BorWin1 – First Experiences with harmonic interactions in converter dominated grids

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Abstract

During the year 2013 the power infeed from offshore wind turbines increased. As BorWin1 is the first HVDC system which connects an offshore wind farm by a small islanded offshore AC grid some phenomena occur. The frequency dependent grid impedance is due to the used assets significantly different from onshore grids. Thus, common methods of investigation during the planning phase are not sufficient and have to be extended. Converters can go into resonance with grid natural frequencies of the grid and oscillations with high frequencies can arise. The paper presents some occurred phenomena and new methods of investigation. Different methods to identify harmonic stability problems are compared and advantages as well as disadvantages are mentioned.

1 Introduction

BorWin1 is the second grid connection system (GCS) of TenneT TSO GmbH which connects an offshore wind farm (OWF) to the onshore grid. However, it is the first project realised using DC technology to connect the OWF Bard Offshore 1. The project name BorWin1 (**Figure 1**) is based on the wind farm cluster of Borkum Island. TenneT installed an offshore converter station named BorWin alpha for transferring wind energy from sea to land. The electricity produced by the wind farm is converted from alternate current (AC) to direct current (DC) by BorWin alpha and is transmitted by a high voltage direct current (HVDC) subsea and land cable to the next grid connection point - a land-side converter station in Diele. At the land-side converter station the DC power is converted back to AC before feeding to the grid.
Since the beginning of December 2010 - with the completion of the first wind turbines of the wind farm BARD Offshore 1 - BorWin1 is feeding green energy into the grid.

Figure 1 Geographical position of BorWin1

As this is worldwide the first connection of an offshore wind farm to the onshore grid by a HVDC connection (in this dimension, for transmitting 400 MW), a new phenomenon occurred. This led to an outage of the HVDC-system and the knowledge gain from the analysis will result in new requirements in the offshore grid code.

2 Technical background

The connection of the offshore wind farm can be separated in a small islanded offshore AC-grid and the HVDC-system which connects the islanded grid to the European onshore grid (**Figure 2**).

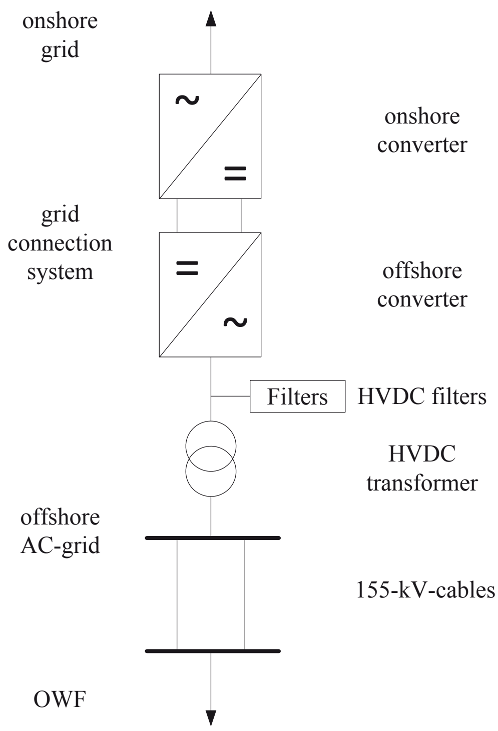

Figure 2 Schematic view of the main components of the grid connection system BorWin1

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Due to the separation of the offshore AC-grid from the onshore grid by the HVDC-system, the electrical behaviour of the offshore grid differs a lot from the onshore grid. It is obvious that all generation units and all big consumers are connected to the grid by power electronics. There is no rotating mass which establishes a physical binding of active power and frequency. The frequency is completely controlled by the offshore converter and can be ramped up or down independently from the infeed of the wind farm. This has disadvantages as damping of rotating machines is missing but has also advantages. For example the frequency can be fixed at a given frequency and the HVDC can control the infeed by the OWFs just by raising the frequency. However, this implicates that every control system of every generation unit is able to measure the correct frequency and reacts properly. As this is no physical relationship it has to be ensured that all controllers are working properly.

