DECARBONIZATION OF OFFSHORE INSTALLATIONS USING STATIC FREQUENCY CONVERTERS AND ACTIVE FRONT ENDS

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Abstract – Offshore oil and gas installations traditionally rely on fossil fuels to drive pumps, compressors and electric loads. To reduce carbon emissions, lower operating costs and boost the available power, offshore platforms may be electrified by replacing or augmenting gas or steam turbines by a static frequency converter system that is supplied by a subsea cable from shore. As an example, this paper presents a Norwegian offshore oil and gas platform that is augmented with a 36 MVA medium-voltage static frequency converter system.

Index Terms — Static Frequency Converter, Variable Speed Drive, Power from Shore, Decarbonization, Sustainability

I. INTRODUCTION

Many offshore installations traditionally rely on fossil fuel driven power generation equipment, such as diesel generators, steam turbines and gas turbines. These are a significant source of contribution to the greenhouse gas emissions in the offshore operations as there is a constant demand and a high-power consumption.

Since the Paris Agreement at the UN Climate Change Conference (COP21), there are now many initiatives among all industries to reduce the carbon emissions and promote sustainable practices that are being proposed and driven by governments, international and industrial organizations, with the goal of “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursing efforts to limit the temperature increase to 1.5°C above pre-industrial levels.”

One means of achieving this goal is decarbonization, by a shift towards electrification of offshore power generation equipment.

Even prior to the Paris Agreement, offshore electrification has already been well-established since the world’s first offshore HVDC transmission that was successfully commissioned in February 2005 which electrified the Troll A platform 65 km away from the coast with two parallel 40M W transmission lines to the mainland grid [1]. Even furthermore, Martin Linge offshore gas field electrification project was commissioned in 2019 with the world’s longest (161 km) AC subsea power from shore at that time, which utilizes the same converter technology as today’s projects [2].

This paper presents a further case example of the electrification of a Norwegian offshore platform and the continuous developments of tools to de-risk and simplify the electrification project.

II. POWER FROM SHORE ELECTRIFICATION

Many offshore installations in the North Sea employ a 60 Hz system, while the national grid in Norway and in major European countries operates at 50 Hz. The electrification of these oil and gas installations require the conversion of the grid supply frequency to match the requirements of the installations to avoid the expensive reconfiguration of the existing equipment.

A static frequency converter (SFC) system based on voltage-source-inverter technology allows the seamless connection between the onshore grid and the offshore installations, which is commonly referred to as a power-from-shore (PFS) system.

In addition, an electrification project normally includes the upgrade of the installations for further emission reduction. The upgrades typically involve the installation of new compressors and pumps that are driven by variable speed drives (VSD) and/or direct online (DOL) motors to replace the turbines for direct drive of compressors and pumps. This equipment is either run at 50 Hz or at 60 Hz.

During the conceptual phase, there are two key alternatives to be evaluated for the offshore platform:

1.) Single frequency electrification, i.e., power is converted onshore to 60 Hz and fed through a 60 Hz subsea cable from the shore to the offshore platform as shown in Fig. 1: Single-line diagram of the SFC installed onshore. To reduce the losses in the ac subsea cable the voltage is typically stepped up.
2.) Dual frequency electrification, i.e., the new equipment is installed at 50 Hz, and the conversion to 60 Hz is performed on the offshore platform for the legacy equipment that is already available, see Fig. 2.

A. *Single Frequency Electrification Concept*

In the single frequency electrification concept, the 50 Hz to 60 Hz frequency conversion is done onshore using an SFC. Compared to rotating frequency converters (RFC), which might have been considered in the past, SFCs offer a higher efficiency, improved availability and a lower footprint. Installing the SFC onshore avoids the addition of equipment offshore. This is particularly important for existing offshore installations, as the weight and space limitations are one of the most critical design factors.

However, this concept requires all the offshore power to be converted from 50 Hz to 60 Hz, which necessitates a higher power rating for the SFC. Moreover, the 60 Hz system limits future extensions of the offshore grid, as new offshore installations are typically restricted to 50 Hz.

The voltage and reactive power control is achieved by the SFC with the help of a shunt reactor. On-load-tap-changers (OLTC) are not required for the onshore step-up

