Matlab/Typhoon based real-time co-simulation platform for distrubuted energy ressouces

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RESUME – Electric microgrids are considered as a new trend for promoting green energy consumption. In addition to classical thermal sources, they are mainly composed of renewable energy resources, featuring high-performance electronic power converters, robust control capabilities, and stable operation modes. This work presents the modeling of the main components of an AC microgrid realized in the Typhoon HIL control center. However, energy management strategies as well as different control loops are performed in Matlab/simulink environment and imported as a Functional Mock-up Unit (FMU) files into the Typhoon HIL control center environment for real-time co-simulation. Tests on co-simulation platform are realized using advanced energy management and control systems (EMS) for various operation modes. Therefore, islanded topology is considered and two control options are investigated. The first one is when diesel-generator forms the grid so that battery-inverter is in a grid following mode. The second option considers that battery-inverter forms the grid. The obtained results prove the effectiveness of the used platfrom and the EMS, and the operation stability of the considered microgrid.

Keywords – Distributed energy resources, electric microgrid, energy management system, power sharing, islanded mode, real-time co-simulation

1. INTRODUCTION

Rising global energy demand, particularly in developing countries, alongside resource scarcity and environmental concerns like global warming, drives the focus on energy and ecological transition [1]. This transition involves modernizing electrical grids with increased renewable energy integration, such as wind and photovoltaic systems. Storage systems enhance microgrid flexibility, reliability, and energy flow management [2] [3]. A strategic energy mix, combining fossil fuels, nuclear, and renewables, ensures energy security by diversifying sources for power, transport, and heating. Technological advancements in renewables over the past two decades support these efforts [4].

This work develops a real-time co-simulation platform using Matlab and Typhoon for distributed energy resources. It focuses on efficient power balance and optimal power sharing management through advanced algorithms and control mechanisms. The Typhoon HIL platform enables rigorous testing of grid following and grid forming controls to evaluate their effectiveness and resilience [5].

The study begins with modeling the different microgrid components, incorporating detailed governor and excitation models for the diesel generator, alongside limitations for the battery system. Photovoltaic and wind turbine systems are designed to improve the integration of renewable energy. Through the cosimulation platform, the project aims to test and validate power balance, power sharing management, and grid-following and grid-forming control strategies under various scenarios. The results will contribute to improved microgrid stability, reliability, and the utilization of renewable energy. Conclusions and future perspectives are presented in the last section to guide the advancement of this work.

2. CONSIDERED MICROGRID CONFIGURATION

The configuration of the microgrid under study is illustrated in figure 1 ; a main power generation realized by a diesel-generator, an energy storage system based on batteries, a wind turbine, and a photovoltaic source. These power sources are all connected, togother with the AC loads, to the same point of common coupling (PCC) trough the AC bus. A switch is used to connect/disconnect the microgrid to the main grid. The diesel-generator is directly connected to AC microgrid as it has AC voltage outputs. The wind power system is connected to AC microgrid via a transformer. Batteries and PV power systems are connected to AC microgrid trough DC-AC power converters.

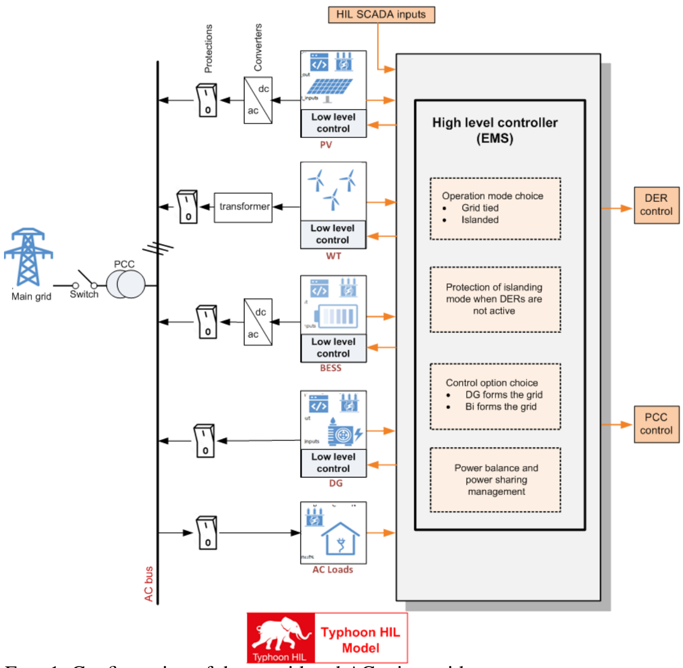

FIG. 1. Configuration of the considered AC microgrid

Given the large number of the DERs in the considered configuration, it is necessary to have two levels of control :