As power electronics can change operating points very fast, it is necessary to take a deeper look into the converter [8], [9]. Every converter has some controllers which act in general slow like the P and Q control. But controllers like the current control and partially the phased locked loop (PLL) are much faster and can have a bandwidth of several hundred hertz. Thus, converters are able to amplify oscillations which are in the system.

Furthermore, the whole connection system is optimized to have low losses. This is important as cooling equipment for offshore installations is expensive and of course operational costs should be kept low. In addition, resistive loads are missing, which could provide additional damping.

In the specific project BorWin1 a two level PWM converter is used. Thus, it is necessary to use a special filter which absorbs the switching frequency of the converter but is loss optimized to keep the above mentioned costs low.

2.1 Grid resonances

The first theoretical analysis of the phenomenon includes the calculation of frequency dependent impedances at different locations. In principle the calculation of resonances is well known. However, the determination of the exact frequency is very difficult because it is nearly impossible to get the needed input data from the manufacturers. But it is still possible to calculate the frequency dependent impedances with sufficient accuracy with the available data and standard models which are described in [1], [2].

If needed it is also possible to calculate the eigenvalues of the system to determine the nodes at which the system could be easily erected. During the first calculations it becomes clear that no analysis of the eigenvalues is needed because of the small size of the system. For example, the frequency dependent impedance of the filter is known and the calculated poles and zero crossings could be easily assigned to the different assets.

2.2 Steady State Harmonics

Steady state Harmonics are well known in the literature. As harmonics could cause damage to assets they have been analysed in power systems since several decades. However, tin the interconnected grid of continental Europe harmonic problems occur only rarely. As enough resistive loads are present, resonances are damped quite well and thus, the amplification factors for harmonics are low. This changes if overhead lines are substituted by cables. The much higher capacitance values lead to resonances with a much lower frequency and due to the lower losses of the cables they are less damped.

Extreme grids are the small islanded offshore grids which consist only of cables, converters and a few auxiliary systems. This leads to a frequency dependent impedance which is shown in the example in **Figure 3**.

