Active Filtering in a Large-Scale STATCOM for the Integration of Offshore Wind Power

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Abstract— **The application of active filtering (AF) in a large-scale STATCOM for offshore wind power integration is presented in this paper. The project topology and its main parameters are introduced to give an understanding of the basic layout of an offshore wind power plant (WPP) integration using an AC connection. The impact of the AF functionality on the measurement hardware of the STATCOM system is described. The methodology and operating principle of the AF within the STATCOM is shown and explained. Harmonic propagation studies illustrate that low-frequency resonances in WPP components, such as HVAC export power cables, reactive power compensating devices and park transformers may introduce amplification of harmonic distortion (HD) at the point of connection (POC). The impact of the AF functionality during operation is shown in real-time simulation cases.**

Keywords: active filtering; harmonic emission; harmonic stability; modular multilevel converter; static synchronous compensator; STATCOM; offshore wind power integration

I. INTRODUCTION

With the continuously growing contribution of renewable power generation in modern power systems, offshore WPPs have turned out to be an enabler for a stable grid and are expected to be able to meet the rising energy demand. Especially in Europe, offshore WPPs are substituting conventional power plants. For the integration of offshore wind power in the electricity networks there are currently two different technical approaches used: (i) integration of wind power via HVDC links (so far only in Germany) or (ii) integration of wind power via HVAC transmission systems (e.g. United Kingdom).

The system complexity of offshore WPPs is increasing with the larger distance to shore and plant size, and with the power converters installed inside the wind turbines (WTs) [1]. Especially for HVAC connected offshore WPPs, harmonics may be amplified by low frequency resonances created by the combination of large offshore transformers and long submarine cables [2]. The amplification of existing harmonic content due to resonances plus additional harmonic distortion emitted by the power converters causes on one hand, additional heating of electrical components and on the other hand, potential issues with grid code compliance and overall system stability [3], [4], [5].

A. *Active Filtering in a Large-scale STATCOM*

To overcome the challenges described previously, passive filter circuits in conjunction with reactive shunt compensation devices using voltage source converters (i.e. static synchronous compensators, STATCOMs) are installed at the onshore connection of the WPP. Due to fluctuating generation of the WPP and thus fluctuating harmonic content introduced, the passive filter circuits effectiveness might be affected (due to the static nature of passive filter circuits).

The STATCOM is mainly required for dynamic voltage and reactive power control at the point of connection to the grid. However, in addition, it is possible to utilize the STATCOM for AF to provide damping of fluctuating HDs thus widening the effectiveness of the passive filter circuits to ensure compliance with the grid code requirements [6]. Also, additional component stress due to harmonic content is reduced. Using the AF functionality is much more flexible as it can be configured in its control, which is much more flexible than passive filter circuits.

II. OVERVIEW OF THE HORNSEA ONE WPP

This paper focuses on the implementation of an AF functionality in the Hornsea Project ONE (offshore wind integration project with HVAC transmission system from Ørsted A/S) for the compensation of HD content at the POC to the grid i.e. 400 kV transmission network as a supplement to passive filters.

Hornsea ONE WPP is located approximately 100 km from the east coast of the United Kingdom, in the English Southern North Sea off the coast of East Yorkshire, see Figure II-1.

A. *Overall Wind Power Plant System Description*

The Hornsea ONE WPP consists of 174 WTs with a rated power of 7.0 MW each and rotor diameter of 154 meters, totalling 1218 MW installed capacity. The WTs are grouped in three clusters of 58 units and 12 strings each, connected to three offshore substations (OSSs) named Z11, Z12, Z13. Two grid transformers (GTs) per substation step up the voltage from 34 kV to 220 kV and the power is then transmitted to shore by means of three HVAC export cables (submarine and land) of approximately 170-190 km of total length, depending on the geographical location of each OSS.

Submarine interlink cables of 13 and 15 km are installed between OSSs to improve the availability of the export system.

