VSC HVDC active damping for the Sylwin 1 offshore wind power plants

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Abstract: SylWin1 is a VSC HVDC link connecting 864 MW offshore wind power generation to Germany’s high voltage network. This paper presents a harmonic performance analysis of the offshore network carried out during the design and commissioning phase with a focus on the distortions at the 155 kV and 33 kV offshore networks caused by the amplification of harmonics generated by the HVDC and wind turbine converters. Low frequency harmonic amplification problems are mitigated by introducing active damping in the HVDC converter controls in order to achieve a cost effective solution with the aim of reducing offshore harmonic current and voltage distortions. The analysis was carried out with the help of detailed frequency domain model offline simulations of the offshore network and on-site measurements.

1 Introduction

Many offshore wind power plants currently under operation and construction in Germany have considerable power rating and long HVDC transmission cables which allow the generated wind power to be transmitted for long distances.

Thanks to the HVDC transmission capacity the power generated by several wind power plants can be transmitted with conventional submarine HVAC cables to an HVDC offshore converter platform, which then transmits the power to the onshore grid through long HVDC submarine cables. The extensive use of several long HVAC and MV cables in the AC offshore network makes it prone to resonances with critical resonance frequencies. Furthermore, the possibility of a great number of steady state switching configurations combining different amount of connected HVAC and MV cables, power transformers and wind turbines causes the resonances to shift in a wide frequency range, adding complexity to the harmonic resonance phenomena in offshore networks.

This phenomenon can potentially cause problems when trying to comply with project specific harmonic distortion limits as well as with wind turbine and HVDC stable operation. The cause of the harmonic amplification problem is the very low damping in the resonances present in the wind power plants’ AC offshore network. The SylWin1 offshore network is above all a generation and transmission network which lacks the presence of important loading that could provide some damping. Lack of sufficient damping leads to very sharp resonance characteristics; this means that even small changes in the offshore grid switching configuration potentially have a significant impact on the harmonic performance. Previous work in [1–3] has presented important issues with respect to harmonics and resonances within wind power plants.

Previous work in [4] has presented a method to carry out harmonic studies for offshore wind power plants with emphasis on the modelling of the different harmonic sources and on how to handle the different contributions to the distortions in the offshore network. In this paper however only the harmonic amplification phenomenon is taken into account and analysed in detail. This paper discusses its causes and the approach taken in order to increase the damping at low order harmonic frequencies.

The paper presents and discusses the results for a real offshore wind power plant, using project specific data. The method used to illustrate the results (LOCI diagrams and frequency scans), is intended to simplify the problem description and facilitate the analysis. This is a practical paper offering an example of a novel practice for offshore wind power transmission through VSC HVDC converters as well as the first large application of active damping for offshore wind power transmission.

2 The Sylwin 1 wind power plants

The SylWin1 offshore converter is located approximately 70 km off the island of Sylt north of Germany and has a total installed transmission capacity of 864 MW. Three wind power plants, DanTysk, Butendiek and Sandbank, with a maximum generation of 288 MW each, connect to the SylWin alpha HVDC platform via 155 kV HVAC cables.

The wind turbines used in all three wind power plants (DanTysk, Butendiek and Sandbank) are based on an induction generator, which is connected to the grid through a fully rated converter. Each turbine has its own transformer that steps up the converter voltage (0.69 kV) to the collection grid voltage level (33 kV).

The WTGs (wind turbine generators) will export electricity at 33 kV, and the inter-array cables will link the WTGs to the three AC offshore platforms (DanTysk, Butendiek and Sandbank). On each of the three AC offshore platforms, two 33/155 kV transformers will step up the voltage. The active power output from the WTGs is then transmitted at 155 kV via two HVAC export cables from each offshore AC platform 2 (in total six HVAC cables). Fig. 1 shows a simplified single line diagram of the SylWin1 offshore network.

3 Frequency domain model

A detailed frequency domain model of the SylWin1 offshore network was created including all 33 kV inter-array cables and all 232 wind turbine generators.