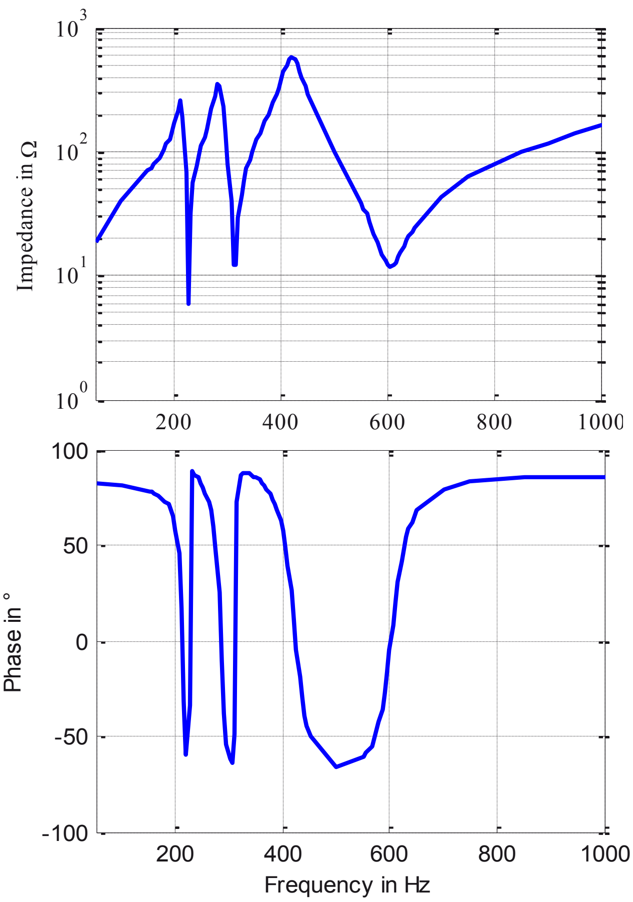

Figure 3 Example of grid impedance in an offshore grid

As it can be seen very easily, the poles and zero crossings could cause problems during the grid operation. As the exact frequency of the resonance is also determined by the switching configuration, it is possible that the resonance can be shifted in specific switching situations to a critical frequency. Most critical are frequencies like 250 Hz or 350 Hz (at fundamental frequency of 50 Hz), which corresponds to harmonics which are present in the systems. If a zero point is shifted to such a frequency, a high current will flow (due to the less damping) and the voltage will get heavily distorted in most cases due to the voltage drop of this current. An example of a measured current is given in **Figure 4**.

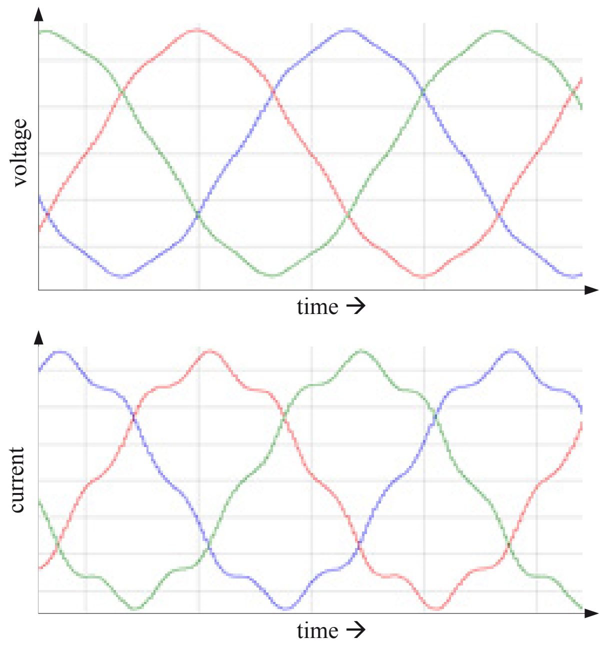

Figure 4 Measurement of a distorted voltage and current

However, in the special situation of the offshore grids of TenneT, the distorted voltage can be low while there is a high distorted current in the system. As harmonics in the current cause additional losses for example in transformers they have also be taken into account during the analysis. State of the art is taking only a look at harmonic voltages but measurements clarifies that this is not sufficient.

2.3 Harmonic Stability

In the power electronic industry it is known that converters could have problems with grid resonances. However, these problems where unknown during the planning phase of the projects BorWin1/Bard Offshore 1 in the power supply industry. Therefore, stability problems due to interactions of converters were not considered.
As it is written for example in [5], converters could go into resonance with the grid if the grid impedance exceeds the input impedance of the converter. If this happens and the phase margin is too small, the system could oscillate with this frequency. This could happen due to several controllers which are present in power electronic converters, but are missing in conventional synchronous generators (**Figure 5**). In the frequency ranges of different harmonic phenomena (valid for the operation of wind power plants) are shown [6].
Of special interest are the PLL and the current control which are active at several hundred hertz, and therefore could get into resonance with the grid.
For analysing the special situation in the offshore grid, a more detailed view at the different converters is necessary.

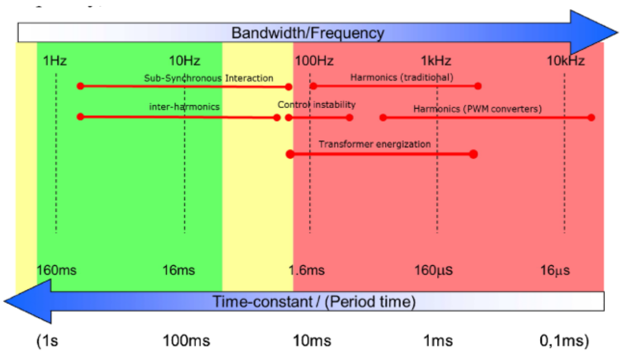

Figure 5 Frequency range of different harmonic phenomena [6]

3 Methods of Investigations

For investigating harmonic problems different approaches are possible. As the root cause of stationary harmonics and harmonic instabilities is different, the methods of investigations differ. As well as the used method is different, other input data is needed.

