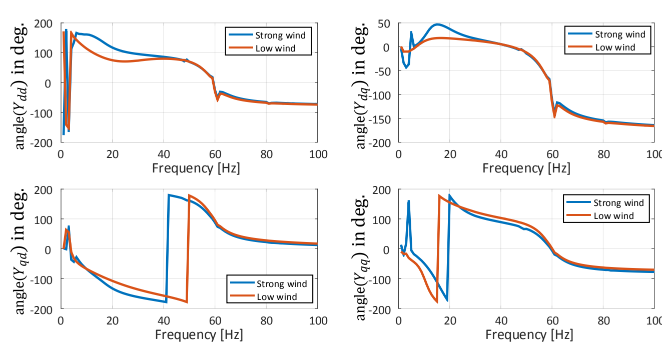

Fig. 8 Phase of WPP5 input *dq*-admittances for strong and low wind.

It can be seen from Fig. 7 and Fig. 8 that the consideration of different operating conditions (i.e., wind speeds) for wind farm WPP5 results in different input *dq*-admittances. These results corroborate, therefore, the importance of assessing the input admittances of wind farms for more than just their rated operating condition during integrations studies.

It is emphasized here that grid input impedances should be assessed for the same wind conditions. It is highlighted that, in case of large-networks, varying injection levels of wind farms may yield the need for adapting, for instance, the import/export level of HVDC interconnectors or for adjusting voltage setpoints for synchronous condensers, which could considerably affect input impedances as seen from the PCC.

Moreover, the consideration of different grid topologies that may result from different operating conditions or contingencies should as well not be neglected, as these could affect the grid input impedances seen from the PCC in a similar manner.

At this point, however, it is emphasized that, although various parametric analysis are feasible in the context of the DQ-Scanning technique on the grid-side, these were disregarded in this work. Additionally, it has been subsequently observed that, for the particular scenarios addressed, the grid input impedances did not vary significantly for the different wind conditions and, thus, only the input impedances for the rated power injection of the wind farm are considered in the interest of simplicity. Their magnitude and phase are illustrated in Fig. 9 and Fig. 10.

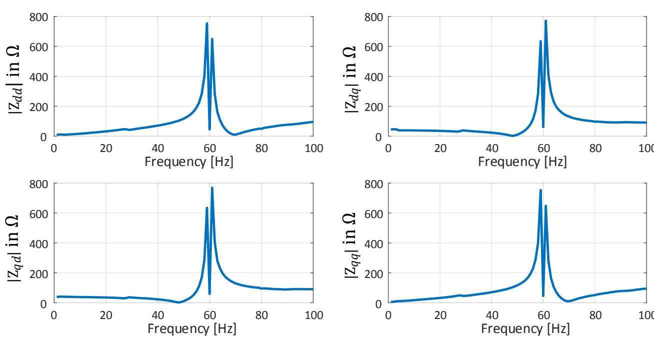

Fig. 9 Amplitude of grid input *dq*-impedances.

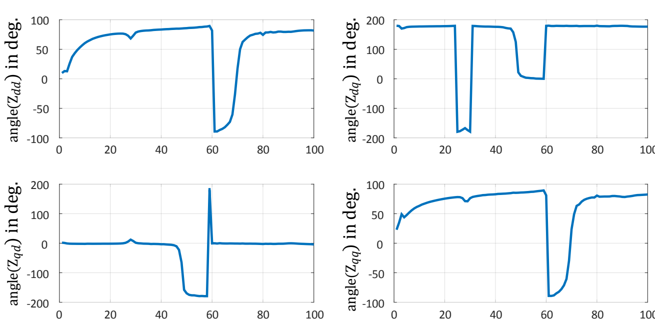
Fig. 10 Phase of grid input *dq*-impedances.

Finally, the GNC contours were plotted for the investigated scenarios using the input *dq*-impedances and *dq*-admittances obtained through the DQ-Scanning application for the wind farm and the grid as seen from their PCC. Fig. 11 and Fig. 12 show the Nyquist contours for the cases of strong and low wind conditions, respectively.

As seen in Fig. 11, in the case of nominal wind speed conditions at wind farm WPP5, the resulting GNC does not encircle the critical point (-1,0) and thus indicates that, for this operating condition, no small-signal stabilities are to be expected.

