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Grid Integration for Marine Renewable Energy Devices in a Real Time Application

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Abstract—This paper describes the integration of real time hardware-in-the-loop (HIL) equipment into a marine renewable test bed. An OPAL-RT real time simulator is to be used for testing of an emulated Marine Renewable Energy (MRE) system on a microgrid in the Lir-National Ocean Test Facility. The flexibility offered by this simulator enables comparison simulated with hardware to show that the simulation method is validated, so that in the future further simulation work at a fraction of the cost can be done. A validation method for the compliance with Triphase power converters with the real time simulator is proposed for the study of power transmission between the microgrid and the grid through transmission lines.

Index Terms—Ocean device testing, hardware-in-the-loop, real-time simulation, microgrid integration, power analysis.

I. INTRODUCTION

Microgrids comprise low voltage distribution systems with distributed energy resources (DER) such as microturbines, fuel cells, photovoltaics (PV), etc. together with storage devices (flywheels, super capacitors and batteries) and flexible loads. Such systems can be operated in a non-autonomous way, if connected to the grid or in autonomous way, if disconnected from the main grid (islanded mode) [1].

OPAL-RT is a leader in the development of PC/FPGA Based Real-Time Digital Simulators, Hardware-In-the-Loop (HIL) testing equipment and Rapid Control Prototyping (RCP) systems. RT-LAB software from OPAL-RT is fully integrated with MATLAB/Simulink and various hardware and software platforms are available for power systems and power apparatus. These systems are used to design, test and optimize control and protection for different systems, such as power grids, microgrids, power electronics, and so forth [2].

To enhance their range of experimental testing, some laboratories using microgrids have integrated an Opal-RT real-time simulator into their facilities. The Electricity Research Centre (ERC) in University College Dublin (UCD), use the RTS OPAL-RT OP5600 real time simulator as a platform for investigation of the interaction between a scaled hardware version of a Doubly Fed Induction Generator (DFIG) wind turbine and the grid. The Opal-RT platform is used for the low frequency AC transmission construction in hardware [3].

Research has been done to simulate the Lanai Island (Hawaii) grid network in MATLAB/Simulink environment. To accommodate real-time simulation of the hybrid power grid system the Opal-RT Technologies RT-Lab has been used. This electric power grid system includes the integration and control of a PV distributed generator system [4].

In the Smart-Grid Test Bed at Washington State University Ibarra Hernandez and his team propose a control strategy for the energy management of islanded microgrids using multi-agents formed by PV solar energy, batteries and resistive and rotating machines loads. The management and control of the PV system is performed in JADE (Java Agent DEvelopment Framework), while the microgrid model is simulated in RSCAD/RTDS (Real-Time Digital Simulator) [5].

A complete technical report written from a collaboration between the MIT Lincoln Laboratory and an industry microgrid controller covers the development of an Opal-RT 5607 platform to evaluate microgrid controllers as this platform accepts models from MATLAB SimPowerSystems. They adopted some built-in models in the MATLAB-Simulink libraries such as three-phase series RL branches, ideal switches, and measurement probes. Their work also involved simulation of cables for different grid strengths and the study of impedances and X/R ratio. Opal-RT simulated system was interfacing Woodward easYgencontrollers via digital I/O [6].So OPAL-RT is already well implanted in the research area of renewable energy however, little has been done on the integration process of the simulator especially in the domain of ocean energy.

The Lir - National Ocean Test Facility (NOTF) has an integrated electrical lab with wave to wire emulation capabilities. The laboratory includes a medium speed rotary emulator and a microgrid. The microgrid consists of a dual-bus three phase 400 V system. Generation, storage and load elements can be added to create a wide variety of test configurations [7]. The microgrid can be operated either with the local grid or as an islanded system. Sources of power include a 33 kVA diesel generator, a wind/ocean energy emulator, and fully controllable Triphase back-to-back 90 kW and 15 kW converters. These converters can exchange power between the

grid and microgrid and offer significant flexibility in testing. Storage is provided by a 5 kWh lithium ion battery with 10 kW peak power flows. Fully controllable and adjustable loads with leading and lagging power factors are available including a 50 kVA loadbank manufactured by Crestchic. Robust system control is provided by industry standard Programmable Logic Controllers (PLCs), while high speed data acquisition is offered by a National Instruments cRIO system.