— **Low level controllers :** The low level controllers are developed for each DER composing the AC microgrid. Each controller operates according to the DER mathematical model in order to obtain the desired level of powers. For this purpose, local PI controllers are used.
— **High level controller :** The high level controller is the central controller in the considered microgrid. It is considered here as the Power Management System (PMS). It supervises the microgrid at the PCC by sensing their vol-

tages, frequency, currents, active power and reactive power. Accordingly, the high level controller commands the connection/disconnection of each DER. It handles power flow regulation through the PCC and then provides the power references for the low level controllers ensuring power balance in the microgrid.

For the considered microgrid, it is important to underline that, since they are only two DERs not based on intermittent energy source, they can be selectively engaged by the high level controller as a grid-forming source. They provide information about power to the MC and receive power references in return.

3. MODELING OF MICROGRID'S MAIN UNITS

3.1. Diesel generator

The DG model in Typhoon HIL is implemented as a synchronous generator with variable speed and voltage regulation. Its control system adjusts the excitation current and the mechanical speed to ensure stable three-phase voltage and frequency outputs at desired levels. This approach enables precise control of generator operation for seamless integration into the microgrid. In this unit, the speed control is accomplished through a governor. Furthermore, the voltage is regulated through the excitation system. Therefore, the excitation current and the mechanical speed at the crankshaft are taken as the control variables to regulate the voltage amplitude and frequency, respectively [Typhoon HIL] [6]. This control should give three-phase voltages at the stator of generator under desired rms voltage and frequecy :

$$\begin{cases} V_{1-dg} = \sqrt{2}.V_{eff}.sin(2\pi.f.t) \\ V_{2-dg} = \sqrt{2}.V_{eff}.sin(2\pi.f.t - \dfrac{2\pi}{3}) \\ V_{3-dg} = \sqrt{2}.V_{eff}.sin(2\pi.f.t - \dfrac{4\pi}{3}) \end{cases} \quad (1)$$

Where ; V_{eff} is the rms value of the voltages (V) and f is the frequency (Hz).

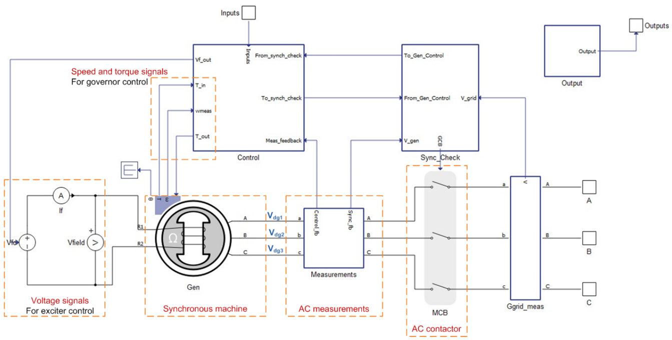

FIG. 2. Diesel generator model implemented with Typhoon HIL schematic

- Governor model : In diesel generator, the governor is responsible for controlling the fuel injected to the cylinders so for controlling the speed of the unit which leads to frequency regulation. In fact, the mechanical speed (rd/s) is given by :

$$\Omega = \frac{2\pi}{60}N \quad (2)$$

N denotes the crankshaft rotation speed. The crankshaft angular speed (rd/s) is given by :

$$\omega = 2\pi f = n_p\Omega = n_p\frac{2\pi}{60}N \quad (3)$$

Where ; n_p is the number of poles pair. From this equation, we can extract the frequency f as follows : $f = n_pN$

Here, it is clear that the regulation of the frequency can be achieved by acting on the crankshaft speed, itself is controlled by the amount of the fuel injected into diesel engine. It is important to underline that for the considered model in our work, the diesel engine is modeled by three main blocks that govern its dynamics ; the electric control box, the actuator for fuel control, and the diesel engine. The model implemented in Typhoon HIL is given in figure 3.