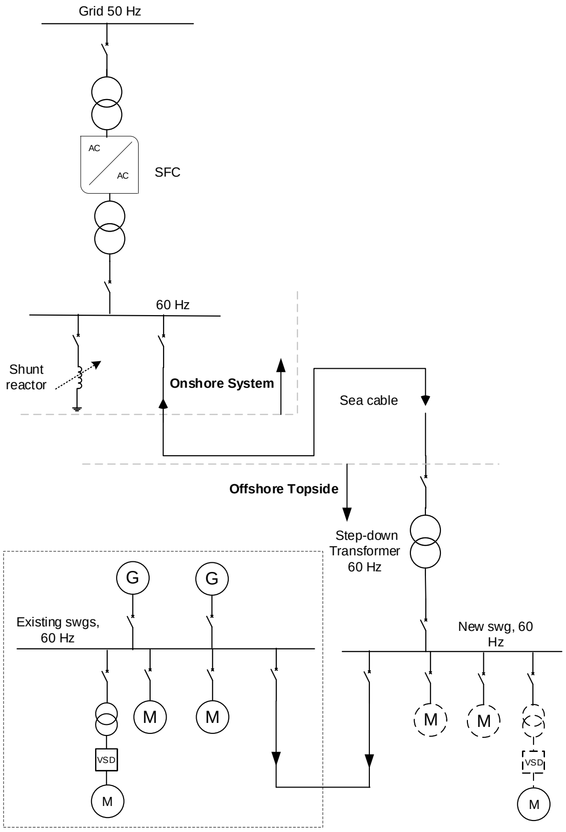

Fig. 1: Single-line diagram of the SFC installed onshore

transformer, as the SFC can control its output voltage to maintain the desired offshore voltage.

B. Dual Frequency Electrification Concept

In the dual frequency electrification concept, the 50 Hz to 60 Hz frequency conversion, which is required for the existing 60 Hz loads, shall be done offshore via SFCs. The new loads will be running at 50 Hz with 50 Hz being the standard grid frequency in Norway. The required power rating of the SFC is lower in this case.

The power from shore system can be used to further power up other installations nearby that run on 50 Hz. As shown in Fig. 2, for example, Platform 2 is connected via Platform 1 to the onshore grid. The cost of the onshore substation and the subsea cable to Platform 1 is split between the two platform operators. As a result, the capital expenditure (CAPEX) for each operator is lower than if each platform required its own PFS system. Furthermore, the system can be used for a future offshore grid integrating an offshore wind farm. For example, an offshore wind farm could be connected to Platform 1 to supply power to both platforms. Surplus power from the wind farm could be transmitted to the onshore substation by the already existing subsea cable.

III. STATIC FREQUENCY CONVERTER SYSTEM

A. SFC System

The SFC interfaces the offshore 50 Hz bus (at a nominal voltage of 132 kV) with the offshore 60 Hz bus (at 13.8 kV). The SFC can transfer power in a bidirectional manner either from the 50Hz to the 60Hz side or vice versa.

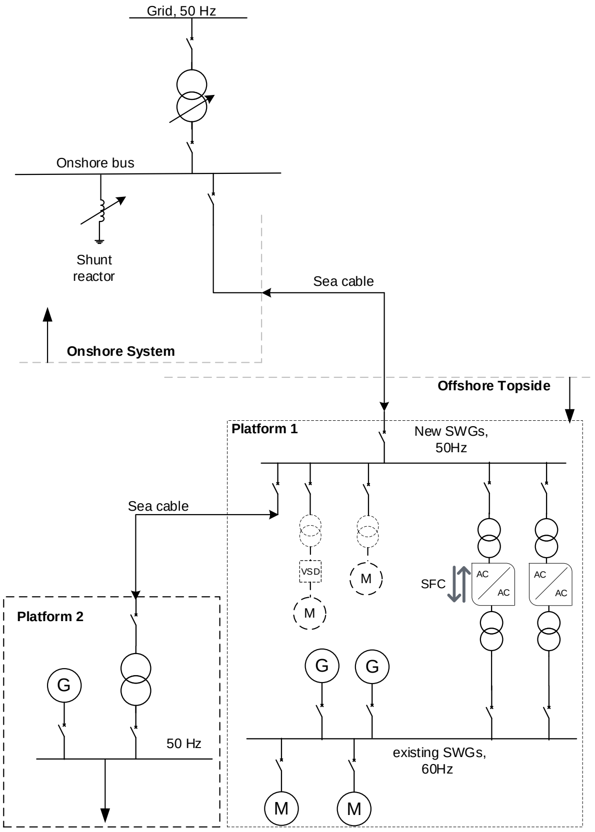

Fig. 2: Single-line diagram of the SFC installed offshore

Assume for the time being the former case, in which the 50Hz bus can be considered as the input to the SFC system, and the 60 Hz bus is its output, see Fig. 3.

Starting on the left-hand side the SFC is connected to the 50 Hz bus via an input circuit breaker and a 12-pulse transformer. Two active front ends (AFEs) operate in parallel and feed a common dc-link. On the output side, two inverter units operate in parallel and feed the output transformer. To further minimize the harmonic distortions at the 13.8 kV bus, a shunt filter is added between the output transformer and the output circuit breaker, which is connected to the 13.8 kV bus.