An Opal-RT power HIL system allows advanced emulation of large grid models. This will allow investigation into large microgrids including DC microgrids, and the effects of long transmission lines, and the interaction between these software-based grid models and laboratory hardware. The OPAL-RT offers a simulation environment to facilitate MRE power take-off integration. An islanded microgrid model with loads, sources, transformers, transmission lines, and batteries can be created in MATLAB/Simulink.

The paper presents the OPAL-RT real time simulator and its installation within the Lir-NOTF Electrical Laboratory in section II. Section III focuses on a method for the validation of the integration including an experimental setup with the theoretical study for results comparison. Section IV suggests options for the integration of a MRE device with the study of microgrid elements such as transmission lines or loads.

II. THE OPAL-RT SIMULATOR INTEGRATION INTO THE LIR-NOTF

A. Real-time simulation

Offshore testing is time and resource intensive. Mistakes at this late stage of the design process are expensive to fix. Simulation tools allow verifications throughout the project and early detection of errors (during design and development). As test coverage is indeed better, a complex system can be studied in detail with simulation and fault conditions are able to be tested safely. Risks and cost are reduced: there is no need for a real system or prototype, faults are detected earlier and malfunctions are minimized after installation. Even after the design of systems, simulation brings valuable help at different stages of a project during validation of control and supervision devices, commissioning, impact studies and maintenance [8]. Real-time simulation establishes the link between the controller and the plant or the actuator. The controller needs to take into account measurements, compute the control algorithm and generate commands within a fixed amount of time. If this fixed time is too little, real time is not achieved and the controlled system may not behave as expected. If the computation time is higher than the time step, the real-time simulator is facing an overrun. As a consequence, real-time is required when hardware is connected, it ensures coherent time responses (determinism) and allows the simulation to integrate the real hardware. The HIL concept is basically the ongoing communication between the simulator and the hardware. The design of the model in a MATLAB/Simulink environment for example is executed on the Real-time target PC to carry out tests and measurements on the hardware and adapts the model in real-time to get the desired behavior. In the

Simulink configuration parameters, the time-step of 50 μs is typically used for most transient simulation studies conducted in power grid design. Variable-step cannot be used in real-time application because the system is causal [2].

Fig. 1: OP5600 simulator

B. The simulator installation

The OP5600 real-time digital simulator in Fig.1 consists of an upper section that contains analog and digital I/O signal modules and a bottom section which contains the multi-core processor computer and FPGA that runs RT-LAB or HYPER-SIM real-time simulation software platforms. The OP5600 can be used either as a desktop system or rack-mounted as part of a network of OPAL-RT simulators communicating through high-speed PCI-e links [2]. The simulator is connected via Ethernet RJ45 cables to be monitored by an engineering computer on which RT-LAB software is also installed. To run a Simulink model on the target PC, the model has to be built and loaded before being executed. However, the authors have found that communication issues can occur and the system has to be restarted.

In the Lir-NOTF Electrical Laboratory, high frequency IGBT based power converters made by Triphase NV, that can exchange powers between a battery system or the main grid and the microgrid based on controls and algorithms developed in Matlab/Simulink. In 2014, Triphase NV and OPAL-RT agreed an industrial partnership to propose an integrated solution for Power HIL applications. The three-phase 90 kW bidirectional power module PM90A30F60 designed and created by Triphase NV is to be used as an amplifier to provide means to integrate high-power equipment with OPAL-RT real-time simulators in a closed loop. Both can be operated using the same MATLAB version: 32bitRelease 2015a Service Pack 1 (R2015aSP1). Although it is required to have two

MATLAB/Simulink windows open, one to operate Triphase power converters and the other to operate the OPAL-RT.

C. Hardware integration

Interface between hardware and software is shown in Fig. 2. One application of the system is for the study of the effects of the power generated from the available MRE emulation generator in the laboratory on the software model. Vice versa, the model effects on the power take-off (PTO) of the DER can then be investigated in this HIL system.
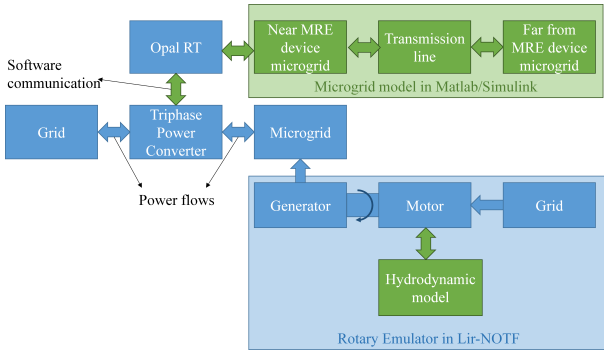