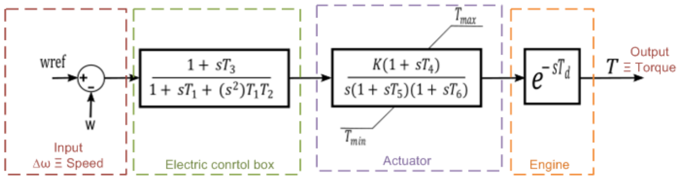

FIG. 3. Governor Model implemented with Typhoon HIL schematic

The response of the governor model depends on several parameters given in the table 1.

Symbol	Specification
T_1, T_2, T_3	Electric control box time constants
T_4, T_5, T_6	Actuator time constants
K	Actuator gain
T_{MAX}	Maximum torque limit
T_{MIN}	Minimum torque limit
T_d	Engine time delay

TABLEAU 1. Governor variables from Typhoon HIL model

- Excitation model : In diesel generator, the exciter system is responsible for controlling the rotor flux so for controlling the stator voltages. In fact, the stator voltages are proportionnal to the excitation voltage V_f :

$$V_{eff} \propto V_f \quad (4)$$

The voltage V_f is done by the exciter system which is basically used to provide direct current to the rotor winding making it able to control stator voltages. As shown in figure 4, the exciter system is composed of a PID (proportional-integral-differential) voltage regulator followed by a saturation function to avoid overexcitation and underexcitation. The main input of the excitation system is the terminal voltage while the output is the voltage which should be applied to the rotor winding. Exciter sytem have several inputs parameters. They are given in table 2.

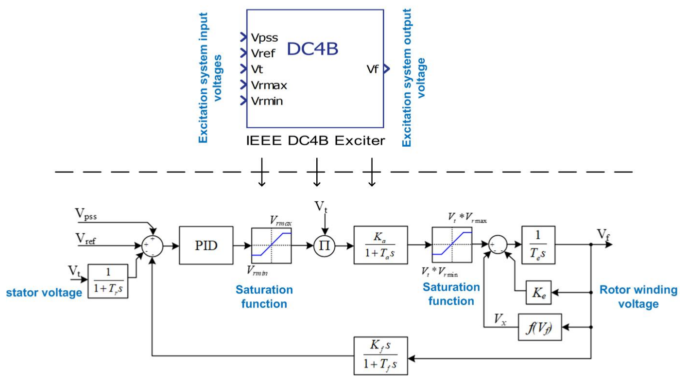

FIG. 4. Exciter model implemented with Typhoon HIL schematic

Symbol	Specification
V_f	Field voltage
V_{ref}	Desired value of the stator terminal voltage
T_r	Time constant
T_a	Major regulator time constant
T_e	Exciter time constant
K_e	Exciter gain
T_f	Stabilization feedback time constant
K_f	Stabilization feedback gain
K_p, K_i, K_{deriv}	Regulator proportional,integral,deriv. gain
V_{rmax}, V_{rmin}	Saturation upper-lower limit

TABLEAU 2. Components of exciter in Typhoon HIL model

3.2. *Battery energy storage system*

As presented in figure 5, the BESS model in Typhoon HIL includes a DC-AC converter and filters to manage power fluctuations in the microgrid. It ensures stability by absorbing or providing power as needed while adhering to constraints on the charge/discharge limits and on the state of charge (SOC).