Instead of a classic Y-YD transformer with a common primary winding, series-connected transformers are used in which the primary windings of the two transformers are connected in series. One of the secondary windings is phase-shifted by 30 degrees to ensure the cancellation of the six-pulse harmonics, i.e., the 5th, 7th, 17th, etc harmonics. Thanks to the series-connection of the primary windings, harmonic currents of the cancelled harmonics are suppressed, thus, reducing the rms ripple current. As a result, the transformer losses are reduced and the peak current in the converters are lower than in the case of a Y-YD transformer. For details on series-connected transformers and their unique benefits, the reader is referred to [3].

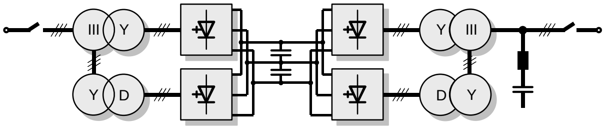

Fig. 3: Static frequency converter system (with the 50 Hz high-voltage bus on the left-hand side and the 60 Hz medium-voltage bus on the right-hand side)

With each of the four SFC converters rated at 9 MVA, the SFC system in Fig. 3 is rated at 18 MVA. As shown in Fig. 2, two such SFC systems are operated in parallel, thus achieving 36 MVA in total. Despite the high power the use of two independent SFC systems achieves a high degree of redundancy and flexibility that offers benefits during the operation and the maintenance of the SFC system.

B. Converter Topology and Technology

The four SFC converters in Fig. 3 are voltage-source converters based on the well-known neutral-point-clamped (NPC) topology [4], see Fig. 4. Using medium-voltage technology each phase leg consists of four integrated gate commutated thyristors (IGCTs), four freewheeling diodes and two NPC diodes that are connected to the neutral point of the dc-link. The semiconductor devices are press-pack devices that are arranged in a stack. The main converter components including the semiconductors and the electromagnetic compatibility (EMC) filter are water cooled, allowing a cost-effective removal of the thermal losses. Three voltage levels are achieved in each phase, leading to low harmonic distortions.

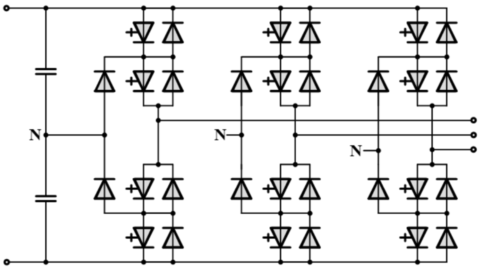

Fig. 4: Neutral-point-clamped converter

The SFC system is based on the ACS6000 / ACS6080 medium-voltage converter platform, which is exemplified in Fig. 5. The AFE is shown on the left-hand side, followed by the terminal and control units (behind the closed cabinet doors), the inverter unit, the capacitor bank unit that forms the dc-link, and the cooling water pump that supplies deionized water to the main power components. Redundant pump configurations are available to maximize the availability of the system.

Fig. 5: Medium-voltage back-to-back converter that forms the building block of the SFC system

The ACS6000 / ACS6080 is based on well-proven and highly mature building blocks with thousands of converter installations running in the field. As a result, these converters have gained a reputation of superior quality and reliability. IGCTs are the semiconductor technology of choice for high-power converters, offering a low part count and low conduction losses. More specifically, the efficiency of the back-to-back converter system exceeds 98%. The converter has a small footprint, which is particularly important for offshore platforms, which tend to be space-constrained particularly when legacy installations are upgraded or retrofitted.

In case of a failure or fault, the protection logic detects a sharp current transient and issues a firing-through command to the IGCTs to safely dissipate the energy stored in the dc-link capacitors. This affords a fuseless design that offers a faster and superior protection method compared to medium-voltage power fuses.

A wide range of converter modules with different current ratings and configurations are available, allowing the operation of up to three high-power converters in parallel. As a result, the power of each SFC scales in small power steps from 9 to 25.5 MVA. By operating two such SFC systems in parallel, up to 51 MVA are available, achieving power levels sufficient for the most demanding applications.

Thanks to the use of tailor-made optimized switching patterns and 12- or 18-pulse transformer arrangements, grid codes at the buses can be easily met despite the relatively low switching frequencies that are commonly used on IGCT-based converters. An optional shunt filter further reduces the harmonic distortions to a minimum.

C. Capabilities

The SFC may operate either in grid-supporting or in grid-forming mode. In grid-supporting mode the SFC feeds power to a bus, either in parallel with another SFC or in parallel with a generator. The real and reactive power are controlled with optional droop characteristics.

In grid-forming mode the SFC sets the bus voltage and its frequency. In a traditional setting, no droop control is used, and the bus voltage and frequency are stiff. As a result, the real and reactive power of the SFC are determined by the load, not by the SFC. The addition of an additional droop control loop softens the grid voltage and frequency, allowing the operation of two converters in parallel.

The converters may be overloaded for a few hundred milliseconds, providing currents in excess of their rated currents. This characteristic is particularly important during load transients as will be discussed in Section IV.