3.1 Modelling of cables and transformers

A detailed frequency model of the wind power plant was created including all power transformers, HV and MV cables, detailed inter array cable string connections, and the wind turbine generators. The impedance frequency characteristic of all transformers and HV/MV cables is modelled according to [5].

3.2 Modelling of the wind turbine generators

For the different wind power plants, the frequency domain model of the WTG has been provided by the wind turbine manufacturer. The WTG is modelled at each frequency as a Thevenin equivalent...
circuit as shown in Fig. 2. The Thevenin equivalent represents the converter input reactor and close loop control effects for each single harmonic frequency. The impedance $Z_{n}(f)$ represents the input line reactance and the contribution of the closed loop current controller [6]. Upwm$(f)$ represents the harmonic voltages generated by the converter itself. Experience has shown that this feature allows a more accurate prediction of the turbine converter harmonic current in the presence of background harmonic voltages. The PWM filters and the wind turbine transformer have to be added separately in order to complete the wind turbine representation.

### 3.3 Modelling of the MMC HVDC converter

The MMC HVDC converter is modelled according to manufacturer data at each frequency as a Thevenin equivalent circuit. The equivalent circuit represents the harmonic voltage distortions generated as a harmonic voltage source in series with a frequency dependent impedance. Fig. 3 shows a single line diagram of the MMC HVDC converter frequency domain model.

The harmonic voltage distortions generated by the MMC HVDC converter vary depending on the operating point [7]. Therefore the SylWin1 offshore converter harmonic voltage distortions were calculated for several operating points including under-excited and over-excited operation at different active power transmission levels. The highest distortions for each harmonic order were selected from all operating points and then used to model the harmonic voltage source $V_{HVDC}(f)$ as shown in Fig. 3. Fig. 4 shows the maximum harmonic voltage distortions generated by the MMC HVDC converter at its terminals.

The frequency dependent impedance $Z_{HVDC}(f)$ shown in Fig. 3 is calculated taking into account the converter reactors as well as the converter control. Section 6 deals with $Z_{HVDC}(f)$ in more detail.

### 4 Harmonic amplifications

With the above information, a positive sequence steady -state frequency domain model of the offshore network can be created, in order to investigate harmonic distortions in the offshore network. Fig. 3 also shows a simplified model of the offshore wind power plant used to explain the harmonic amplification phenomenon.

For each harmonic frequency a simplified model as shown in Fig. 3 can be created.

In Fig. 3 $Z_{offshore}(f)$ is the equivalent wind power plant impedance taking into account the different offshore elements which are in service (e.g. high voltage cables, wind turbines, transformers). A change in the wind power plant switching configuration (e.g. switch event of cables, transformers or wind turbines) will also result in a change of the impedance seen from the offshore converter platform PCC, therefore this impedance $Z_{offshore}(f)$ should try to cover a good portion of the wind power plant normal switching configurations once fully in operation and during the different commissioning phases, as well as during planned/unplanned outages due to maintenance/contingencies (e.g. outage of power transformers, export cables, etc.).

The offshore converter platform PCC individual voltage distortions excited by the HVDC injections can be calculated as:

$$V_{i,PCC}(f) = V_{i,HVDC}(f) \cdot \frac{Z_{offshore, total}(f)}{Z_{HVDC}(f) + Z_{offshore, total}(f)} \quad (1)$$

The offshore converter platform PCC individual voltage distortions excited by the wind turbines’ injections can be calculated as:

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**Fig. 1** Simplified Single Line Diagram of the Sylwin 1 offshore network

**Fig. 2** Single line diagram of the wind turbine model

**Fig. 3** Positive sequence simplified frequency domain model of the offshore network

**Fig. 4** MMC HVDC converter maximum harmonic voltage distortions
Highlighting the problematic area where weakly damped resonances occur

Using (1), (2) the harmonic voltage and current contributions of each individual harmonic can be calculated at the PCC. For the superposition of the two harmonic sources, it is common practice [8] to use the IEC Summation Law is used [9].