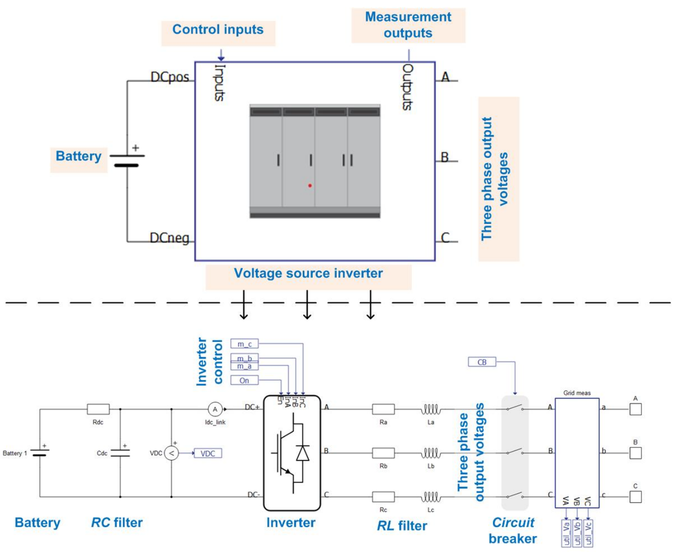

FIG. 5. Proposed battery model in Typhoon HIL

The constraints that should be taken into account for the battery :

- Charge/discharge limitation :

$$P_{bat-min} \leq P_{bat} \leq P_{bat-max} \tag{5}$$

Where ; P_{bat} : denotes the charge/discharge power (W), $P_{bat-min}$: is the minimal power of charge/discharge (w) and $P_{bat-max}$: is the maximal power of charge/discharge (w).

- Protection against deep charge/discharge :

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{6}$$

Where ; $SOC(t)$: denotes the state of charge of the battery, SOC_{min} : represents the minimum state of charge, SOC_{max} : is the maximum state of charge.

The state of charge of the battery, $SOC(t)$, can be calculated as follows :

$$SOC(t) = SOC(t - \Delta T) - \left(\frac{P_{bat}\Delta T}{3600 C_{bat-max} V_{bat-0}}\right) \tag{7}$$

with, $C_{bat-max}$, V_{bat-0} and ΔT denote, respectively, the capacity of the battery (AH), the initial voltage value of the battery and the sampling time. $SOC(t - \Delta T)$ represents the state of charge of the battery at $t - \Delta T$.

Regardless the operation conditions, the management of the battery as well as the control of the DC/AC converter should give three-phase voltages at the AC microgrid side (inverter output voltages) under desired rms voltage and frequecy :

$$\begin{cases} V_{1-ess} = \sqrt{2}.V_{eff}.sin(2\pi.f.t) \\ V_{2-ess} = \sqrt{2}.V_{eff}.sin(2\pi.f.t - \dfrac{2\pi}{3}) \\ V_{3-ess} = \sqrt{2}.V_{eff}.sin(2\pi.f.t - \dfrac{4\pi}{3}) \end{cases} \tag{8}$$

Where ; V_{eff} : is the rms value of the voltages (V) and f : is the frequency (Hz)

3.3. *Photovoltaic System*

The configuration of the PV unit is shown in figure 6. It is realized by PV panels, DC-DC converter followed by an inverter and a 3-phase RL filter, all connected to the main AC bus. The role of the DC-DC converter is to regulate the voltage at panels outputs considering the MPPT (Maximum Power Point Tracking) strategy.

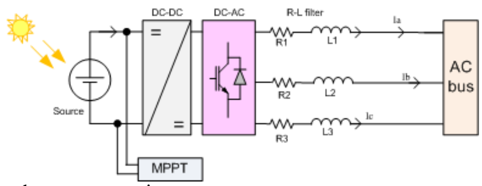

FIG. 6. PV subsystem overview

The basic element of solar PV system is solar cell. These basic cells are connected together to form solar PV panel. PV cells connected in series increases the voltage output but when they are connected in parallel they increase the current. The solar panel is a combination of many cells electrically connected in series-parallel association to generate desired current and voltage.

The electrical schema of a solar cell is shown in fig 7. It consists in a parallel connection of a current source and a diode. The output of the current source is proportional to the light coming from sun falling on the cell (photocurrent Iph).