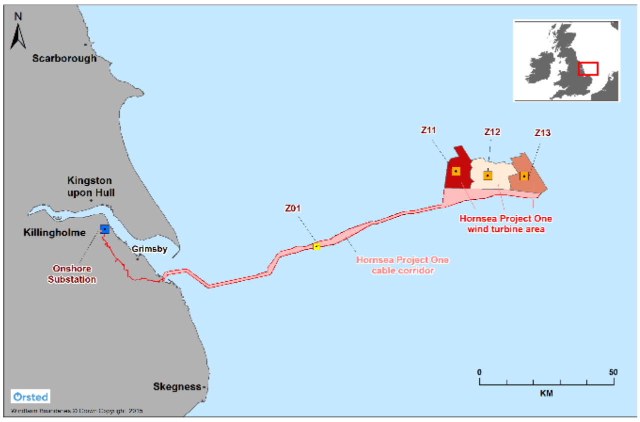

Figure II-1 Geographic location of Hornsea ONE WPP

The reactive power generated by these cables is compensated via three fix shunt reactors at the OSSs of 85, 105 and 135 Mvar, three fix shunt reactors at the reactive compensation substation (RCS) of 220 Mvar each and three variable shunt reactors at the onshore substation (OnSS) of 120-300 Mvar each. The RCS is required to be able to meet the transmission capacity of 1200 MW.

In addition to the above and connected to the OnSS 220 kV busbars, there are three C-type harmonic filters (band-pass) each rated at 100 Mvar and connected to the 220 kV busbars, designed for damping the export system low-frequency resonance. Three STATCOMs each rated at ±200 Mvar are responsible for the voltage and reactive power compliance at the WPP POC to the 400 kV network. Three auto-transformers each 500 MVA rating are used to step up the voltage to 400 kV before connecting to the transmission network at Killingholme substation via two underground cables of approximately 0.5 km length each. In addition, two C-type harmonic filters (high-pass), each rated at 75 Mvar, are connected to the 400 kV busbars of the OnSS to damp high frequency harmonics with two fix shunt reactors of the same size as compensation.

The single line diagram below indicates the most relevant electrical components (please refer to Figure II-2).

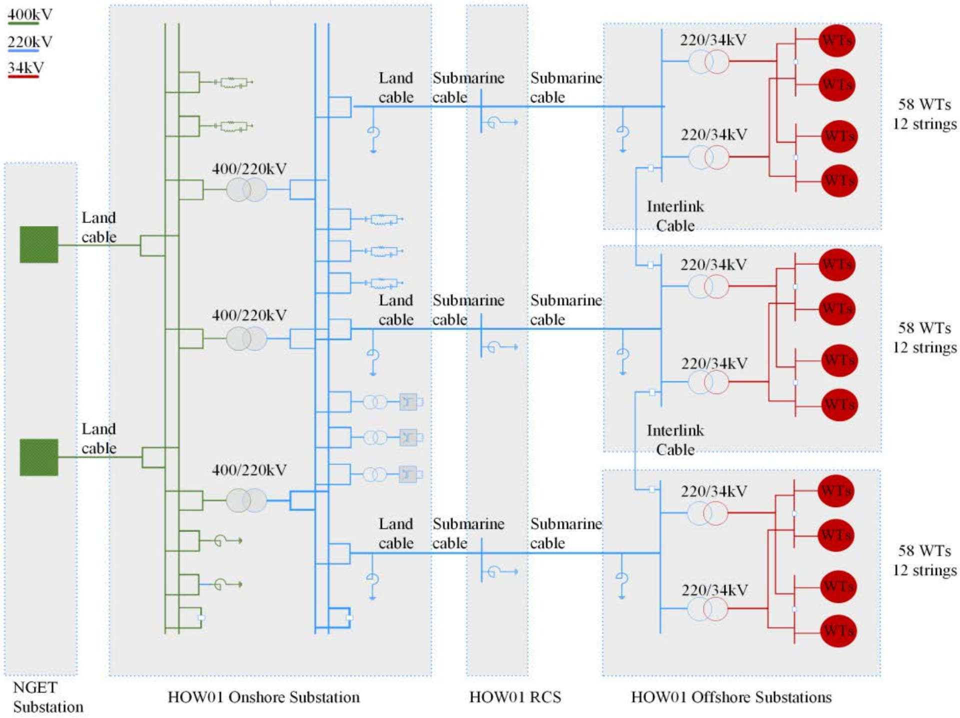

Figure II-2 Single line diagram of Hornsea ONE offshore WPP and export system

B. *STATCOM Unit*

For the Hornsea ONE Project three identical STATCOM stations delivered by SIEMENS AG each comprising two paralleled multilevel voltage source converters (VSCs) are installed to provide transient voltage stability which are described in more detail next [7], [8].