When a short-circuit occurs on the bus or at one of the connected loads, the SFC feeds a certain short-circuit current to facilitate the operation of protective relays. As in the case of overloadability, a short-circuit current beyond rated current can be sustained only for a short time.

D. Modes of Operation

As mentioned at the beginning of this section, the SFC system is capable of transferring power in a bidirectional manner. Power transfer from the 50 Hz to the 60 Hz side corresponds to *power from shore* (PFS) mode, in which loads connected to the 60 Hz bus are powered from the onshore 50 Hz grid and the subsea cable. The SFC may supply the loads on its own or run in parallel with the existing generator(s).

Conversely, when the PFS system is out of service and the subsea cable is disconnected, loads at the 50 Hz bus must be powered by the generators at the 60 Hz bus, giving rise to the *island mode*. The power flow of the SFC system is from the 60 Hz to the 50 Hz side. On the 50 Hz side, the SFC forms the grid and supplies the 50 Hz loads. As there are on-site generators on Platform 2, the SFC can also be run in parallel with the generators.

The SFC system can quickly reverse the power flow when needed and switch between the two modes of operation. Seamless transitions between different operation modes are paramount to avoid interrupting the production of oil and gas. For example, when the offshore system runs in *island mode* and is required to transition to the *PFS mode* the two grids must be synchronized. The phase angles of the two grid voltages must match each other when the circuit breaker between the two grids is closed. Since the PFS system is connected to the national grid with its phase given, the SFCs are required to synchronize toward the PFS system.

E. Utilization of Active Front Ends for VAR Compensation

The ac subsea cable requires VAr compensation at the onshore and offshore terminals. At the onshore terminal a shunt reactor is installed, see Fig. 2. At the offshore terminal, however, due to the limited available space, compensation is not considered and a dynamic reactive power compensation such as STATCOM or SVC is not used. Instead, the AFEs (at the 50 Hz bus) of the SFC systems can provide reactive power compensation during steady state operation and during transients. The AFEs of the drives that power additional pumps, see Fig. 2, may provide additional VAr compensation. During steady state operation, the SFCs and AFEs can be used to adjust the load power factor to adjust the current of the subsea cable at the offshore terminal. By doing this, optimal power flow can be achieved at different offshore load conditions.

The cable from shore is connected to the offshore platform through a tube called “J-tube”. The current capacity of the cable inside the J-tube is typically lower than the subsea section, as the thermal conductivity there is smaller. At high load conditions offshore at low power factor, the current in the J-tube may exceed the maximum current capability. The AFEs can be used to adjust the load power factor to reduce the cable current at the offshore terminal.

Load rejection due to process or emergency shut-downs on the platform can cause over-voltages offshore. In normal operation, the voltage control is done by the onshore OLTC transformer, which reacts very slowly (each tap change requires 3 to 8 seconds). A fast dynamic voltage control is required to meet voltage stability requirements. Typically, a STATCOM or SVC can be utilized. However, this equipment can only be installed onshore due to the limited space available offshore and, as a result, it is not as effective as a dynamic voltage reactive power control close to the disturbance. By implementing some voltage control function in the overriding control system, the reactive power capacity of the AFEs can be used to improve the offshore voltage stability.

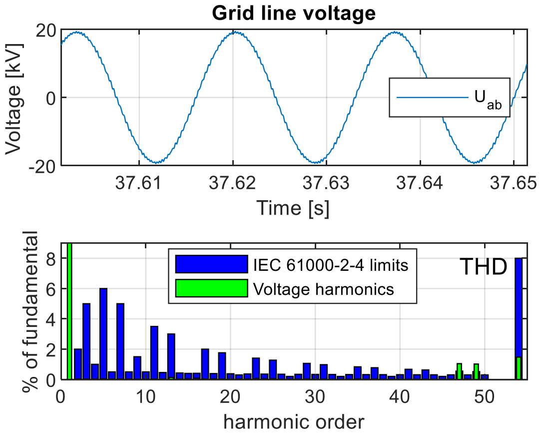

Fig. 6: Harmonic spectrum of the SFC output voltage

Large DOL motors with power ratings between 5 and 10 MW are common in offshore oil and gas installations. These motors have a start-up current of around 4 to 8 pu. The DOL motor starting current can cause a significant voltage dip on the offshore bus as well as the subsea cable system. The voltage dip on the cable system will lead to an increased cable current and a further voltage drop across the subsea cable. In the worst case, the offshore voltage collapses. In this case, the AFE can supply capacitive reactive power to support the offshore bus voltage.

IV. SYSTEM STUDIES

Various simulation and testing tools are required to aid the system design. During the conceptual design and front-end engineering design (FEED) phases, software-based simulation tools are used to verify and validate the performance of the SFC and PFS systems. The equipment specification and system control philosophy are also specified in accordance with the simulations.

In the engineering phase, a hardware-in-the-loop (HIL) simulator is employed, see Section V. The HIL simulator allows one to further verify and test the overriding control layer, the settings for the control parameters and the system interface. Thanks to these tests, the offshore commissioning and testing time can be reduced to a minimum.