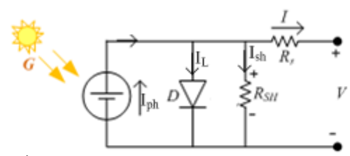

FIG. 7. PV Cell circuit

The module photocurrent Iph is equivalent to the voltage–current characteristic equation of the PV cell given by :

$$I = I_{ph} - I_L - I_{sh} \tag{9}$$

with, I_{ph} : photo generated current (A), I : Output current (A), I_L : Diode current (A) and I_{sh} : Shunt current (A).

Finally, the complete PV cell model shown in figure 7 is given as follows :

$$I = I_{ph} - I_0(\exp\frac{e(V+IR_S)}{mkT_C} - 1) - \frac{V+IR_S}{R_{SH}} \quad (10)$$

where; I_0 : reverse saturation current (A), V : voltage output terminal, R_s :series resistance, k : Boltzmann's constant, T : absolute temperature.

In this work, a PV plant together with a three-phase DC/AC converter from the Typhoon HIL schematic editor is used. This configuration is given in figure 8. Here, it is important to underline that an emulation stage of the PV panel is used. Accordingly, a controllable DC voltage source is used instead of a real PV pannel.

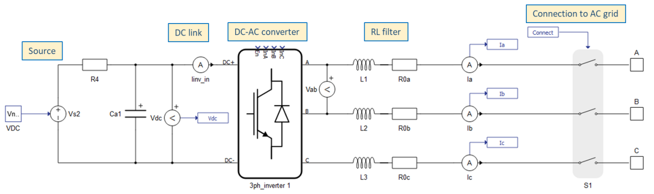

FIG. 8. Proposed model on Typhoon HIL

3.4. *Wind Turbine*

The considered configuration in this work, shown in figure 9, is a fixed-speed wind turbine.

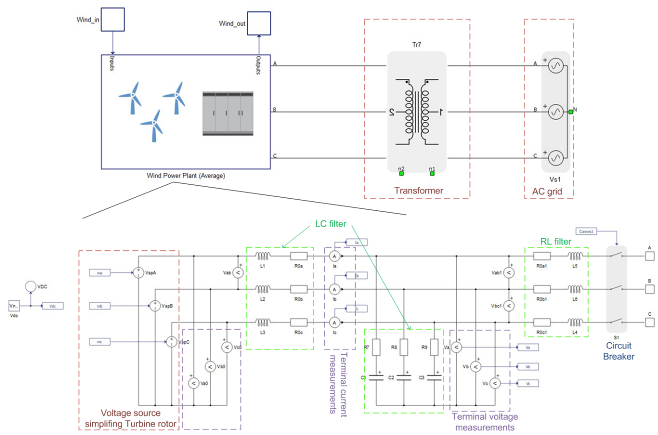

FIG. 9. Wind power model implemented in Typhoon HIL schematic editor

For this type of wind power plants, the kinetic energy $E(J)$ is given by :

$$E = \frac{1}{2}mV_{wind}^2 \quad (11)$$

where; m : Air mass (Kg) and V_{wind}^2 : Speed of air mass m (m/s).

The wind power (W) through a specific area A is given by :

$$P_{wind} = \frac{1}{2}\rho AV_{wind}^3 \quad (12)$$

Where A is the area wipped away by the rotor blades, and as a result of the nature of the rotor, only an amount of this power may be captured tacking into account the extraction coefficient C_p defined by :

$$C_p = \frac{P_{rotor}}{P_{wind}} \quad (13)$$

From this equations, we can extract the power captured by the turbine rotor by :

$$P_{rotor} = \frac{1}{2}\rho C_p.\pi.R_{rotor}^2 V_{wind}^3 \quad (14)$$

with, ρ : Air density (Kg/m^3)

4. MATLAB/TYPHOON-BASED REAL-TIME COSIMULATION PLATFORM

The real-time cosimulation platform is presented in FIG. 10, integrating distributed energy ressources models with EMS via the FMI standard.