3.1 Steady state Harmonics

Steady state harmonics in wind farms are analysed in conventional power systems most by using IEC 61400. However, this method has some inaccuracies. By performing this analysis according to the IEC standard it is assumed that grid impedances are similar. From generation units like wind turbines harmonic currents are measured during the certification process. As DFIG- and full converter-wind turbines are voltage sources and not current sources, the harmonic current depends also on the grid impedance. As the impedance is not measured, this method can only be used if grid impedances are similar. Grid impedances in the TenneT offshore grids are significantly different from nearly every onshore grid impedance. Thus, this method is not suitable to analyse stationary harmonics. Additionally, the input impedance is mostly neglected. This leads to very high harmonic voltages if the grid impedance has a pole at a frequency where the generation unit produces a high harmonic current. Otherwise, if the grid impedance has a zero point, the current is not as high as in reality and possible problems are not detected.
If the input impedance of for example wind turbines is taken into account, additional damping is present in the grid and the calculated results are more related to reality.
Thus, reasonable results are only calculated if generation units are modelled as harmonic voltage sources and not as current sources and the input impedance is considered.
Another possibility is to perform an EMT-simulation. However, this method takes a lot of time as the simulation time step has to be very low to get every harmonic source which results of the PWM of the converters. Unfortunately, the generation of harmonics changes with the operating point. Hence, several simulations with different operating points have to be performed.
To combine the benefits of both simulation methods new approaches like the harmonic domain are under research.

3.2 Harmonic Stability

To make sure that harmonic stability problems won't occur in further offshore projects, a new stability criterion is under development [7]. It is based on the Nyquist criterion and does not need all details of the control code as input parameter. The control code is the intellectual property of the manufacturers and it is difficult to get detailed knowledge about it. Therefore, only the frequency dependent impedances of the converters are needed. In difference to the conventional frequency dependent impedance, the control code has to be considered. Thus, the impedance is not only based on passive elements [5].

During the planning phase of a new HVDC system and OWF, both impedances will be calculated and analysed. If a resonance problem is expected to occur possible countermeasures could be applied before hardware is built.

Other methods to analyse the stability like the calculation of eigenvalues are considered as well. However, this method needs very detailed data of the control codes which is possibly not available at this planning phase neither wants the manufacturer disclose his intellectual property. Therefore, the Nyquist based stability criterion seems to be a constructive criterion to achieve a stable grid operation.

3.2.1 Eigenvalue Analysis

An eigenvalue analysis is a well-known method to determine possible oscillations in a power system and to identify the assets which are part of a resonance. However, it is very difficult to consider the frequency dependence of assets. Of course it is necessary to include converters into the analysis. Therefore, detailed knowledge about the controls of converters is necessary. As this is the intellectual property of the manufacturers, it is very difficult to get this detailed information. At last, the implementation of converters into an eigenvalue analysis is part of current research at universities.

3.2.2 Electro-Magnetic-Transient-Simulation

Performing an electro-magnetic transient simulation (EMT-simulation) can always deliver best results if the used models are in a sufficient level of detail. Depending on the source of emission of voltages and/or currents at higher frequencies it can be necessary to use a model which has the PWM-generation included. Hence, a very small simulation time step has to be used.

To identify possible harmonic instabilities in a grid it is necessary that all fast controllers like the PLL and current control are modelled in detail including all time constants. Depending of the frequency range which should be analysed it can be necessary to model the much faster controls like the IGBT firing control as well (**Figure 6**).

All passive elements of the grid should be modeled with its frequency dependent equivalent circuit. As the damping increases a lot with frequency it can be the difference between a stable and non-stable system.

However, performing an EMT-simulation to identify harmonic instabilities needs experience in EMT-tools and detailed knowledge of converter controls. Slight deviations between model and reality are sufficient to falsify the results.

