Co-simulation of Shortcircuit Current Measurement in LVDC Systems

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***Abstract*—Emerging low-voltage direct current (LVDC) microgrids represent a compelling alternative for efficient renewable energy use in multiple residential and industrial scenarios. Typical concerns regarding safety of DC systems are currently being addressed through the sustained development and deployment of solid-state circuit breakers (SSCBs) and current limiter (CL) devices. Design of such elements requires suitable simulation approaches and tools for accurate understanding of short-circuit current behavior under multiple usage and parametrisation scenarios, in accordance to established norms and regulations. This paper presents a co-simulation approach to derive short-circuit current profiles in a typical off-grid home setting supplied by solar energy. The implementation has been carried out by integration of Simulink models with the TyphoonHIL environment for real-time simulation through the dedicated FMU/FMI interface. We report on the numerical results achieved and derive insights for improved protection of LVDC microgrids.**

***Index Terms*—dc microgrids, shortcircuit current, co-simulation, protection, hardware-in-the-loop**

I. Introduction

In recent years, the energy sector has undergone a rapid transformation, mainly driven by the emergence of renewable energy sources such as photovoltaic panels and wind power and of flexible loads including electric vehicles. This shift has brought microgrids, in particular direct current (DC) microgrids, to the forefront as they offer advantages in the integration of energy storage batteries, renewable sources, and electric vehicles due to their compatibility with native DC-based technologies and the reduction of DC-AC and AC-DC conversion losses.

DC microgrids offer technical solutions for the interconnection of renewable energy sources (solar panels, fuel cells), modern loads (LED lighting, computer servers, telecommunications equipment, power electronics, electric vehicles), and energy storage systems. All of this equipment operates natively on direct current, which means that integration with an AC-based grid requires multiple AC-DC-AC conversions, leading to significant power losses of up to 10-15% [1].

In addition, DC grids enable bidirectional power flow, a characteristic of smart grids of the future, where consumers can also become producers (prosumers), and electric vehicles can operate as temporary power sources (V2G). Furthermore, the evolution of DC-DC power converters allows the voltage of the DC supply to be adapted to meet the internal requirements of individual devices. These converters integrate advanced control, protection, and communication functions, helping to maintain grid stability.

In terms of the physical infrastructure required for DC distribution: it is more compact, requiring up to 55% less conductive material such as copper or aluminum, due to the reduction from a three-phase plus ground AC system to a two-wire plus ground DC system and the absence of reactive power transfer. Therefore, direct current has become again a relevant option for power transmission and distribution, not only at high voltage direct current (HVDC) levels, but also at low and medium voltage levels, as discussed in [2].

Low-voltage direct current (LVDC) systems are becoming an increasingly viable option for realizing a smart energy infrastructure adapted to today's requirements for the following reasons [3]:

- In LVDC grids, energy balance is maintained using the droop control principle, which allows load sharing based on voltage levels without requiring a communication network. This feature provides autonomous local control;
- The arhitecture of LVDC systems provides scalability and modularity, as it allows a local grid to gradually expand from a minimal set of sources and loads to fully functional microgrids with batteries, EV charging stations, additional consumers or generators;
- The capability of LVDC grids to operate in islanded mode (off-grid), i.e. independently from the AC grid, makes them ideal in remote areas, critical infrastructures

(hospitals, telecommunication systems) or in emergency situations where the AC grid is unavailable;
- Without phase imbalances and frequency variations specific to AC systems, LVDC systems have a higher level of security and reliability, while offering lower level of energy losses.

However, all these advantages also present several challenges, in particular related to short-circuit protection [4]. Unlike AC grids, fault currents in DC are higher, rise rapidly and do not pass through zero, making them difficult to interrupt and to estimate correctly. Moreover, the integration of renewable energy sources, batteries and power converters further complicates the system's behavior, under fault conditions [5].

