Experimental Validation of a Power Electronics Dominated Microgrid: A Study Case of an Offshore Wind Powered Water Injection Process.

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***Abstract*—The offshore micro-grid concept is an interesting and promising solution for remote places where renewable energy is available to supply power to industrial applications. As a result of multiple power electronics grid interfaces within the featured micro-grid, this type of isolated micro-grid represents a power electronics dominated power grid. The proposed MW offshore micro-grid concept is challenged by zero power system inertia; extremely short electrical distance between components; no coupling transformer from the individual subsystems; and a generation-driven process that must cope with the variability of wind power output. The aforementioned features of the micro-grid present the technical challenges for the controllability of the micro-grid. This paper presents the proof-of-concept of the proposed offshore micro-grid, modelling and design of the power electronics controller, the selection of test cases, the experimental test setup and the results of the validation carried out by a variant of Power Hardware in the Loop methodology. The validation focuses on the electrical small-signal stability of the low-level controllers used in the power electronics applications (i.e. a wind turbine generator, a battery energy storage, and a variable speed drive for the water injection processes) within the offshore micro-grid and the generic functionalities of the proposed master controller implemented for the power management system (PMS)of the micro-grid. The main objective for the lab test phase is to identify the main risks and develop guidelines to be considered for the connection and inter-operability of multiple power electronics applications within an offshore micro-grid concept. The lab test results affirmed the overall process behaviour and demonstrated the proposed micro-grid can operate in stable manner without invoking small signal instability due to harmonics.**

I. Introduction

Driven by the mandate of Paris Agreement to significantly cut CO2 emission and improve energy efficiency, the oil and gas industry is actively seeking new technology alternatives to improve the energy footprint of their oil and gas extraction activities. Water injection is a common practice to maximize the oil recovery from oil reservoirs. However, this approach demands large amount of electrical power, and therefore results in costly offshore energy infrastructure.

Moreover, the energy availability is not guaranteed in all the offshore platforms, and it is dependent on the available infrastructure on the platform or the distance to the shore plus the availability to the grid connection. The energy availability is a constraint for many projects for which a technical solution is needed to do any investments. Given the rapid development of the wind power industry in the offshore sector and the proven demonstration projects of the floating wind turbines, oil and gas is turning to wind turbine generator for powering their offshore industrial processes.

The WINd powered Water INjection (WIN WIN) concept integrates the use of a floating wind turbine generator and an electric battery storage to power up the process of water injection in a micro-grid (Fig.1). This concept has been proved to be cost-competitive solution to reduce the emission and meet the technical requirements of the extraction activities. This paper presents the experimental work carried out to prove the technical feasibility of an offshore micro-grid.

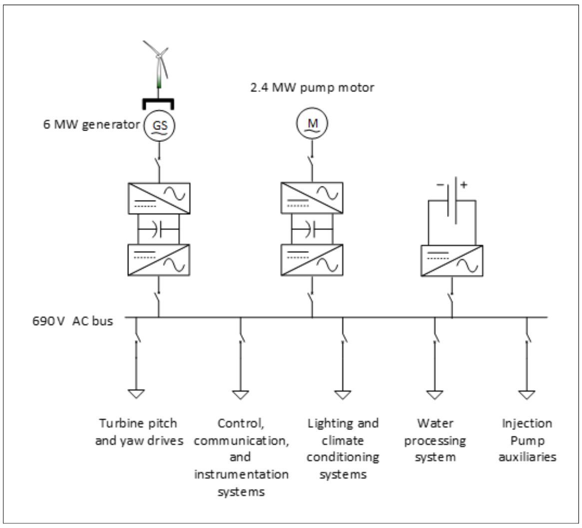

Fig. 1. WIN WIN Microgrid

The WIN WIN micro-grid represents a challenging electrical power system, where the unique features are summarized below:

- MW offshore micro-grid with no power system inertia;
- No transformer at the point of connection for the main subsystems to the common busbar;
- Extremely short electrical distance between subsystems;
- Variable wind power generation;
- Generation-driven process, i.e. water injection processes based on the available power.

To successfully operate this offshore micro-grid, both low-level and high-level controllers design is of high importance to maintain a stable voltage and frequency at all time and is elaborated in the following section.

II. Design of micro-grid

Firstly, a process demand assessment was performed to define the system size and system operation philosophy, based on the safety and operation regulations of offshore oil and gas platforms.

Following the technical specification of subsystem in the offshore micro-grid, a real-time model of the micro-grid is built. The model focuses on the design of the generic low-level power electronics controllers to connect the individual subsystem (i.e. a floating wind turbine, a battery energy storage system and a water injection pump driven by variable speed drive) to the micro-grid and the master controller that oversees the PMS of the micro-grid.

The battery energy storage system low-level power electronics controller is the backbone of the micro-grid and is operated as a grid-forming voltage source converter (VSC) with the active-damping function to improve overall system stability. The wind turbine and water injection pump low-level power electronics controllers include the phase-locked loop (PLL), the AC current controller and the DC bus chopper control. The choice of the controller parameters in conjunction with the output filters selection are fundamental aspects to ensure the small-signal stability of the proposed offshore micro-grid.