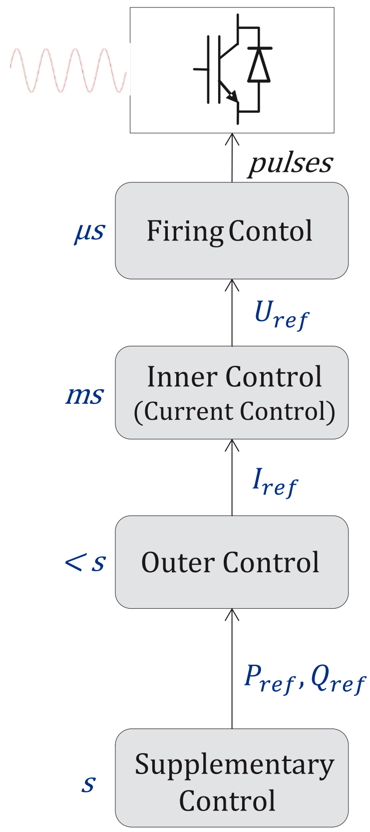

Figure 6 Different controllers within a converter

Additionally, the duration of one simulation can be very time consuming, especially if the PWM-generation has to be considered. As one simulation run usually covers one operating point, lots of runs have to be performed to cover all significant operating points and switching situations. Due to the performance increase of personal computers in the last years it can be possible to perform such a simulation but it will still take a lot of time.

Especially if a new switching status has to be analysed in short time as it is common in a grid operating centre, this method is not adequate.

3.2.3 Stability Criterion

In contrast to the mentioned methods a simple stability criterion is more suitable. It must be able to analyse a big system in short time to evaluate if a new switching status is possible. To achieve this, input data has to be aggregated that not every single controller of hundreds of converters has to be simulated.

A good method to evaluate the stability of a system is the nyquist criterion. It provides information about the gain and phase margin and thus, it is possible to estimate how far the system is away from the stability limit. Furthermore, the manufacturers don't have to provide detailed data which affects their intellectual property as they only have to provide a frequency dependent impedance of their generation unit. This impedance must include all passive

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elements as well as the change of impedance due to active controls.

Stability problems occur if engineers only take a look at their equipment or don't have sufficient data in detail to analyse the whole system. This can be explained on a simple example. In a very simple grid, consisting of a source and a load, both elements are stable if they are not connected to each other. However, if they get connected, the system can get instable as they influence each other (**Figure 7**) [7].

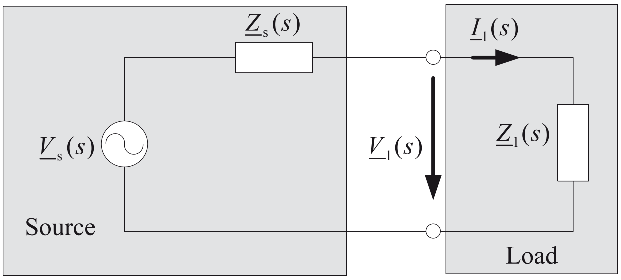

Figure 7 Simple grid, consisting of source and load

If the current I_l is calculated, it is clear that it depends on the frequency dependent impedance of the source as well as on the frequency dependent impedance of the load.

$$I_l = \frac{V_s(s)}{Z_s(s) + Z_l(s)} = \frac{V_s(s)}{Z_l(s)} \frac{1}{1 + \frac{Z_s(s)}{Z_l(s)}} \qquad (1)$$

This expression can also be displayed as loop gain. Thus, it becomes clearer that the system is stable if the source has a zero and the load an infinite output impedance. For stability the expression $|Z_s(s)/Z_l(s)|$ has at least to be below 1 for all frequencies (**Figure 8**). If the Nyquist criterion is met, this is a necessary and sufficient condition for a stable system operation.