In this context, traditional methods for fault currents estimation, based on static assumptions and simplified models, are often insufficient to capture the dynamic response of an LVDC microgrid during a fault. A more advanced method of analysis and testing that also captures the dynamic behavior of the system is co-simulation. It combines detailed offline modeling with real-time testing in a hardware-in-the-loop (HIL) environment. Platforms such as Typhoon HIL enable fast and realistic simulation of the electrical system, while MATLAB/Simulink allows for development and testing control algorithms.

This paper proposes a co-simulation framework for measuring short-circuit currents in an off-grid LVDC microgrid, using the "Cottage in the Sun" scenario, developed as part of the "Novel Current Control for Climate Neutral Energy Infrastructure" (NOVETROL) project [1] as a case study. The aim is to show how the integration between MATLAB/Simulink and Typhoon HIL helps to validate models and test protection strategies in a safe and realistic way.

The rest of the paper is structured as follows. Section II briefly introduces the context of our work with reference to existing approached for DC shortcircuit current modelling and simulation. Section III discusses the typical structure of a LCDC microgrid, together with existing technical regulations and standards. The chosen use case and co-simulation approach is presented in Section IV, while Section V illustrates the obtained results. Section VI concludes the paper.

II. Related Work

Short-circuit protection remains one of the most critical challenges in low-voltage direct current (LVDC) microgrids, as the absence of natural current zero-crossing significantly complicates fault interruption. Real-time simulation has emerged as an effective approach in this context. Salehi Rad et al. proposed a cost-effective Controller-Hardware-in-the-Loop (CHIL) platform using MATLAB/Simulink to evaluate the coordination of solid-state circuit breakers (SSCBs) in DC microgrids under fault currents up to 430 A [6].

In terms of fault detection, Li et al. introduced a diagnosis method based on local fault current measurements, enabling rapid identification of both low- and high-resistance faults without requiring complex communication infrastructures [7]. Complementary to this, Shea et al. [8] provided a detailed analysis of short-circuit current waveforms in converter-based DC networks, offering practical insights into their transient characteristics.

Furthermore, Valbuena Godoy et al. [9] demonstrated the limitations of traditional analytical fault analysis methods, showing that their accuracy decreases in networks with multiple converters or non-negligible fault impedances. These findings emphasize the need for advanced approaches such as co-simulation to capture the dynamic behavior of LVDC systems under fault conditions.

III. LVDC Microgrids

A DC microgrid is a small-scale electricity grid that operates mainly at direct current (DC) and acts as a localized and integrated energy system, capable of operating both connected to the public grid and independently, in islanded mode.

The foundation of a DC microgrid architecture is the DC common bus, which interconnects generation sources, storage systems, and energy consumers. Basically, it manages the energy of the microgrid. Through this concept, DC microgrids significantly reduce losses from inefficient conversions (AC-DC) that occur in traditional AC grids, as they optimize the energy flow.