The master controller is in charge of fulfilling the operation philosophy required by the process (i.e. maintain the power balance in the micro-grid and handle any alarms/faults in the system)

Since the aim of the lab test is to confirm the electrical stability at the micro-grid bus, the model of the wind turbine generator and variable speed drive were simplified with their application specific generation and consumption stages represented by a current source connected in parallel to their DC link capacitance.

III. Experimental work

The experimental work focuses on the validation of the electrical stability of the micro-grid during the different operation modes and the transitions between them. The transitions between modes are the most interesting, since the electrical transients will be present and the controllers are challenged to the extreme conditions, which could make the micro-grid unstable leading to an unfeasible concept.

The test cases consider the normal operation scenarios and operation scenarios when the major subsystems are suddenly disconnected at its nominal power i.e. a load rejection or a generation disconnection. For these test cases, two fundamental assumptions were made:

1) all the communication and control are always available for the continuous execution
2) the micro-grid can only handle single failure.

It is important to mention that short-circuit calculation and protection coordination studies were not included in the scope of work.

A. Experimental setup

The experimental validation of the WIN WIN micro-grid concept, using a variant of PHiL, was carried out in DNV GLs Flex Power Grid Laboratory (FPGL) in Arnhem, the Netherlands.

1) Experimental methodology: A Power Hardware in the Loop (PHiL) methodology was chosen as the experimental method in the laboratory, and the equipment under test are the digital controllers of the micro-grid built in the real-time simulator and inter-connected via power amplifiers that receive voltage/current set-points from the digital controllers. Compared to an offline EMT simulation study, the proposed PHiL setup allows explicit consideration of the digital delay critical to the stability of the micro-grid, the non-ideal current/voltage measurement, and the power coupling of multiple power electronics connected to the vicinity of each other.

The micro-grid is divided into four nodes, three of them are at the point of connection of the power electronics subsystems and the fourth one is where the passive loads are connected. These nodes will be the interfacing points to the amplifiers in the PHiL testbench. The voltage ideal transformer method (ITM) is the interfacing method for the battery energy storage system within the micro-grid, since it is the grid-forming node. The other three nodes are interfaced through the current ITM.

2) Power setup: The test bench consists of a real-time simulator and 16 independent amplifiers. The amplifiers have a bandwidth from DC to 5 kHz, which renders good representation of the fast electrical dynamics to be expected in the MW micro-grid.

The test bench is in the kilowatt range, this means that there is a scaling factor between the model and the test bench.

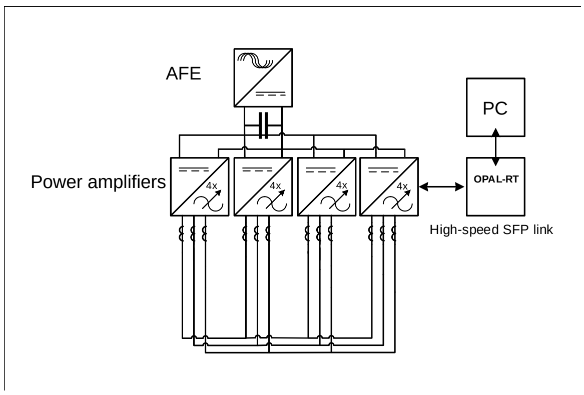

Fig. 2. Power setup

3) Monitoring interface: For the demonstration and monitoring of the experiment, a Human Machine Interface (HMI) was developed to help operate and visualize the different operational states of the microgrid.

B. Results

The testing phase included ten base test cases with the distinct wind profiles and the controller settings. In this paper the case of the water injection pump subsystem (WIPS)

Fig. 3. 16 independent amplifiers

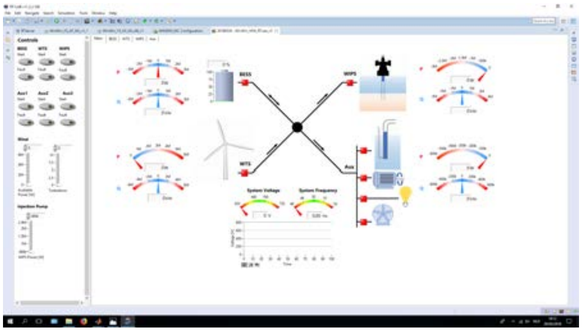

Fig. 4. Visual interface

disconnection is presented. In table I, the load profile of the micro-grid before the disconnection of the water injection pump is shown. Before the disconnection contingency, the micro-grid is in nominal operation conditions, this means the wind turbine and load is at maximum possible operation conditions.