Fig. 2: Wave-to-wire block diagram

An hydrodynamic model developed in MATLAB/Simulink reproduces the PTO forces on the simulated MRE device. The rotatory emulator feeds the microgrid as a source and power flows can be studied. A more detailed schematic with signal cables is shown in Fig. 3. This diagram shows the different devices inside the Lir-NOTF laboratory with their mutual connections and the signal cables. Power is flowing through the Triphase power converter which is externally supplied by the grid, it enables the main switch to be opened for islanded mode. If the main switch is closed, then the study of microgrid to grid integration is possible.
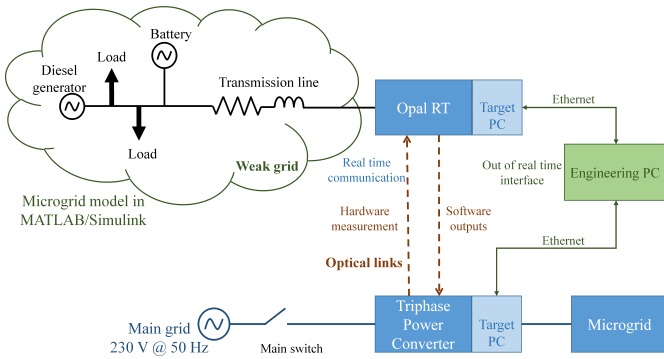

Fig. 3: Laboratory hardware setup

Moreover, different levels of complexity of weak grid models can be simulated on MATLAB/Simulink and run inside the OPAL-RT target PC. Two optical cables link the OPAL-RT and Triphase target PCs, it enables real-time communication between them enabling constant mutual feedback.

III. SYSTEM VALIDATION

A. Validation process

Once the engineering PC communicated to the OPAL-RT simulator and the Triphase target PC individually, it had to be confirmed that the optical fibre ensuring the connection between the two devices operated and enabled their communication channel. To that extent, a loop back test had to run on each target computer before being connected for real-time communication. The test consists in determining if the devices' communication works correctly. One signal is sent through the optical cable and returned to the same target computer. Once established, each entity has separate function:

- The OPAL-RT simulator contains the main software model. Its environment is handled by RT-LAB running with MATLAB/Simulink for the model design. It collects the data from the Triphase power converter and model through the optical fiber.
- The Triphase system includes a target PC. The Triphase software controls the power converters and interacts with OPAL-RT. The Triphase hardware consists of back-to-back converters, power amplifiers and sensors for signal acquisition.

The software RT-LAB interface is shown in Fig. 4 and Fig.5. A model running in OPAL-RT is composed of at least of two subsystems. One is the master which is synchronized in real-time, the other is the console and interfaces the engineering PC in real-time, however the connection is asynchronous. This can bring some delay in the real-time visualization of signals through the console.
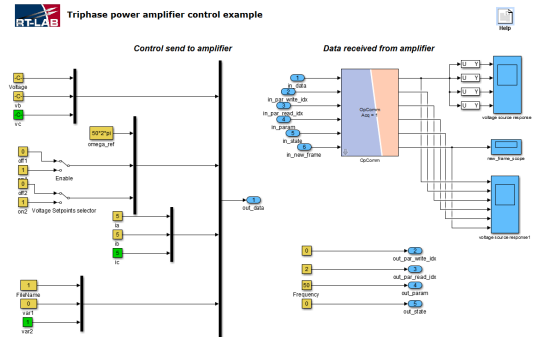

Fig. 4: Console subsystem view

The console subsystem has been designed to allow the user to observe the signals through scopes and interface the model parameters in real-time. However, some fundamental block elements from Simscape Power Systems (formerly SimPowerSystems) in Simulink library have non accessible parameters for real-time modification. This issue can be bypassed with switches between the same blocks with different settings.