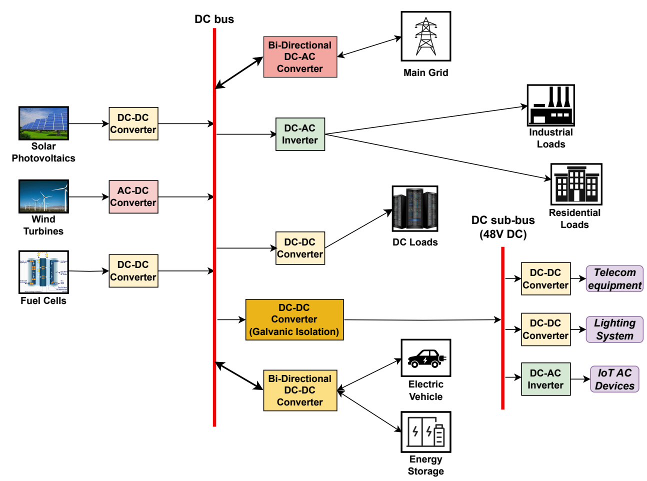

Fig. 1. Structure of a DC microgrid

The structure of a typical DC microgrid configuration is illustrated in Figure 1. Solar panels, wind turbines, and fuel cells are connected to the DC bus through converters. Solar panels are connected to the DC bus through a DC-DC converter. Wind turbines are connected to the DC bus through an AC-DC converter. Fuel cells are connected to the DC bus through an DC-DC converter. In addition to renewable and conventional sources of power generation, the DC bus is also connected to the public grid. The connection to the main AC grid is realized through bidirectional DC-AC converters, which allow both the import of energy from the grid when local generation is insufficient and the export of surplus energy to the main grid.

Energy storage systems and electric vehicles are connected to the DC bus through bidirectional DC-DC converters, facilitating energy transfer in both directions: from the DC bus to the storage systems and electric vehicles and from the storage systems and electric vehicles to the DC bus.

DC microgrids enable a multi-level approach to operating voltages. Within this architecture, in addition to the main bus, we also have a sub-bus at lower voltages, such as 48V, specifically designed for particular applications such as telecommunications or electronic devices.

DC microgrids offer numerous advantages, including increased energy efficiency, simplified integration of renewable energy sources, enhanced reliability and reduced maintenance costs. The spread and evolution of DC microgrids makes efficient energy management more and more relevant. This involves load forecasting, i.e. estimating how much electricity will be needed to supply future demand, to optimize system performance as discussed in [10] and [11].

Besides their technical advantages, LVDC systems require clear voltage level definitions and standardization to ensure safe and reliable operation. The accelerated development of DC-based technologies makes it essential to define interoperable and scalable voltage classes, while also addressing the specific safety concerns of DC distribution.

According to IEC standards, voltage levels are classified as shown in Table 1. This classification also reflects how DC interacts differently with the human body compared to AC. According to IEC 60479-1, DC is generally less harmful at the same voltage, but it has a higher perception threshold (around 2mA for DC vs. 0.5 mA for AC).

TABLE I
VOLTAGE BANDS ACCORDING TO IEC [3]

Voltage Band	AC	DC
HV (High voltage)	> 1000 V	> 1500 V
LV (Low voltage)	≤ 1000 V	≤ 1500 V
ELV (Extra-low voltage)	≤ 50 V	≤ 120 V

The IEC 23E/WG2 group considers the ELV voltage band to be well standardized and relatively safe, while the LV band remains insufficiently regulated, especially above 400V (DC system), where direct contact can be lethal. The standardization process (Figure 2) is currently being accelerated due to two key technical challenges:

- Fault detection and disconnection at DC is more difficult than at AC due to the absence of zero-crossing points;
- Residual current devices (RCDs) for DC are not yet widely available on the market.

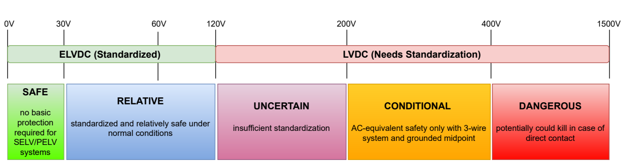

Fig. 2. LVDC classification: Standardization status and safety assessment [1]

Figure 2 illustrates the current state of LVDC voltage classification and the associated safety domains. Voltage levels up to 120V DC are considered Extra-Low Voltage (ELVDC) and are already well defined and generally regarded as safe under the SELV and PELV protection schemes. However, the uncertainty still characterizes the Low Voltage DC range, particularly above 400V, where further standardization and protection strategies are required.

IV. Case study: "Cottage in the Sun"

A. Description

The "Cottage in the Sun" system represents an off-grid LVDC microgrid supplying a holiday cottage located in a remote area. The system operates entirely in isolated mode, without connection to the legacy AC grid. Power generation is based on a photovoltaic (PV) array with a total rated power Pmax, supplemented by additional grid-forming power sources without constraints on generation capacity. All loads are supplied directly at DC through a common busbar operating at the rated voltage Un. The PV strings are configured to deliver the busbar voltage Un at the maximum power point Pmax.