Each STATCOM consists of two multilevel VSCs each providing a reactive power output of ±100 Mvar (see Figure II-3) [9]. The STATCOM transformer and an HVAC cable provide the connection of the STATCOM station to the HV substation (220 kV bus, STATCOMs POC). The control interface point (CIP) for the regulation of the voltage is the 400 kV bus.

The multilevel VSC consists of three identical phase legs connected in delta. Each phase leg of the multilevel VSC is a series connection of multiple full-bridge submodules and a coupling reactor.

The full-bridge submodule consists of a power module and one DC capacitor (refer to Figure II-4). The power module itself contains 4 HV IGBT modules. Each HV IGBT module is a setup of IGBT semiconductors and antiparallel connected diodes. Each submodule can contribute to the total output voltage of the respective phase by three different voltage levels, namely $+V_C$, $-V_C$ and zero volts. Low distortion of the converter's output voltage is achieved by superposition of the cascaded submodules.

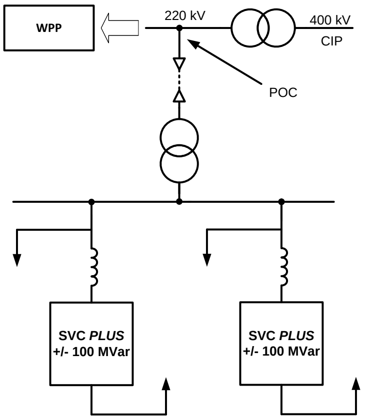

Figure II-3: Simplified equivalent circuit of Hornsea ONE STATCOM provided by SIEMENS, i.e. SVC PLUS station, excluding switchgear, transient overvoltage protection and auxiliary station services

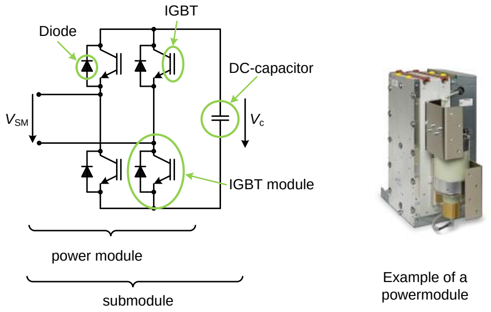

Figure II-4: Simplified equivalent circuit of a full-bridge submodule as building blocks of the multilevel converter

1) *Design of the SVC PLUS station for AF operation*

A special requirement of the Hornsea ONE project was that the impact of the AF functionality on the station design shall be as little as possible. That includes a design which is not limited to economic aspects but a space saving solution as well. As a result no additional power (i.e. additions submodules) shall be installed in order to enable the AF operation. The necessary reactive power for the fundamental frequency operation defines the power rating of the multilevel converter. Only inherently available power shall be used for the AF functionality.

Therefore the maximum harmonic current which can be generated by the STATCOM needs to be in accordance with the requirements of the converter system itself, the coupling reactors, the main station transformer of the SVC PLUS system [10], [11] and the auxiliary system of the STATCOM in order to avoid overloading or premature ageing of hardware due to the AF operation.

C. *Measurement Equipment for Active Filtering*

The correct measurement of harmonic content in HVAC networks is challenging. Standard measurement equipment such as inductive or capacitive voltage transformers (VTs), which are generally used in substations and for FACTS devices, is not suitable for an accurate capture of harmonic data in order to actively and effectively compensate HD in the network. To overcome the measurement uncertainties across various frequencies of inductive or capacitive VTs, resistive capacitive voltage dividers (RCVDs) are used for the AF [12]. RCVDs are resistor damped capacitive voltage dividers and therefore, offer high measurement accuracy over a wide frequency range (from DC up to 20 kHz).

In Figure II-5 an exemplary representation of the amplitude error in dependency of the frequency of conventional HVAC measurement equipment (inductive and capacitive VTs) in comparison to an RCVD is shown. As can be seen inductive and capacitive VTs have high gain sensitivity across the relevant frequency range. This leads to incorrect measurements for the respective frequency, possible resonances and hence, is unfavourable for an effective AF operation (amplitude measurement error even of more than 200%).