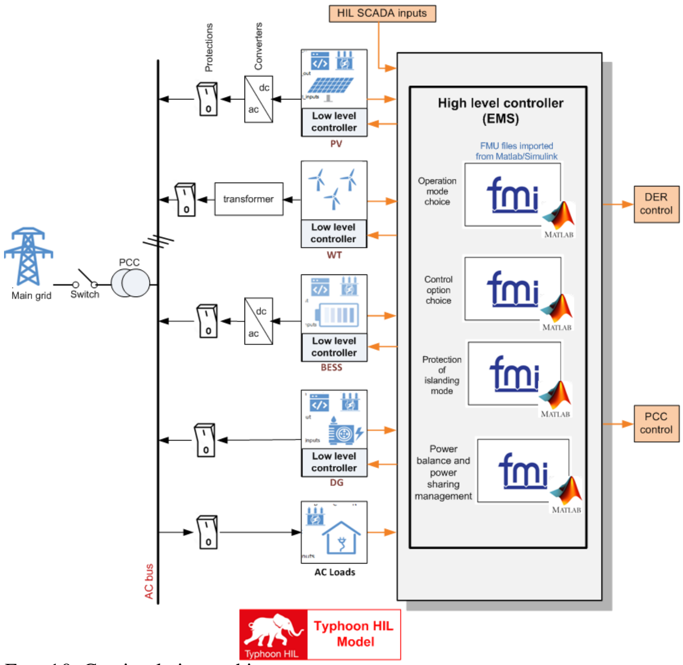

FIG. 10. Co-simulation architecture

The first three blocs, shown in figure 10 are dedicated to manage the microgrid operation modes and protection and represent the high level controller.

The principle of this controller is detailed in figure 11.

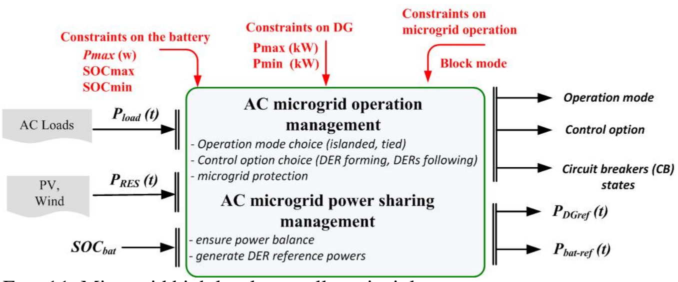

FIG. 11. Microgrid high level controller principle

The last FMU file presented in the co-simulation model (Bloc 4 in figure 10) is realized by Matlab Simulink functions in order to ensure the power balance and the power sharing between the DERs into the microgrid as illustrated in figure 12.

In this work, we have chosen a simple power balance and power sharing management strategy for co-simulation test purposes. The objective is therefore to maintain the DG and the battery in their operating ranges while ensuring the power balance in the microgrid taking into account the constraints on the battery and diesel-generator. The power balance equation is as follows :

$$P_{Load}(t) = P_{DG}(t) + P_{BESS}(t) + P_{RES}(t) \quad (15)$$

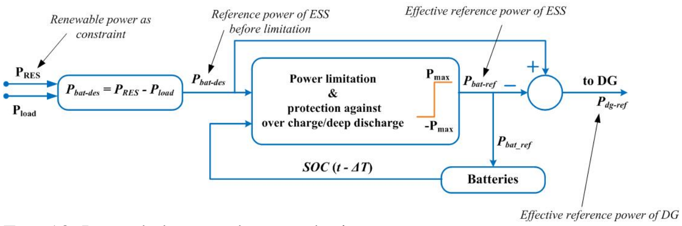

FIG. 12. Power balance and power sharing strategy

with, $P_{Load}(t)$ represents the total instantaneous power of the AC load, P_{DG} represents the instantaneous diesel-generator power, P_{BESS} is the battery energy storage system power and P_{RES} is the renewables (PV and wind) power.