A. Software-Based Emulator

The grid components and power hardware are modelled in Matlab/Simulink using basic Simulink and Simscape blocks. The control software of the SFC and VSD products, which includes the various control loops and the protection logic, is available in a so-called *Emulator*. Through a shared memory interface, measurements, control signals, status signals, etc. are exchanged between the Emulator and Matlab/Simulink. One Emulator is used for each AFE and SFC. The Emulator contains all parameter settings for the AFE and SFC control. Several simulation results are discussed in the remainder of this section.

B. Harmonic Spectrum

The main loads of the offshore system, such as compressors, pumps and heaters, are driven by power converters, such as VSDs and thyristor rectifiers. These loads inject voltage and current harmonics into the grid. In the worst case, the offshore power electronics loads exceed 90% of the total offshore power demand. Moreover, the SFC, which is a voltage source converter, generates voltage harmonics. The combination of (capacitive) cables and (inductive) transformers and DOL motors tends to result in harmonic resonances in the offshore system. The exact harmonic frequencies of these resonances vary depending on the specific offshore configuration, such as the subsea cable(s), transformers and motors in operation. This poses challenges on the system design, and imposes tight limits on the harmonic amplitudes that can be tolerated in the offshore grid.

The 12-pulse configuration of the SFC and the utilization of optimized switching patterns ensures that the output voltage harmonics are of low harmonic amplitudes, as shown in Fig. 6. During normal operation, the SFC only generates 47th and 49th harmonics. Based on the system studies, a shunt filter with a very small VAr rating is installed on the 60 Hz side of the system to further reduce the higher order harmonics. On the 50 Hz side, no harmonic filter is considered as the subsea cables act as filters.

C. *Reactive Power Compensation During Transients*

With the SFC system operating in *PFS mode*, the load shedding of all loads on Platform 2 was studied, which is connected via a subsea cable to the 50 Hz bus of Platform 1. As depicted in Fig. 7, the load shedding occurs at t = 90.4 s, resulting in an overvoltage of about 1.1 pu at the 50 Hz bus of Platform 1. As commanded by the overriding control system the AFE of the SFC system absorbs reactive power of about 12 MVAr. The offshore bus voltage is restored to about 1.02 pu within 100 ms. The SFC system successfully isolates the 60 Hz system from the affected 50 Hz system with minimal disturbances at the 60 Hz system.

The fast dynamic VAr compensation achieved by the AFEs reduces the duration of high voltage stress on system critical equipment and shortens the recovery time to sufficiently low bus voltages. The offshore AFEs are also more effective than an onshore STATCOM. With about 12 MVAr compensation required offshore, the reactive power required onshore is reduced from about 40 MVAr to close to zero, as can be seen in the lower plot in Fig. 7.

D. *DOL Motor Start*

Consider again the SFC system operating in *PFS mode*, powering the 60 Hz bus in *stand-alone mode* with the generators turned off. Fig. 8 shows the reaction of the SFC to the start-up of a large DOL motor at the 60 Hz bus. The magnetization of the motor results in an instantaneous voltage dip of 11 %, which the SFC reduces to 3 %. Once the motor has reached its nominal speed the bus voltage is restored to 1 pu.

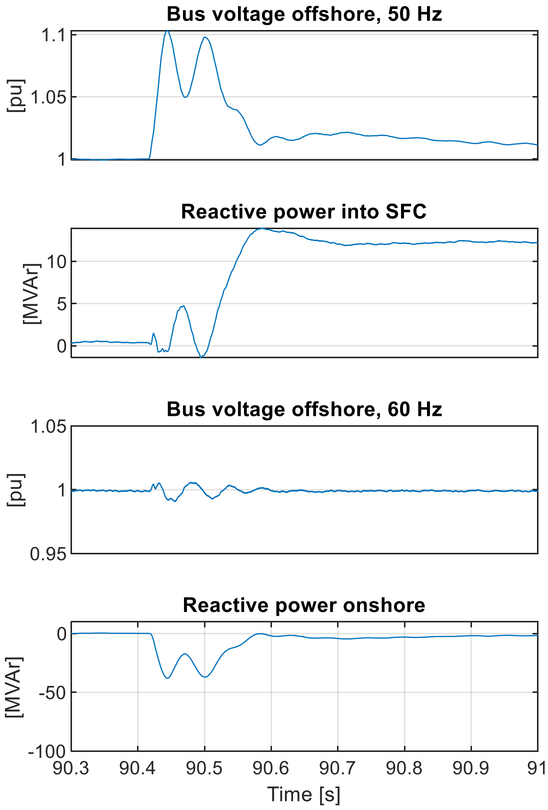

Fig. 7: Reactive power compensation during transient

Note that the voltage control loop of the SFC is much faster than that of a generator with an automatic voltage regulator (AVR). The close-to-nominal bus voltage reduces the time required to start up the motor.