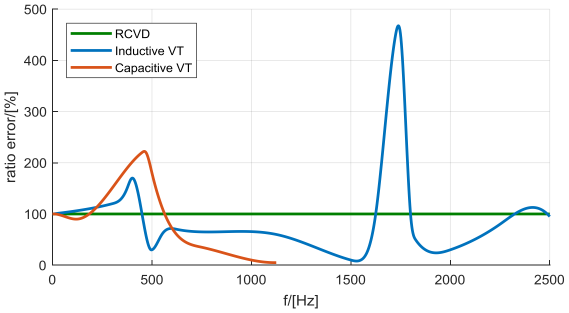

Figure II-5: Exemplary representation of amplitude measurement error of different voltage measurement devices

III. ACTIVE FILTERING OPERATION

The defined AF control objective for all STATCOMs in the Hornsea ONE WPP is to reduce the total harmonic voltage levels of the 3^{rd} and 7^{th} harmonic content at the CIP to 0.25% and 0.2% (with reference to the fundamental frequency system voltage), respectively. The compensation of the harmonics is focused on stationary (steady-state) harmonic content in the 400 kV network. The reason for that is the fact that during transient events, harmonic quality is of low priority and hence, the full capacity of the STATCOM is needed for voltage stabilization in order to minimize the stress on the network. As a result, the AF functionality shall not interfere with the transient voltage control at any time to ensure system stability. Due to the nature of the AF functionality, it is possible to react against changes in the harmonic content of the grid as a result of varying network conditions.

In Figure III-1 the basic operating principle of the AF function is shown. Before the AF operation can commence, a test signal is generated to estimate the network response to a harmonic signal (automatic controller tuning or Autotuning). After the Autotuning, operation the AF is initiated and the controller will compensate the measured harmonic voltage content within the network automatically in order to minimize the distortion of this harmonic.

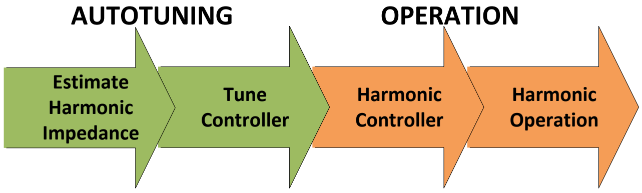

Figure III-1: Basic operating scheme of the AF functionality

A. *Estimation of Impedance*

By actively injecting a small harmonic current, the harmonic network impedance can be estimated by the measurement of the corresponding voltage response in the connected network. With this method, only the relative change on the test signal will be measured to ensure correct tuning of the harmonic controller. This process ensures the initial definition of the necessary amplitude and the phase angle for the compensation with the AF controller to impose minimum stress onto the grid. The network response measurement is executed automatically before every operation of the AF.

B. *Tuning of Harmonic Controllers*

The measured network response to the small harmonic current test signal is used to tune the harmonic controller for correct operation. This allows minimal impact on the waveform quality of the network and a faster compensation of the target harmonics by the AF functionality.

C. *Harmonic Control*

For the AF compensation, the harmonic controller needs to identify the necessary harmonic current to be generated by the converter to minimize the harmonic voltage distortion at the CIP. With a dedicated bus for harmonic measurement (to ensure as little interference with the fundamental frequency operation as possible) and the information derived from the Autotuning, the measured voltage harmonics are damped by using PI-controllers. Changes within the measured harmonic content will be immediately identified and the controller output will be automatically adjusted to achieve optimal compensation of the measured harmonic voltage distortion.

D. *Harmonic Operation*

The converter is equivalent to a controllable voltage source, where the submodules of each phase are switched in a controlled manner to achieve the desired output signals.

In order to control the reactive power output of the STATCOM in fundamental frequency operation, the converter voltage amplitude will be adjusted to absorb or drive current into the network that the multilevel converter is connected to.

In case of AF activated the same operational approach is used to inject harmonic currents. The generation of harmonic converter voltages will drive the requested harmonic current in order to compensate harmonic content in the connected network.

IV. ANALYSIS

The studies and simulation described in the following are used to identify the feasibility of the AF functionality as well as the performance and stability of the functionality to install the AF in the Hornsea ONE project.

Using the harmonic propagation study cases and the system frequency sweep study, influencing factors for the design and the performance of the AF (e.g. impact of passive filters on the AF) is identified and analysed.