The blocks in the master subsystem ensure the data transmission with the Triphase Power Converter. They are separated
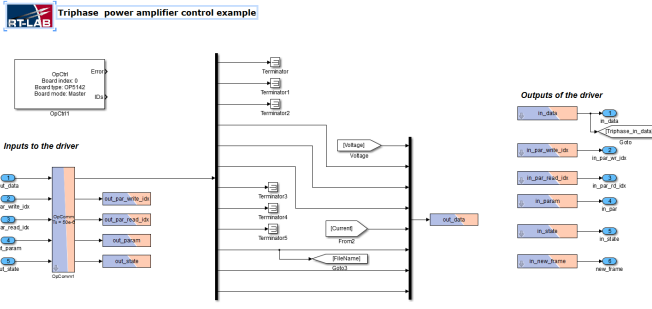
Fig. 5: Master subsystem view

Fig. 7: Parallel models in back-to-back configuration

between inputs (to the simulation model) and outputs (signals to the Triphase Power Amplifier).

B. Experimental Setup

This section describes an approach to prove the compatibility of equipment in the lab and its integration to properly carry out tests. The goal is to test the quality of the signals communicated between the Triphase power converter and OPAL-RT to see if it can be used to feedback into the simulated model. A simple model is studied to validate the integration. A voltage source V_g and associated line impedance Z_t can be simulated to power an available external variable load R_h. Fig. 6 shows the single phase equivalent model.
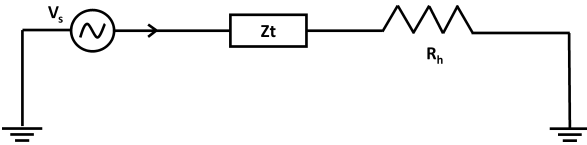

Fig. 6: Simple single phase model for experimental validation

The first step involved creating the full circuit as a Similunk based model. The second step consists of splitting the model into a hardware part and a software part. Fig. 7 shows the operation principle of the experiment. The source voltage V_g and the transmission line impedance Z_t are set in software and the voltage output is sent to set the hardware voltage source V_s which powers the load bank R_h. Both V_h and I_h are controllable.

The resistive load bank is adjustable using switches. The experiment is the following:

- The resistive load bank is connected with no load.
- The load is decreased manually from 80 Ω to 40 Ω to 20 Ω before being increased to 40 Ω to 80 Ω to open circuit.
- The voltage phase to ground waveform and its RMS value, the current and the THD are logged in a MAT-file in software. It is possible to get hardware measurements with sensors and power analyzers which are logged at a
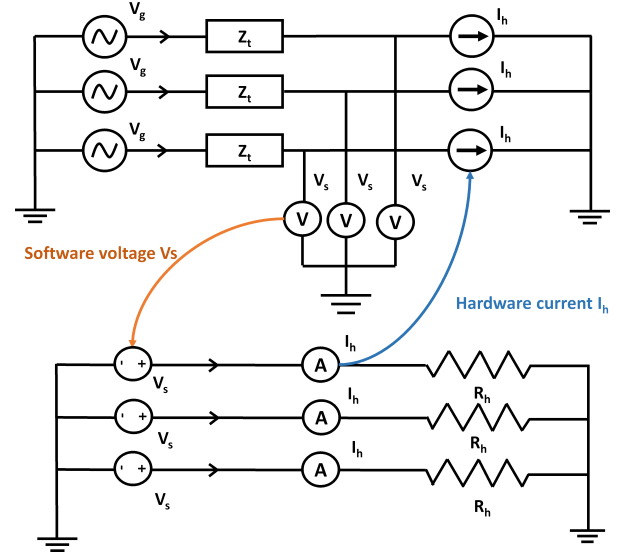
point where the Triphase power converter is connected to the microgrid and in this case the external load bank.

C. Expectations

Theoretically if it is assumed Z_t is a constant parameter, V_s is also constant. The power of the load bank is $P = \frac{U^2}{R_h}$, so when it increases R_h decreases. And,

$$V_h = V_s \frac{R_h}{R_h + Z_t} \tag{1}$$

It is seen in Equation 1 that the voltage V_h is an increasing function of the loadbank resistance R_h. If the load increases, the voltage decreases.

D. Results

Once the OPAL-RT simulator and Triphase power converters are running together, the resistive load bank can be connected to the microgrid buses and the operator can manually change the load. OPAL-RT features enable data to be recorded in a MAT-file at a sample time of $T_s = 50$ μs.