TABLE I
LOAD PROFILE BEFORE WATER INJECTION PUMP DISCONNECTION

Subsystem	Active Power	Reactive Power
Wind Turbine	3 MW	0 kVAR
Electric Storage	-121 kW	160 kVAR
Water Injection Pump	-2.4 MW	-241 kVAR
Auxiliary Loads	-550 kW	-250 kVAR

When the WIPS is disconnected, the micro-grid experiences a load rejection of 2.4 MW in about 100 ms. This event causes a significant electrical transient at the micro-grid common busbar, which is handled successfully by the battery energy storage subsystem.

Figure 5 shows that voltage increases up to 12% more than the nominal voltage for about 30 ms. This case proves stability of the micro-grid system is maintained despite transient voltage overshoot.

The response of the battery energy storage system is shown in figure 6, where it portrays how it takes over the lost load and helps the wind turbine ramp down its power output to the minimum load in the micro-grid.

After the disconnection of the WIPS, the load profile of the micro-grid is summarized in table II. It is important

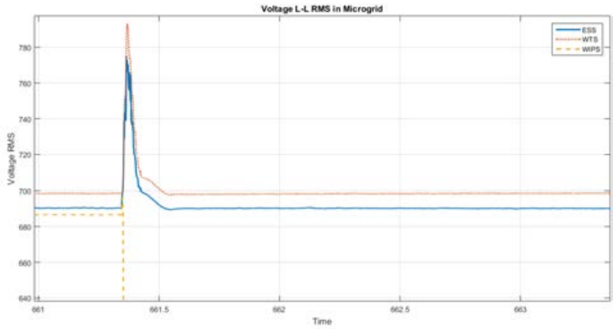

Fig. 5. Vrms in all subsystems

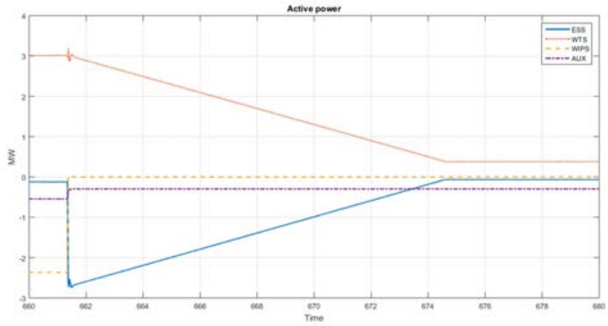

Fig. 6. Active power in all subsystems

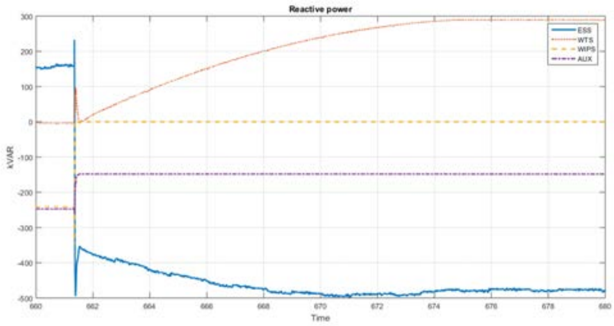

Fig. 7. Reactive power in all subsystems

TABLE II
LOAD PROFILE AFTER WATER INJECTION PUMP DISCONNECTION

Subsystem	Active Power	Reactive Power
Wind Turbine	380 kW	290 kVAR
Electric Storage	-63 kW	-477 kVAR
Water Injection Pump	0 MW	0 kVAR
Auxiliary Loads	-300 kW	-150 kVAR

to add that the load profile is affected by the test bench by approximately 330 kVAR capacitive reactive power, this is due to the charging currents of the output filters in the amplifiers. These are in the mA range, however when scaling up the test bench measurements it is seen in the kVAR range in the simulation results.

IV. Conclusion

This project has proven that the controllability of the WIN WIN micro-grid concept will not be a show-stopper. The different test cases have validated normal operation modes and the transitions between them. The most demanding cases were the disconnection of the wind turbine and the water injection pump. However, the results also showed the expected transient behaviour that is a fundamental input to determine the proper specification of equipment (including their respective controller) and the coordination of equipment protection and insulation.

1) Master controller: The master controller was validated and in compliance with the required operation philosophy. It was also possible to identify the impact of the micro-grid master controller logic's on the overall system stability. When it is not properly programmed to handle the disconnection/transition states it can compromise the small signal stability of the low-level controllers. Moreover, this controller also has an effect on the electrical transients hence affect the specification of the electrical equipment.

2) Low level controllers: A fundamental point for the low-level control of the wind turbine and water injection pump is the design of its PLL. It is important to restrict the bandwidth to avoid small-signal instability as a result of low short circuit power in the micro-grid.

A system study on the harmonic emissions of the battery energy storage system is required to determine the output filter for the current controllers in the micro-grid in order to avoid any harmonic interactions. This is particularly necessary in this configuration since there is no transformer with galvanic isolation at the point of connection.

The proposed PHiL methodology has proven to provide a holistic controller function and performance verification and increase the level of confidence on the WINWIN concept.

Future work for this concept requires a short circuit and protection coordination study.

ACKNOWLEDGMENT

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