Real-time simulations of the complete WPP system indicate the performance of the AF functionality in the simulation environment. Controller stability during transient events and varying grid conditions can be monitored. The signal propagation times within the measurement system and the internal converter control hardware – is significantly impacting the AF functionality and can also be observed in analysis of real-time simulation results.

A. *Harmonic Simulations*

1) *Harmonic propagation studies*

Harmonic propagation studies were conducted by Ørsted A/S, in the PowerFactory DIgSILENT© simulation tool, at an early stage of the offshore WPP design phase to identify the worst harmonic voltage distortion levels at the CIP and the WPP POC, and to evaluate the need for passive harmonic filters to damp potential low-frequency resonances and to comply with the power quality requirements defined in the connection agreement. Harmonic studies performed for all harmonic frequencies in the range of 2nd-100th harmonic provided the maximum HD levels across the WPP and at the CIP.

In this study, all harmonic sources such as the neighbouring 400 kV network, all three SVC PLUS stations and all 174 WTs were modelled by their Thévenin equivalent circuits based on National Grid (NGET) and supplier's harmonic data. Network data provided by NGET consisted of frequency-dependent impedances for three different load levels at the system (Annual Average Cold Spell (ACS) 30%, 60%, 100%) and the background distortion levels measured at the CIP. Similarly, validated impedance and harmonic emission data was received from the STATCOM and WT manufacturers. Export and array cables, as well as step-up transformers, were also modelled with their frequency-dependent impedance characteristics.

Multiple Hornsea ONE and NGET network electrical infrastructure configurations including the intact configuration (i.e. all components are running in normal operating conditions according to the control and operational philosophies), were considered during these studies.

A conservative approach to calculate the total harmonic distortion at the CIP was taken, summing up arithmetically the incremental distortion of the WTs (assuming the same harmonic voltage angle for all) and the STATCOMs to the network background harmonic levels. Skin and proximity effect in the export cables and transformers were modelled via their frequency-dependent impedance.

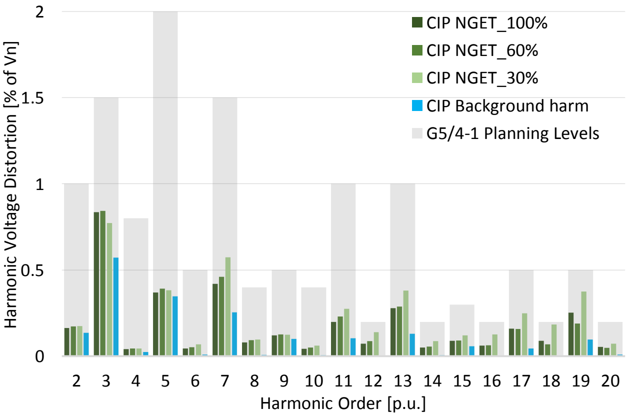

Figure IV-1: HD level estimation at the CIP for Hornsea ONE WPP at low order harmonic range (no harmonic filters included)

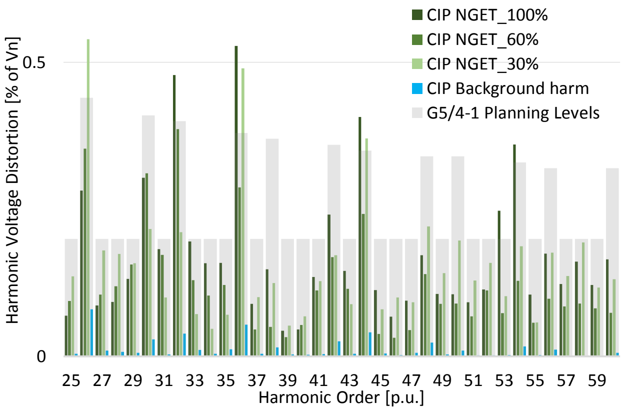

Figure IV-2: HD level estimation at the CIP for Hornsea ONE WPP at high order harmonic range (no harmonic filters included)

Estimated HD level at the CIP are shown in Figure IV-1 and Figure IV-2. The studies revealed some HD levels exceeding G5/4-1 Planning Levels (which builds the basis for the permissible voltage distortion level in the network the Hornsea ONE substation is connected to) at high frequencies for specific network and WPP configurations. High-pass harmonic filters at the CIP were designed to damp these harmonic distortions. At low frequencies, the most onerous HD levels are for the 3rd and the 7th harmonic. The investigation of the most onerous HD content will be used to select the harmonic orders for the AF functionality.