5 Sylwin 1 harmonic amplifications

In order to calculate the harmonic distortions in the offshore network, it is necessary to perform several harmonic flows using the nodal analysis (admittance matrices), varying the selected switching configuration of the wind power plants (see Fig. 1).

For the SylWin1 offshore network, more than 7500 different switching configurations were analysed, the different switching configurations considered offshore transformer outages, 155 kV export cable and 33 kV inter-array cable outages. Furthermore, due to the important impact of the number of connected WTGs in the system resonances [10], the selected switching configurations also take this aspect into account.

If no countermeasures are considered the resonances in the offshore network can cause harmonic voltage and harmonic current distortions which may lead to the trip of the HVDC and/or wind turbine converters. These high harmonic distortions are a consequence of the amplification of the harmonic emissions of the HVDC and wind turbine converters.

In order to simplify the analysis of the harmonic amplification phenomenon, a set of figures were created showing the harmonic impedance of the AC offshore network for all the considered switching configurations (i.e. $Z_{\text{offshore}_{\text{total}}}$ (f)) in Fig. 3, together with the impedance of the HVDC PLUS converter (i.e. $Z_{\text{HVDC}}$ (f)).

Fig. 5 shows the scattered impedance (marked with ‘x’) representing the equivalent 5th harmonic impedance of the wind power plant seen from the HVDC terminals $Z_{\text{offshore}_{\text{total}}}$ (f). Each scattered point represents a different wind power plant switching configuration. Furthermore, Fig. 5 also depicts the HVDC impedance $Z_{\text{HVDC}}$ (f) shown in Fig. 3.

To obtain the different wind power plant impedances shown in Fig. 5 (scattered points), a frequency scan was performed for each switching configuration, looking from the offshore converter platform PCC into the wind power plant (see Fig. 3).

The critical frequencies determined by the simulations are 250 Hz and 350 Hz since for these frequencies there are weakly damped resonances in the offshore network and at the same time a small amount of harmonic generation from the power electronic converters. In Fig. 5 the problematic area where weakly damped resonances occur is zoomed in and highlighted. It is here (in the highlighted area) where different offshore wind power plant configurations produce a 250 Hz impedance $Z_{\text{offshore}_{\text{total}}}$ (f) which when combined with the HVDC impedance $Z_{\text{HVDC}}$ (f) cause a harmonic amplification which leads to high harmonic distortions.

When combining the values of these two impedances, the denominator of (1) and (2) becomes low enough to allow for high harmonic currents to flow in the offshore network.

The same harmonic amplification phenomenon occurs at 350 Hz as shown in Fig. 6. It becomes clear that the problematic area highlights offshore network configurations which have impedances with a low resistance value and a similar reactive value to the HVDC impedance but with opposite sign.

In order to further illustrate the weakly damped resonance problem Fig. 7 shows a frequency scan looking at $Z_{\text{offshore}_{\text{total}}}$ (f) and $Z_{\text{HVDC}}$ (f) connected in series (Fig. 3). In this case, only two of the studied switching configurations investigated are shown. The two offshore network switching configurations presented in Fig. 7 result in particularly low damping when combined with $Z_{\text{HVDC}}$ (f).

According to the frequency domain model, the harmonic currents that flow through the HVDC converter when these particular switching configurations take place are 180 A (250 Hz) for configuration 1 and 394 A (350 Hz) for configuration 2. Due to the very low impedance at the resonance frequency, even a very low harmonic generation of both the HVDC converter and of the wind turbines is amplified by the resonance condition causing high current and voltage distortions all over the offshore network. These high harmonic currents potentially endanger offshore generation and transmission equipment. It is important to note that the currents calculated above result from the superposition of the HVDC and WTG harmonic injections using the IEC summation law [9].

Without a damping contribution, the HVDC converter current THD exceeds the protection trip level of the offshore equipment in...
8% of the simulated cases. About 16% of the simulated switching configurations exceed a 3.5% THD voltage in the 155 kV offshore network and about 5% of the simulated scenarios exceed the 6.5% THD recommended voltage distortions at 33 kV [9].