When the motor breaker is closed, a high inrush current results, which might exceed the SFC overcurrent trip limit. The SFC control scheme is equipped with a methodology to quickly detect such an imminent overcurrent situation and to issue switching vectors that prevent the current from further rising, thus preventing an overcurrent trip of the SFC system. This function is always active in the SFC and will also react to an overcurrent caused by a transformer being energized.

E. *Equal Load Sharing with SFCs Operating in Parallel*

Recall that, in general, two SFC systems operate in parallel. For this reason, the equal sharing of the load currents is mandatory both during steady-state operation and transients. The latter being more demanding, the load sharing during a transient is considered here using the example of the previous subsection of a DOL motor start-up.

The two SFCs have the same control and parameter settings, but their transformers have slightly different impedances due to the transformer tolerances. As shown in Fig. 9, the current response is fast and the peak current of the inverter currents after the motor start is similar for the two SFCs systems.

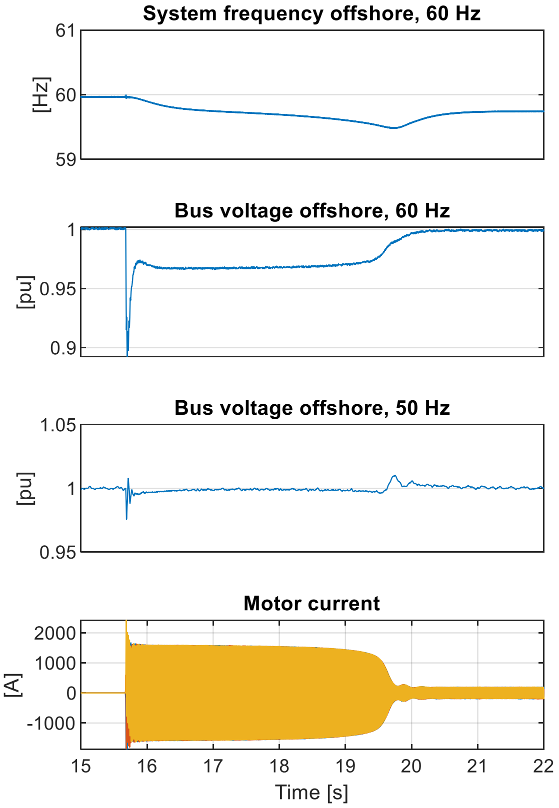

Fig. 8: DOL motor start at 60Hz bus

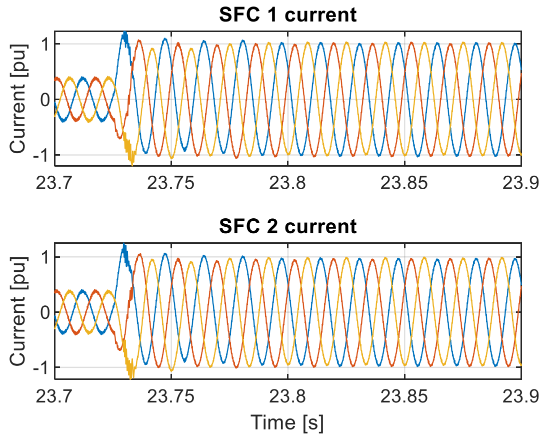

Fig. 9: SFC load sharing

F. *Short Circuit*

A three-phase fault at one of the DOL motors at the 60 Hz bus is studied while the SFC supplies the 60 Hz side in parallel with a generator. When the fault occurs at t = 21.5 s, the SFC output current quickly rises, as shown in Fig. 10. Due to the collapsed bus voltage the SFC concludes that a short-circuit has occurred. It prevents a further increase in the phase current and switches to the short-circuit mode during which it supplies a pre-determined short-circuit current that exceeds its nominal current. The generator with its higher short-circuit current capability provides most of the fault current.

The short-circuit current is detected by the protective relay of the DOL motor, which clears the fault after 100 ms. It takes less than 50 ms for the SFC to detect that the short circuit has been cleared (at t = 21.65 s, see the lower plot in Fig. 10). The SFC stops modulating and synchronizes its output voltage with the 60 Hz bus voltage. Once this has been achieved, the SFC operates again in parallel with the generator and helps to restore the bus voltage.

Note that the fault on 60 Hz side system does not affect the 50 Hz side system voltage.

G. *Short Circuit and Generator Trip*

Consider a similar fault scenario as in the previous subsection with the SFC operating in parallel with one generator to supply the 60 Hz loads. After the fault has occurred at t = 25.34 s on the generator terminal, the SFC controls its output current to the defined short-circuit current value, as shown in Fig. 11.

After the generator has been tripped by its protection relay and the fault has been cleared, the SFC switches from short-circuit current control mode to *grid-forming mode* after having received the *generator tripped* signal. The SFC then starts to ramp up the 60 Hz bus voltage with a pre-defined ramp-up time, see the lower plot in Fig. 11.