2) *Frequency sweep*

Harmonic frequency scans (also known as frequency sweep) provide additional information about the potential resonant frequencies of the WPP connected to the grid by calculating the harmonic impedance profiles at the buses of interest. Impedance magnitudes tending towards infinity at a particular frequency indicates the appearance of the parallel resonance at that frequency. Similarly, impedance magnitudes tending to zero indicates a potential series resonance at that frequency. Apart from this, the total impedance changes from inductive to capacitive or vice versa at the resonant frequencies. This appears as change of sign of the impedance phase.

In this study, the harmonic sources of the system i.e. the NGET network, the STATCOMs and the WTs, were also modelled by their Thévenin equivalent circuits. The frequency-dependent impedances are according to data from NGET and the component manufacturers.

The categorization adopted here differentiates between the Hornsea ONE system as intact configuration and during export cable energization phase (see Figure IV-3). The NGET external grid was assumed in 100% load intact conditions. The measurement point is the STATCOM POC i.e. the onshore 220 kV double busbar, with export cables 1 and 2 connected to the main busbar and cable 3 connected to the reserve busbar.

The impedance profiles plotted in Figure IV-3 provide relevant information about the variation of the export system lowest resonance (112-150Hz) depending on the WPP configuration. Harmonic filters at the STATCOM POC were tuned to damp this impedance and prevent harmful amplification of harmonic voltages at low frequencies. The AF functionality incorporated in the STATCOMs serves as a supporting measure to damp the HD levels

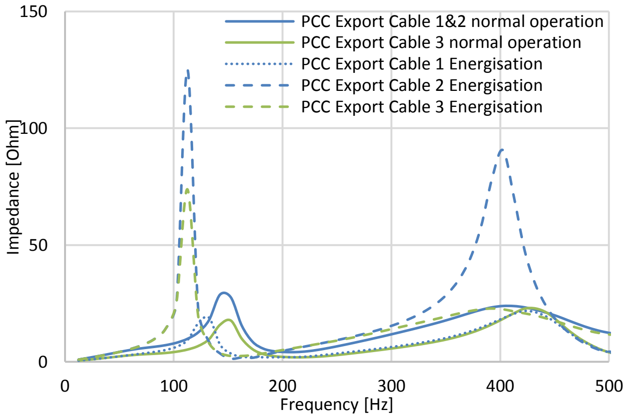

Figure IV-3: Frequency sweep at the STATCOM POC (220 kV) with and without the 220 kV harmonic filters for normal WPP operation and export cable energisation and NGET intact ACS 100% network configuration

The frequency sweeps allow for a more qualified interpretation of the harmonic propagation studies and constitutes a useful input for the design of harmonic mitigation measures as well as for control stability studies [13].

B. *Real-Time Simulations*

The impact of the AF functionality during operation is shown in real-time simulation cases using the actual control and protection hardware for on-site installation at the Hornsea ONE SVC PLUS stations.

1) *Harmonic voltage control at the CIP*

For stationary tests, a constant positive sequence 3rd and 7th harmonic content of ~2% (based on the nominal system voltage at the CIP) is simulated as a contribution from the grid.

After the Autotuning process (not indicated in the figures below), the AF functionality is released. The converter supplies 3rd and 7th harmonic current by providing the corresponding harmonic converter voltage to compensate the measured harmonic content at the CIP as presented in Figure IV-4 a).

As can be seen in the Fast Fourier Transformation (FFT) results of Figure IV-4 b) and c), the initial harmonic content at the CIP (refer to Figure IV-4 b) is reduced significantly after the activation of the AF by a factor of 1.25 to 1.43 (refer to Figure IV-4 c). The main influencing parameter to the degree of harmonic compensation of the AF is the predominant harmonic short circuit level (SCL) of the network measured at the CIP [14]. The AF functionality provides full selectivity on of the selected frequencies for harmonic compensation. There will be no influence or impact on the harmonic content at other frequencies but the targeted ones (i.e. only 3rd and 7th harmonic content will be filtered for the Hornsea ONE project).