There are some constraints that should be taken into account for the battery and diesel-generator use. Regarding the battery, the charge/discharge power should be limited between $P_{bat-min}$ and $P_{bat-max}$:

$$P_{bat-min} \leq P_{bat} \leq P_{bat-max} \tag{16}$$

In addition, to protect the battery system against deep charge/discharge, the state of charge should be limited between SOC_{min} and SOC_{max} :

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{17}$$

For the diesel-generator, the only constraint taken into account in this work is linked to the operating range defined as follows :

$$P_{DG-min} \leq P_{DG}(t) \leq P_{DG-max} \tag{18}$$

The following pseudo-code guarantees the power balance and power sharing of the considered AC microgrid :

Algorithm 1 Power balance and power sharing management

```
Inputs : P_Load, P_Wind, P_PV
SOCmin, SOCmax
P_bat min, P_bat max
P_dg min, P_dg max
P_bat des = P_RES − P_Load

if SOCmin ≤ SOC ≤ SOCmax then
    if P_bat des ≤ P_bat min then
        P_bat ref = P_bat min        ▷ reference power of battery
    else if P_bat des ≥ P_bat max then
        P_bat ref = P_bat max
    else
        P_bat ref = P_bat des
        if SOC < SOCmin then
            P_bat ref = −P_bat max        ▷ charging of battery
            if SOC > SOCmax then
                P_bat ref = P_bat max ▷ discharging of battery
            end if
        end if
    end if

P_dg ref = P_Load − P_bat ref − P_RES  ▷ Reference power of DG
```

5. TEST AND VALIDATION

After creating the co-simulation model in the Typhoon HIL schematic editor, importing the FMUs from Matlab and in order to be able to remotely regulate power and visualize internal data from the typhoon HIL control center, a HIL SCADA platform is used. It acts as a small real time simulator, which is able to measure and visualize power from the simulated power system.

To test the co-simulation platform of the considered AC microgrid developed in this work, several scenarios are realized. We will considered the islanded mode case and will be interesting in two main control options of the AC microgrid :

- Control option 1 : In this case, the diesel-generator forms the microgrid while the battery-inverter is grid-following, and wind and PV systems are grid-feeders ;
- Control option 2 : In this case, the battery-inverter forms the microgrid while the diesel-generator is grid-following, and wind and PV are grid-feeders ;

The parameters of the DERs presented in the microgrid under study are given in table 3 .

	ESS	Diesel Gen	PV	Wind
Nominal active power	1600 kW	2200 kW	250 kW	500 kW
Nominal frequency		60 Hz		
Nominal voltage		480 V		

TABLEAU 3. DERs parameters in cosimulation system

5.1. *Control option 1 : co-simulation results and comments*

The obtained co-simulation results for this case are shown in figure 13. It presents the time-evolution of the diesel-generator active power, $P_{DG}(t)$, the battery active power, $P_{ESS}(t)$, the renewables active power (wind and PV), $P_{RES}(t)$, the frequency of the AC microgrid, $f_{MG}(t)$, and the state of charge of the battery, $SOC(\%)$.

Firstly, the considered AC microgrid operates under a fixed frequency $f_{MG} = 60Hz$ and a constant AC load of $1100kW$. The PV and the wind systems are switched off and there is no power injected in the microgrid by these producers. After that, the battery inverter is integrated with an initial state of charge fixed to 20%. Because of the low level of the SOC, the diesel-generator supplies extra power for battery charging. Then, PV and wind are enabling successively which results in decrease of the diesel-generator power. Here, it is clear that the usage of renewable energy sources is maximized to help in power supply. Regarding the frequency, it oscillates during changes of the DERs power and then recovers back to the initial value.

5.2. *Control option 2 : co-simulation results and comments*

The obtained co-simulation results for this case are shown in figure 14. It presents the time-evolution of the battery active power, $P_{ESS}(t)$, the diesel generator active power, $P_{DG}(t)$, the renewables active power (wind and PV), $P_{RES}(t)$, the frequency of the AC microgrid, $f_{MG}(t)$, and the state of charge of the battery, $SOC(\%)$.