6 HVDC PLUS active damping

In order to avoid the harmonic amplification phenomenon and the potential problems it causes, the critical offshore resonances had to be damped. For this, three main options were analysed. On one hand, the offshore impedance $Z_{\text{offshore total}}(f)$ (see Fig. 3) could be shifted by use of AC filters. This solution is however not feasible due to the high costs of offshore AC filters and offshore platform space requirements. Since $Z_{\text{offshore total}}(f)$ also includes the influence of the wind turbine generators and their controls, a second option is to provide damping through the controls of the wind turbine generators. However, due to the amount of wind power plants normally involved in an HVDC offshore connection and the large amount of wind turbines, it is often the case that more than one wind turbine manufacturer is involved in the different wind power plants. This would add complexity to coordinate the damping provided by the wind turbine controllers between several parties.

The third possibility to add damping to the critical offshore resonances is to provide this damping through the HVDC controls i.e. $Z_{\text{HVDC}}(f)$. This option has the advantage that it does not require any hardware changes or extra space in the offshore platforms. Moreover, only the HVDC control system is adjusted to provide the necessary damping as opposed to several hundred wind turbines.

6.1 Control system adjustments

The option to influence $Z_{\text{HVDC}}(f)$ through the converter controls was selected due to the above mentioned advantages. Therefore in order to increase the damping of the offshore network an extra signal is modulated and added to the voltage reference going to the MMS (module management system in charge of switching of the sub-modules within MMC). The signal is based on measured AC currents and is modulated such that it adds a resistive behaviour for the critical frequency range. Fig. 8 shows how the active damping function influences the HVDC impedance $Z_{\text{HVDC}}(f)$. The additional damping is realised by measuring the converter side AC currents and modulating a voltage so that the desired damping is achieved. As shown in Fig. 9 the damping function significantly increases the resistive content of the HVDC impedance $Z_{\text{HVDC}}(f)$ in the 100–500 Hz range. The magnitude of the impedance is only slightly changed in the whole frequency range.

It is important to notice that the active damping characteristic was designed in order to provide damping at low order harmonics (i.e. 5th and 7th) since frequency domain study results pointed out the need of damping at these frequencies.

7 HVDC PLUS damping effectiveness

When the active damping of the HVDC converter is enabled, simulations results show that its use effectively provides significant damping to the offshore network mitigating the high voltage and current harmonic distortions. The same two different offshore network switching configurations presented in Fig. 7 are shown in Fig. 10 including the active damping effect of the HVDC controls. For configuration 1 the impedance at resonance frequency (250 Hz) is increased from 2.1 Ohms to 11.6 Ohms. The impedance at the resonance frequency (350 Hz) in case of configuration 2 is increased from 1.2 Ohms to 10.3 Ohms.

Thanks to the impedance increase of the active damping function the harmonic currents that flow through the HVDC PLUS converter when these particular switching configurations take place...
are 32 A (250 Hz) for configuration 1 and 11 A (350 Hz) for configuration 2. It is important to note that the currents calculated above result from the superposition of the HVDC and WTG harmonic injections using the IEC summation law [9].

Table 1  Active damping result comparison

| Configuration | HVDC Plus Active damping | I_HVDC (A) | Resonance Frequency (Hz) | Impedance at resonance frequency (Ohms) |
|---------------|--------------------------|------------|--------------------------|-----------------------------------------|
| Conf 1 enabled | 32                       | 250        | 11.9                     |                                         |
| Conf 1 disabled | 180                      | 250        | 2.1                      |                                         |
| Conf 2 enabled | 43                       | 350        | 10.8                     |                                         |
| Conf 2 disabled | 394                      | 350        | 1.2                      |                                         |

Table 2  Model verification results

| Switching configuration | On-Site Measurements | Frequency domain model |
|-------------------------|----------------------|-----------------------|
|                         | Converter Current    | Converter Current     |                       |
|                         | Frequency (Hz)       | Amplitude (A)         | Frequency (Hz)        | Amplitude (A)         |
| Configuration A         | 250                  | 17                    | 250                   | 24                     |
| Configuration B         | 350                  | 18                    | 350                   | 28                     |