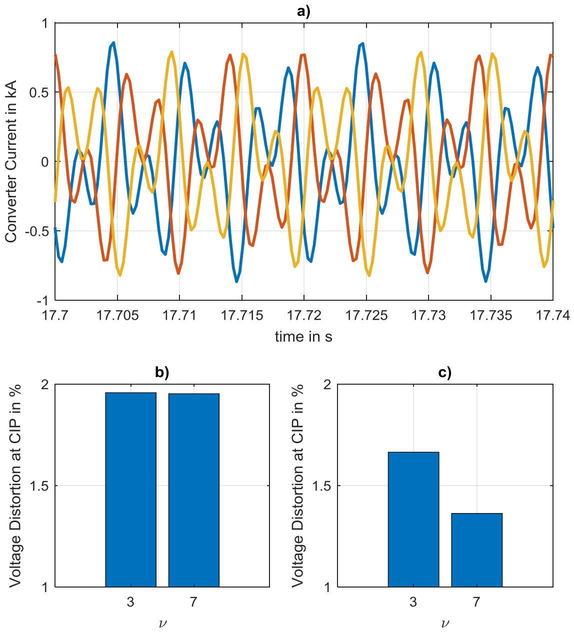

Figure IV-4: a) Three phase time characteristic of generated converter harmonic currents in AF operation b) FFT analysis of harmonic CIP voltages without AF c) FFT analysis of harmonic CIP voltages with AF

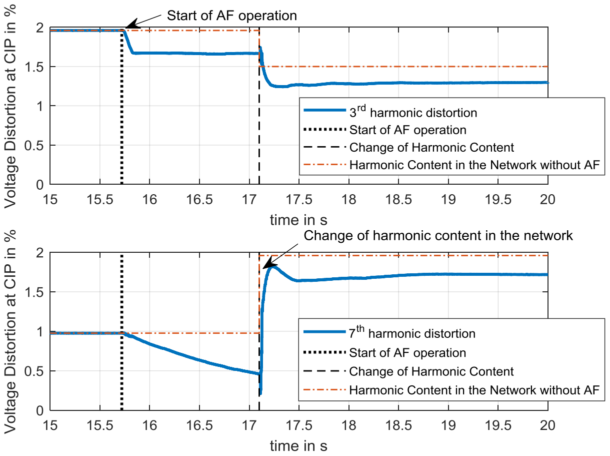

Figure IV-5: 3rd and 7th harmonic content change and AF reaction on adapted distortion level in the CIP network (sliding window FFT analysis)

2) *Change of harmonic content at the CIP*

Changing load conditions and varying network configurations lead to a constant change of harmonic content (i.e. amplitude and phase angle of harmonic content). For the AF functionality it is essential to identify such changes and adapt its output to receive a constant compensation of the stable harmonic content within the grid.

The network operates with a stable 3rd and 7th harmonic content. For the test a positive sequence 3rd harmonic distortion level of ~2% and a negative phase sequence 7th HD level of ~1% is imposed to the network. The Active Filter is tuned for operation (Autotuning successfully executed) and commences its operation at the time instant indicated with the dotted line in Figure IV-5. It can be seen that the AF functionality automatically reduces the harmonic distortion of the 3rd and 7th harmonic based on the given short circuit level as much as possible only limited by the maximum permissible rating levels of the converter.

At the time instant indicated with the dashed line in Figure IV-5, the amplitude and phase angle of the harmonic distortion at the CIP is changed instantaneously. The AF functionality recognizes the changed harmonic conditions and automatically adjusts its tuning settings to receive a compensation of the harmonic content at the CIP.

V. SUMMARY AND CONCLUSIONS

Multilevel STATCOMs in HVAC connected offshore WPPs can serve as dynamic and controllable damping device for harmonics (in addition to dynamic voltage support) which can replace or supplement passive filters used to ensure compliance with the grid code requirements and reduce harmonic component stress effectively.

Active filters are much more flexible than passive filters as they can be dynamically adjusted to the varying system conditions locally via parameter setting and remotely via software. Furthermore, the STATCOMs will normally use little of their capability for fundamental frequency operation during most of the WPP operation lifetime which means that the available capacity can be utilized to improve harmonic distortion levels.

The AF functionality results from real-time simulations for Hornsea ONE WPP STATCOMs presented in this paper indicate the great potential of this technology with regards to harmonic distortion compensation at the CIP.

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