Fig. 8 shows the phase to neutral voltage at the PCC over time. The resistance of the transmission line is set at 10 Ohms to make the gaps dramatic. The voltage frequency is set at 50 Hz. The RMS values of the measured voltages are shown in Fig. 9. They are compared to the voltages which are expected from theoretical calculations for load values from 0 kW to 8 kW. The decreasing load voltage profile with increasing load power draw is as expected. However, we can still observe a gap between the measured voltages and the theoretical ones obtained by calculation and verified in a full idealised simulation. The error evaluated for this experiment was up to 15%. Currently, work is ongoing to identify the cause of this relatively large error and implement measures to achieve
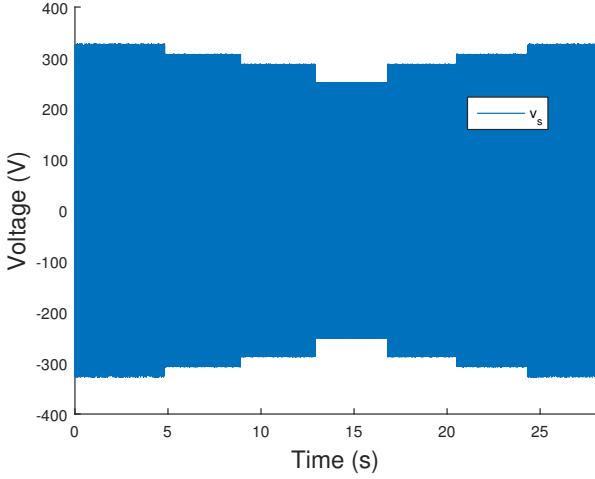
Fig. 8: Load voltage steps

a better correlation between theory and experiment. Once this work is completed further work with hardware experiments will be carried out. Validating a setup with a simple load in hardware was the first step before working with a MRE device emulator.
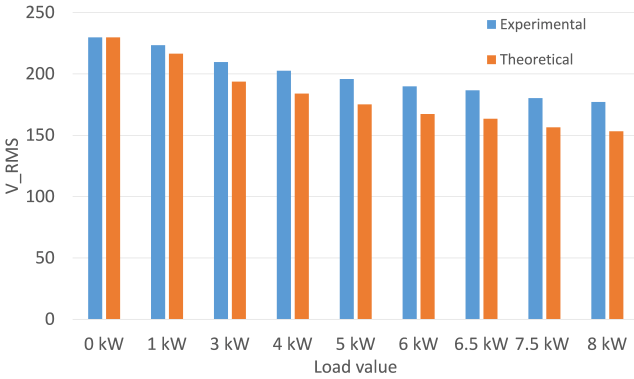

Fig. 9: Comparison of voltage levels at the load

This phenomenon does not come from an incorrect calibration of the voltage measurements as when the load is set as an open circuit and drawing 0 kW, the error is zero between voltage and hardware. However, we suspected a constant gain in the communication chain between the measurements and the target PCs. This gave similar results to those gained when put into the full simulation model created. Accordingly, further investigations have been carried to verify this hypothesis. After sending simple signals and trying to loop back the Triphase and the OPAL-RT target PCs in both directions no gains were found. This method consists in looping each target PCs output to the input, if the signal sent is equal to the signal received in real-time, it means that no error comes from the

communication. Initial measurements also verified the gains of the current and voltage sensors in hardware and in software. The work in [9] gives some recommendations on control loop bandwidth and filter design. A control issue is suspected in the Opal RT And Triphase power converter controller system, and this is currently being investigated.

IV. MRE DEVICE INTEGRATION

Once the system is improved so that experimental results more closely resemble simulated and theoretical results, further microgrid and MRE device integration studies can take place.

A. Power Analysis

As most of the work on simulation has been done using perfect sources and elements, the theoretical THD study is not realistic. Nevertheless, a spectral analysis can be held for power quality purposes on hardware experiments with the total harmonic distortion:

$$THD_\% = 100 \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \qquad (2)$$

where V_1 is the amplitude of the fundamental and V_n the harmonics of the PCC voltage. THD levels can also be measured with sensors.

The study of voltage fluctuations is helped with the study of the short-circuit level. To size a transmission electrical installation short-circuit currents must be calculated for every point of the network. In our case, the transmission line in a simplified network with a single AC voltage source and a load and a transmission line with a complex impedance $\bar{Z}$ defined in Cartesian form by:

$$\bar{Z} = R + jX \qquad (3)$$

where R and X are respectively the resistance and reactance of Z.