H. *Grid Synchronization*

Initially, the offshore system runs in *island mode* with the PFS system disconnected. To allow the connection of the PFS system, the 50 Hz SFC grid must be first synchronized to the PFS grid. In doing so, the SFC (the follower*)* grid must adjust its voltage, frequency and phase to match the PFS (the master) grid before closing the circuit breaker between the two grids.

A synchronization device is used for measuring the grid voltage and frequency differences and for providing raise and lower commands for voltage and frequency. These

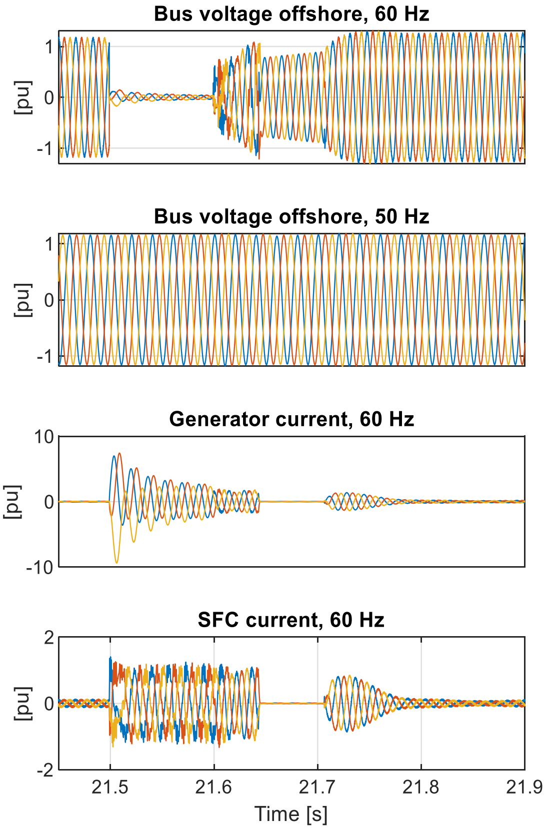

Fig. 10: Short circuit at 60 Hz bus

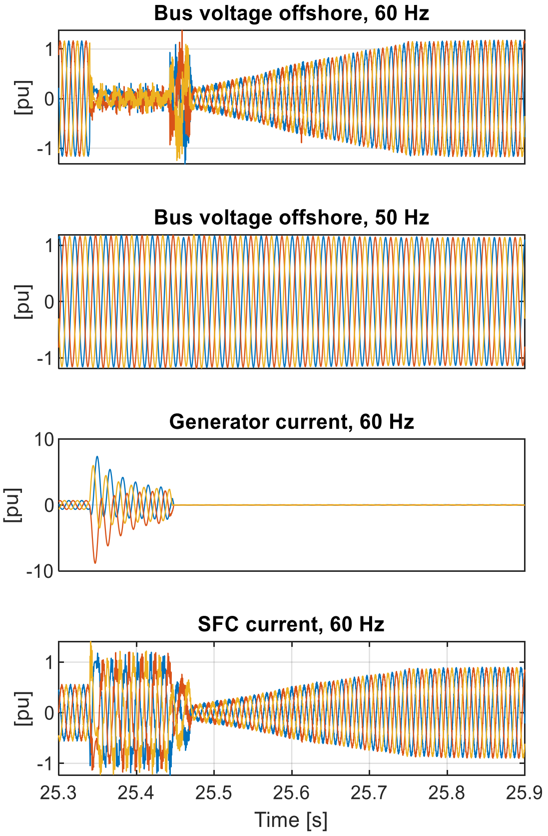

Fig. 11: Short circuit at 60 Hz bus with trip of generator

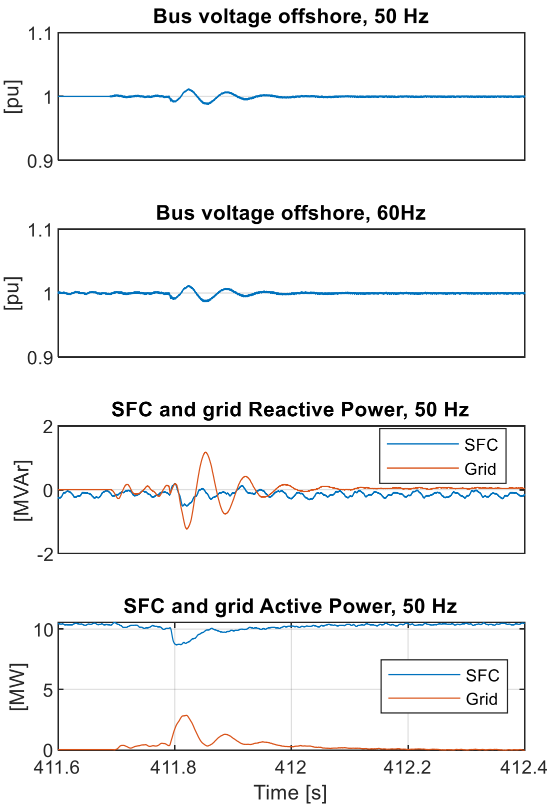

Fig. 12: Synchronization towards shore connection

commands are sent to an overriding controller, which translates them to reactive and real power references that are forwarded to the two SFCs. To avoid any significant impact on the grid, the power of the SFCs should be constant when closing the breaker between the two grids.