Fig. 10  Frequency scan of the series connection of \( Z_{\text{offshore\_total}}(f) \) and \( Z_{\text{HVDC}}(f) \) with the active damping function enabled and disabled

Fig. 11  Measured harmonic content of the HVDC converter current with the active damping function enabled and disabled

are 32 A (250 Hz) for configuration 1 and 11 A (350 Hz) for configuration 2. It is important to note that the currents calculated above result from the superposition of the HVDC and WTG harmonic injections using the IEC summation law [9]. Table 1 shows a summary of the results of two of the critical switching configurations presented in Fig. 10.

When the HVDC active damping is enabled, the HVDC converter harmonic current is limited to maximum 43 A rms over the whole range of switching configurations studied.

7.1 Model verification

In order to gain confidence in the modelling approach, the results of the frequency domain model have been compared against on site measurements for a small number of switching configurations. The results show a good correlation. Table 2 shows the comparison between on-site measurements and the frequency domain model for two different switching configurations.

As can be seen the model correctly predicts the resonance frequency that will be present in the offshore network. Furthermore, the converter current amplitude at the resonance frequency can also be predicted with some margin of error. Due to the conservative modelling approach, the model results always show higher current/voltage distortions than the measured values.

It is important to enumerate the sources of errors that influence the comparison between on-site measurements and frequency domain model results.

- Operating point dependent harmonic generation: As explained in section III.
- IEC summation law: The harmonic distortions calculated in the frequency domain model use the IEC summation law to add the contributions of the different harmonic sources. In the on-site measurements, the phase angle difference of between all harmonic generation sources is unknown.
- Frequency domain modelling of passive elements: The damping provided by cables and transformers was assumed to follow the characteristics described in [5], whereas the passive elements in reality may deviate from the proposed characteristics.
- Component tolerances: Component tolerances were not taken into account in the offline simulations.

7.2 On-site measurements

In order to test the active damping function on site, the harmonic content of the HVDC PLUS converter current was measured at the converter side of the converter transformers. At the beginning of the measurements the active damping function is enabled and about 20 seconds after the recordings start the active damping function is disabled. Fig. 11 shows the increase in the THD harmonic content of all three phases of the HVDC PLUS converter current once the active damping function is disabled. For this specific configuration the active damping provides a 50% reduction in the current THD.

Fig. 12 shows the most important frequency components making up the THD values shown in Fig. 11. It can be seen that the damping is significantly increased at the resonance frequency (350 Hz) in this particular switching configuration.

8 Conclusions

The harmonic amplifications caused by the weakly damped resonance conditions in the SylWin1 offshore network generated voltages and currents that exceed the planning levels in [9] and led to protection trips due to high harmonic contents.

Through detailed harmonic studies involving impedance frequency scans of the wind power plant it was possible to design a
solution, which mitigates the distortions and improves the operational performance of the offshore network.

The offshore network resonances were damped by means of an HVDC converter control adjustments. This HVDC function effectively provided the necessary damping to the offshore system, and reduced the effect of the 5th and 7th harmonic amplifications, while at the same time it did not negatively affect other harmonics.

The simulation results have been compared against on-site measurements showing good correlation as shown in Section 7.1. The effectiveness of the active damping has been measured on site as shown in Section 7.2 showing a significant reduction in the harmonic content of voltage and currents.

Weakly damped resonances nearby 200 Hz, 300 Hz, 400 Hz and 450 Hz were also present for many switching configurations. These resonances should not present a problem during steady state operation since they are not excited by harmonics generated by the connected equipment. Nevertheless, even for these frequencies the described HVDC function has a positive impact on damping.

The solution presented in this paper was implemented in the SylWin1 offshore VSC HVDC converter. Subsequently, this solution has also been implemented in other offshore VSC links from Siemens.

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10 References

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