Normally, X is much greater than the resistance R and the study of the R/X ratio gives an evaluation of the grid strength. For low values, this ratio equals $\cos(\phi)$:

$$\cos(\phi) = \frac{R}{\sqrt{R^2 + X^2}} \qquad (4)$$

ϕ can also by defined by:

$$\phi = \arctan(\frac{X}{R}) \qquad (5)$$

The strength of a grid is qualified regarding the voltage fluctuations. If these fluctuations are negligible then the grid is strong, it is referred to as weak if these fluctuations are significant. The strength of a grid is closely related to the short-circuit ratio (SCR), if we note V the line voltage and I_{SC} the short circuit current, then the short circuit power is defined as:

$$S_{SC} = \sqrt{3} V I_{SC} = \frac{V^2}{\sqrt{R^2 + X^2}} \qquad (6)$$

Such analysis enables the study of a fault in the grid and there exists different ways to calculate the SCR for the considered network and some basic definitions of short-circuit conditions are given in the IEC standard 60909-0 [10]. If we introduce the apparent rated power S_n of an installation we can define the SCR as follows:

$$SCR = \frac{S_{SC}}{S_n} \tag{7}$$

B. Creation of Models

In literature most of variable loads are modeled for a 24-hour period to reproduce the needs of households or industries. A load can possibly be modeled to add in complexity and different needs to the study of an electrical network [11].
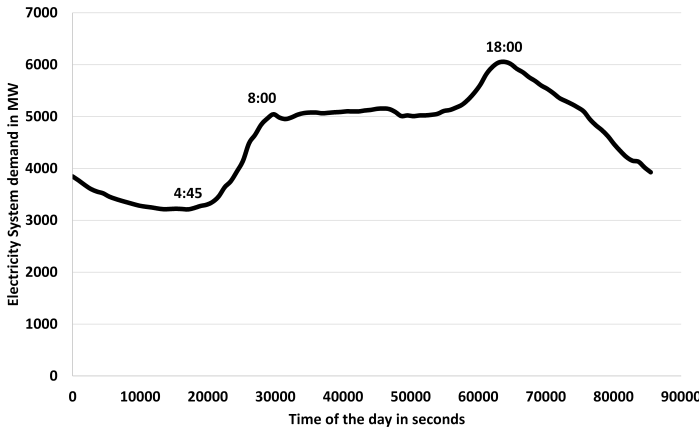
Fig. 10: Daily electricity system demand load profile in Ireland and Northern Ireland on 17th January 2017

A way to find a pattern for a load representing a house in a microgrid is to take the curve of the electricity system demand on a grid. Indeed, we can make the assumption that the whole power demand in a grid like the Irish grid can be scaled as a unique load represented by a house. Eirgrid provides daily curves of the Irish power consumption in open source [12]. From the pattern shown in Fig. 10 it is possible to build a single load scaled to match the power supply ability of the microgrid. This can be used as a first step, and responses to step changes in the load profile can further add to the investigations on possible voltage fluctuations.

C. Parameters of a Transmission Line

The specifications of an example cable size from MRE generators to shore stations power converters are referenced below. Useful information can be extracted to feed our experiment. The cable size is 2 AWG and the conductor size is 33.6 mm^2. The resistivity of copper is $1.68 10^{-8}$. The resistance of the cable is given by equation

$$R = \frac{\rho l}{A} \tag{8}$$

For a length of 1 km the resistance value is $R = 0.5\Omega$. This data gives starting point to set simulation parameters, the acquisition of such a cable in hardware is considered to conduct further in laboratory experiments.

D. Further Work

A model currently under study proposes another level of complexity by adding a 22 kW source in parallel of the load. The source represented by an ideal current source reproduces the effect of the medium speed rotatory emulator. A switch allows the connection of the power source. Power flows, voltage level and flicker level are ways to measure the impact of the connection of the device as they are more or less affected regarding the strength of the grid. This model tries to comprise the preparatory work in the previous sections.

V. CONCLUSION

The integration of the OPAL-RT OP5600 simulator inside the Lir-NOTF microgrid facility using Triphase power converters has been presented. The method used during the validation consists of a step by step integration of each element. Identifying and solving issues for a complex system is more challenging than for a smaller and simpler system. As seen in the paper, errors might arise and can prevent further hardware experiment until the problem is completely solved. The approach used to tackle the problem is described even if investigations are still ongoing Such a method might be time consuming but allows a better understanding of the overall system to proceed to further studies. The next stage is to develop simulated models to run in the OPAL-RT in order to study the effects of other elements such as renewable sources or more complicated loads on the MRE device power take off.

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