Firstly, the considered AC microgrid operates under an initial battery SOC $= 86\%$, a fixed frequency $f_{MG} = 60Hz$ and no-load. The Diesel generator and the renewable power systems are switched off and there is no power injected in the microgrid by these producers. A constant AC load of $1100kW$ is then integrated. For that, we observe the immediate response of the battery to supply the power required, which leads to its discharge. After that, the diesel generator is enabled to deliver a constant active power of $900kW$. As a consequence the battery goes back to charging as the power supply decrease. Then, PV and wind are enabling simultaneously which results in decrease of the battery power. Lastly, the battery inverter responds to the load change

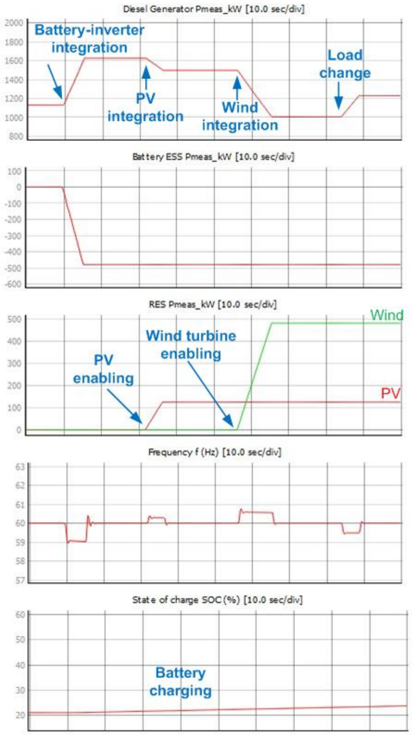

FIG. 13. Control option 1 : Real-time results when the diesel-generator forms the grid

by suppliying an amount of the power demanded as the diesel generator and RES deliver always the same constant power. Regarding the frequency, it oscillates during changes of the DERs power and then recovers back to the initial value.

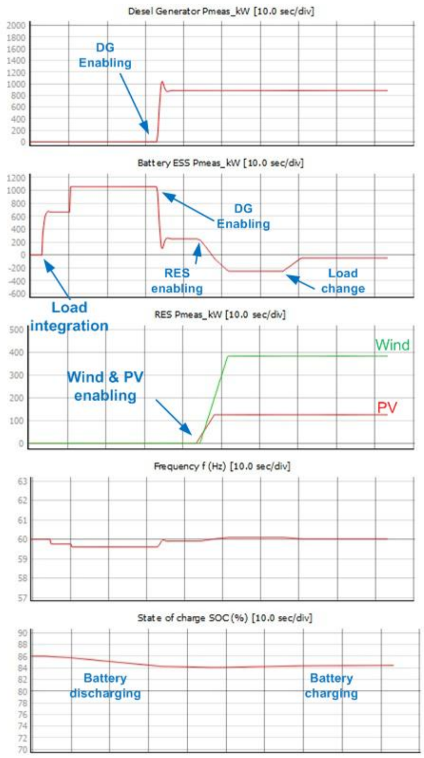

FIG. 14. Control option 2 : Real-time co-simulation results when battery-inverter forms the grid

In the both co-simulation cases, we observe that in the presence of a disturbance (load change, DER integration ..) the system responds immediately and supplies needed power. The power supplied guarantee always the power balance and power sharing management strategy studied previously.

6. CONCLUSIONS AND PERSPECTIVES

The findings of this study reveal several important conclusions :

- During islanded mode, the presence of at least one grid-forming distributed energy resource (DER) is crucial to maintaining voltage and frequency stability within the microgrid. These grid-forming DERs play a vital role in responding to disturbances and fluctuations, ensuring a stable operation.
- Integrating renewable energy sources, such as photovoltaic and wind power, allows for a reduction in diesel generator operation. This decrease in reliance on the diesel generator results in lower fuel consumption and an increase in the utilization of green energy, promoting sustainability and environmental benefits.
- The scenarios analyzed demonstrate that both the diesel generator and the battery-inverter, acting as grid formers, are capable of compensating for power fluctuations caused by load changes or the integration of DERs. This flexibility in grid formation ensures the stability and reliability of the microgrid system.

Looking ahead, this study opens up several promising perspectives for future work in the field of microgrids and distributed energy resources (DERs). Firstly, there is potential for exploring advanced control strategies to further enhance the power balance and power sharing management in microgrids. By investigating and developing innovative algorithms and control techniques, the performance and efficiency of microgrid systems can be optimized.

Another perspective for future research lies in the integration of emerging technologies into microgrid systems. This includes the incorporation of energy management systems and smart grid components, which can enhance the overall operation and stability of microgrids.

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