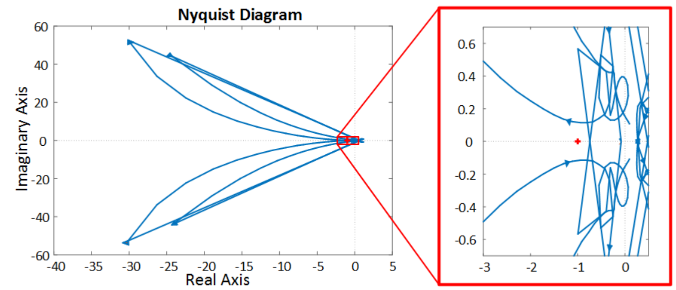

Fig. 11 GNC for the case of strong wind.

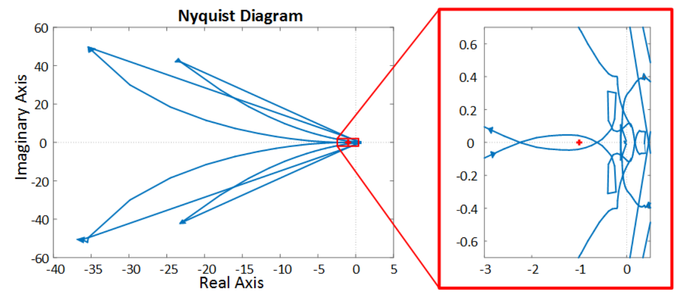

Fig. 12 GNC for the case of low wind.

Differently than for the case of nominal wind speed at wind farm WPP5, it can be observed in Fig. 12 that the consideration of a new operating condition with low speed for WPP5 results in a Nyquist contour that encircles the critical point, thus, indicating a potentially critical condition.

To verify these results, simulations were conducted with the detailed model representations in EMTP [32]. The system was initialized for nominal wind speed, which is expected to be stable (see Nyquist plot in Fig. 11) and, then, the wind speed was reduced to 8 m/s. The simulation results are shown in Fig. 13, in which the positive sequence voltage and the active and reactive powers measured at the PCC are illustrated.

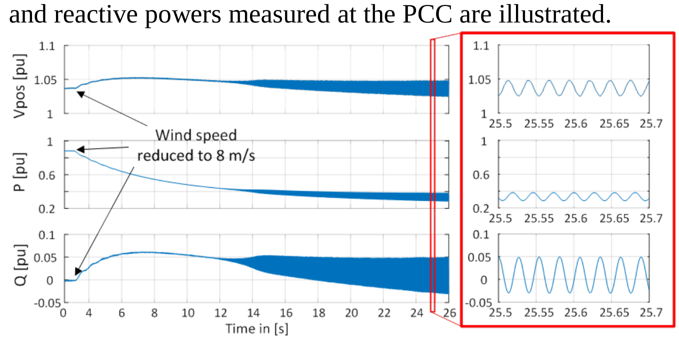

Fig. 13 Detailed simulation results conducted in EMTP.

It can be seen in Fig. 13 that the system was able to achieve a stable operating condition for the nominal wind speed. All three measured quantities are initially stable. However, when the wind speed is reduced, it can be observed that a low frequency oscillation of approximately 38 Hz builds-up and the system becomes unstable.

It is noted that these results corroborate those predictions obtained through the GNC analysis, which indicated instabilities for low wind speeds, and, thus, indicate that the DQ-Scanning method can be successfully applied to large-scale networks in the presence of several GCIs.

V. Conclusions

This work deals with the small-signal stability of multi-converter large-scale power systems and addresses the ever increasing need of the industry for effectively assessing potentially critical scenarios during interconnection projects.

It outlines a recently published technique, namely, the DQ-Scanning technique, which aims at extracting the input *dq*-impedances and admittances of grid and grid-connected inverters as seen from their PCC. It is also demonstrated how small-signal stability can then be assessed based on the resulting matrices by means of the Generalized Nyquist Criterion.

The effectiveness of the methodology is demonstrated and verified for the case of a new wind farm interconnection into a large-scale grid. For this, a realistic multi-converter benchmark grid containing detailed representation of other four wind farms as well as one HVDC interconnector is used.

It is shown that input small-signal characteristics of grid-connected inverters may significantly vary for different operating conditions and qualitatively impact stability assessment. This is verified by assessing the stability of the new wind farm interconnection under two different wind speeds. It is demonstrated that the system is stable when nominal wind speed is considered, whereas instabilities are seen whenever the wind speed is reduced to a certain level.

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