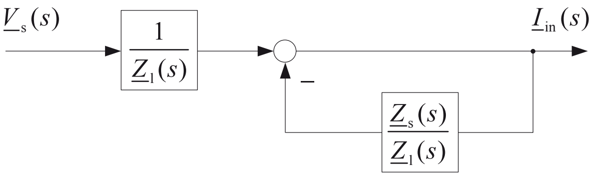

Figure 8 Loop gain of the simple grid

A system can be analysed if the frequency dependent impedance of the load and source are known. On the first view it seems to be very easy to define what elements are parts of, for example, a generation unit. But if a real grid is considered it can be discussed of the transformer between generator and grid is part of the generation unit or the grid. As the best point of division is still under investigation, the line of property is used for the intersection. Hence, an impedance curve of the generation unit and grid is needed. A big advantage of this method of investigation is that the frequency dependent impedance can be calculated with an analytic model, calculated with an EMT-tool or measured at a real generation unit.

If both curves are plotted in a Bode diagram, each intersection of the curves can be critical. Therefore, the phase margin has to be calculated at each intersection. If it is below 30° the system can be instable.**Figure 9** illustrates the determination of the intersection of the curves and the phase margin. At the frequency where the curves of the amplitudes have an intersection, the phase margin will be calculated according to:

$$\phi_m = 180° - \Delta\phi) \qquad (2)$$

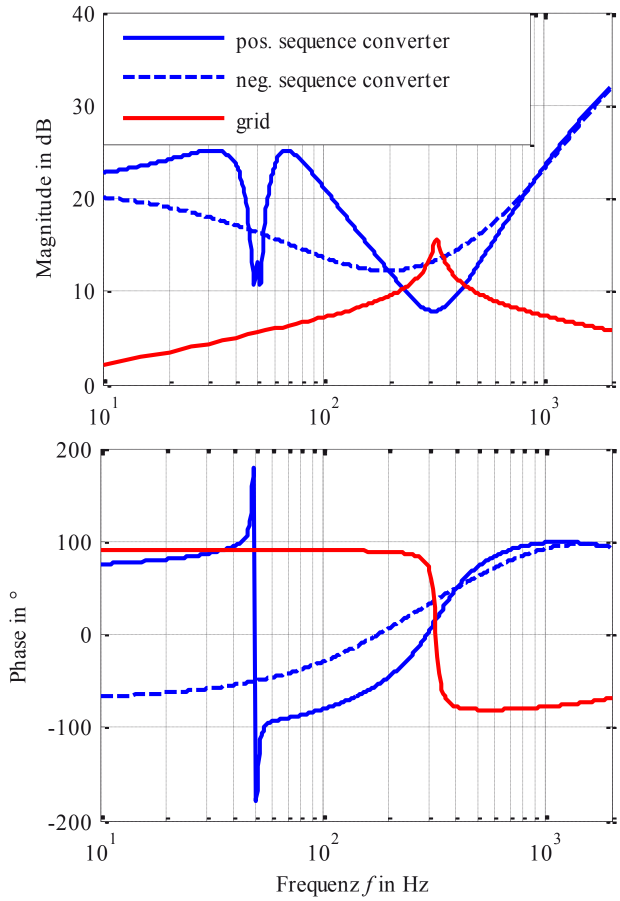

Figure 9 Bode diagram of the frequency dependent impedance of a generation unit and the grid

Additionally, the phase margin can also be determined in a Nyquist plot. As the information about the frequency is missing in this plot, it is more productive to use the Bode diagram.

Table 1 shows the determined phase margins at the intersection of the curves of the amplitudes. It clarifies that there shouldn't be any instabilities in the system. The lowest phase margin at an intersection in the positive sequence is still 41.9° at 435 Hz. However, only slight changes in the grid impedance are sufficient that this intersections causes in instable operating point.

	Frequency	Phase margin
positive sequence	230 Hz	58.9°
	435 Hz	42.9°
negative sequence	295 Hz	135.1°
	350 Hz	74.9°

Table 1 Phase margins at intersections

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4 Solution approach

Solution approaches for harmonic problems are very difficult. The best approach is to discover a possible problem during the design phase and modify appropriate equipment that resonance problems won't occur.

If the assets are already built, some options like the installation of additional assets are possible. If converters are present in the grid these elements can also be used to solve harmonic problems.