As shown in Fig. 12, the system runs initially in *island mode* with the SFC being in grid-forming mode and supplying the loads at the 50 Hz side. The SFC then synchronizes towards the PFS grid. The breaker is closed at t = 411.70 s when the angle difference between the two grids is less than 1 degree. With the proposed overall synchronizing logic, there are no transients during the synchronization and after the breaker has been closed.

The SFC keeps running in grid-forming mode for another 100 ms when it is set to parallel mode (at t = 411.80 s). Some small transients can be seen at this instant, which are caused by the current controller of the SFC.

V. HARDWARE–IN–THE–LOOP TESTS

Further testing capabilities are possible beyond a PC-based digital twin, which provide a different testing range. One such testing method is utilizing a Hardware-in-the-Loop (HIL) simulator for a digital string test. The hardware to be integrated into the HIL simulator can be done at different levels. Naturally, large components such as transformers, grids, and static and dynamic loads tend to be emulated within the HIL, see Fig. 13 and Fig. 14.

The following case example presents the used case of a HIL where the SFC control hardware is integrated with a real-time simulator which emulates the grid, loads, and other VFD's. The HIL simulator is then able to substitute as a "digital" string test. A key component to such test is to cross-collaborate among the converter supplier, system integrator(s), EPC, and customer to define a thorough HIL testing campaign protocol.

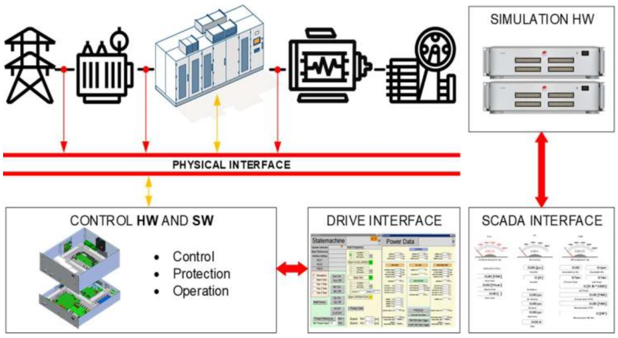

Fig. 13: Hardware in the Loop (HIL) simulator solution

The testing after a PC-based simulator is the interface with the converter control hardware and an over-riding controller system (OCS) or power distribution control system (PDCS). Actual software and parameters can be utilized on both the OCS/PDCS and the converter without the need for manual manipulation such as forcing fieldbus or I/O signals.

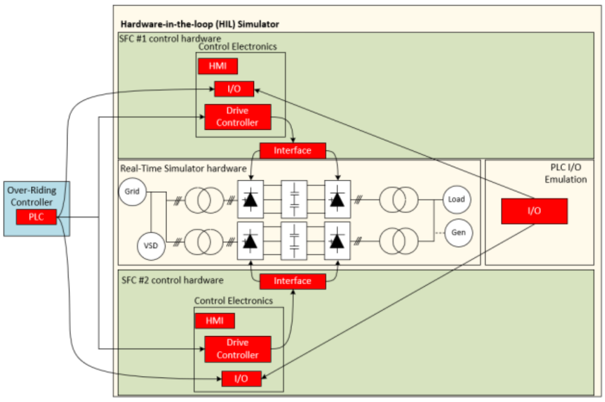

Fig. 14: Diagram of example HIL simulator for system integration testing

Once the drive controller and over-riding control software are validated for proper interface and data communication, then system simulations can be done in real-time with the advantage of simulation hardware. The HIL can be used to further validate the PC-based simulations earlier mentioned in Section IV.

With the HIL system thoroughly tested according to a HIL test specification, the converter parameters can be extracted from the HIL drive controller hardware for implementation on the full-scale converter at the time of commissioning. This provides a significant risk mitigation for the onsite activities to take place.

VI. CONCLUSIONS

This paper has presented one method of decarbonizing offshore operations by electrification by an onshore grid, also called power from shore (PfS). Some key enablers to achieve such electrification are the use of static frequency converters (SFC) and active front ends (AFE), which are used for frequency conversion for specific equipment and to compensate the grid. Lastly, tools such as PC-based digital twins or hardware-in-the-loop (HIL) simulators provide system integration tests and validation prior to going full scale.

VII. ACKNOWLEDGEMENTS

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VIII. VITA

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