4.1 Passive Elements

The use of passive elements is theoretically always possible. Resistive elements are excellent to damp resonances and with additional inductances or capacitances the frequency of the resonances can be shifted. As nearly every resonance problem can be solved by installing additional equipment it has to be checked if the installation is practically possible.

Passive elements require lots of space and are expensive, especially for high voltage grids. In the offshore grids of TenneT space is very limited as every asset has to be placed on a platform. Furthermore, resistive damping of resonances causes additional losses which have to be cooled and are expensive over years. As already space requirements leads offshore to problems, additional cooling of equipment can also be impossible as the cooling system of an offshore platform is dimensioned to a specific value.

A big disadvantage of extra inductances and capacitances is that a new resonance is generated with every new element. Thus, it is complex to add these elements without creating resonance problems at other frequencies.

4.2 Active Damping

As it was stated in section 4.1 damping resonances with passive elements is practically not applicable, but there is the possibility of active damping. For this method a kind of a virtual resistor can be implemented in the converter control of a VSC-HVDC. The design and impedance value for this filtering has to be calculated with the knowledge of the current problems and specific grid configurations.

In general [4] it is possible to use active damping when reaching specific limits for harmonic magnitudes and harmonic ordinal numbers or over the whole spectrum. Mostly it is only needed for specific frequency ranges, but is more complicated to implement such a function. There is a risk of control interactions or neglecting possible critical frequency ranges which were not observed during the first problem occurrences.

Besides the above mentioned facts it is also useful for stationary harmonics in case of weak grids with a high amount of cables. For instance you could have low order harmonics which are less damped. To avoid problems active damping is also an opportunity, of course the negative impacts, e.g. as higher losses, have to be investigated.

However, without knowing the exact root cause and the way of interactions during resonance problems, it seems reasonable to use the advantages of the HVDC converters to damp resonances. Especially, in the AC offshore grids the HVDC converter has the same installed power as the generation units. As the most significant resonances are determined by the high voltage equipment, the HVDC has the best possibility to damp oscillations. Nevertheless it is also applicable to install similar damping functions in every single wind turbine converter, but as above mentioned the effort is much lower by using such a function in one big converter.

At last, it has to be kept in mind that this doesn't solve the root cause of the problem but reduces the symptoms.

4.3 Tuning of Controls

The silver bullet of solving resonance problems is tuning of controls, if possible. If converters with high power are present in the grid, they could be used to solve resonance problems. Tuning of controls can be performed with several approaches.

If converters are not able to feed in active power at high frequencies, they are not able to erect resonances. As every resonance has a natural damping, oscillations in a system would go away. To tune controllers a limit frequency has to be defined. This frequency has to be below grid resonance which can occur due to operating points or switching scenarios. However, any converter must not be able to feed in active power above this frequency. This criterion guaranties that oscillations, which occur due to grid resonances are not amplified by feeding in continuously active power at that frequencies.

As mentioned above, a system is stable when the Nyquist criterion is fulfilled for every frequency. From this follows that controllers can be tuned that the Nyquist criterion is fulfilled. However, the change of controller settings is limited to some general requirements, but it seems so be possible [10].

5 Conclusion

The paper illustrates that resonances are of mayor interest in converter dominated cable grids. Due to the used cables the capacity per km is very high and thus, the first resonances drops to only a few hundred hertz. As nearly no resistive damping is present poles in the impedance curve reaches very high values and zero points can get down to only a few ohm. Such distinct resonances support harmonic problems.

Because of the significantly different impedance characteristic even the analysis method for steady state harmonics are productive. In addition, converters can get instable due to grid resonance and oscillate at nearly every frequency. By performing an EMT-simulation with models of sufficient detail every resonance problem can be detected. However, an EMT-simulation takes a lot of time and effort. Thus, methods of investigations of stationary harmonic problems have to be developed further. Additionally, there is no method of investigation in standards for harmonic instabilities. Hence, a simple stability criterion was presented which will be improved in the future.

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