B. Matlab Implementation

For this case study we first implemented a model in Simulink. It represents a LVDC off-grid system powered by a photovoltaic panel, with a DC-DC Boost converter, resistive load and a DC busbar. The model also includes a Perturb & Observe (P&O) MPPT algorithm, a Boost converter control loop and modules for measuring the main parameters, such as voltages, currents and powers.

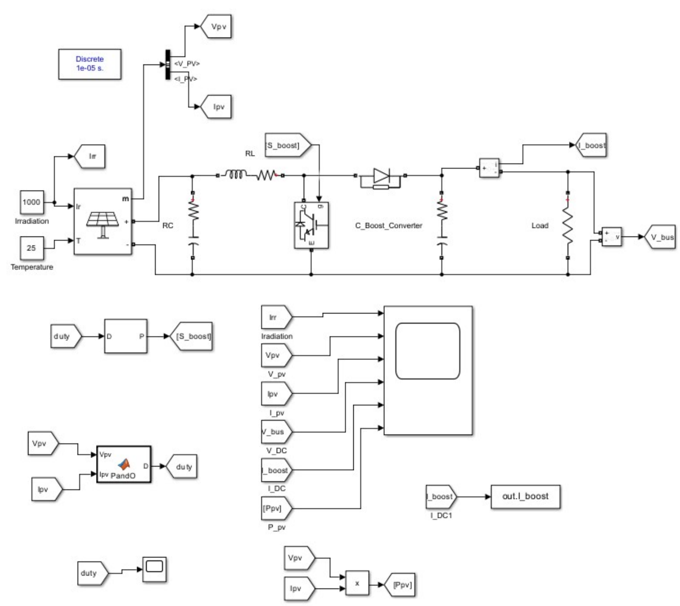

Fig. 3. Simulink Model

The PV generator is modeled with irradiance and temperature as external inputs, which determine its output voltage and current based on its I-V characteristic. The PV array is

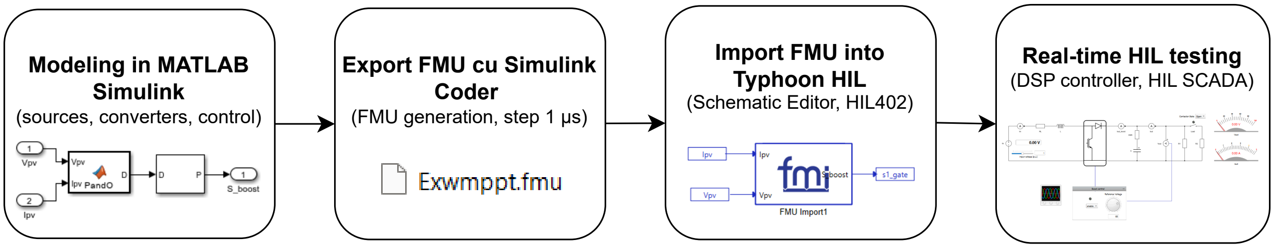

Fig. 4. Co-simulation workflow

dimensioned to deliver its maximum rated power (P_{max}) at the nominal bus voltage (U_n) when operating at the maximum power point. The resistive load is directly connected to the DC busbar, and the user can adjust its value to simulate different levels of power profile. The duty cycle of the DC-DC Boost converter is controlled by the output of the MPPT algorithm. It uses an IGBT switch, a diode, an inductor, and an output capacitor. The P&O algorithm MPPT uses real-time measurements of PV voltage and current to figure out the optimal duty cycle that maximizes the power extracted from the PV panel. In addition to the MPPT, a control loop regulates the converter operation to ensure that the DC busbar maintains a stable voltage even when the temperature, irradiance, or load conditions change.

The model includes measurement and logging blocks to monitor key variables at every stage of the system, such as the PV side, converter input/output currents, and the DC busbar voltage and load current. The simulation runs in discrete mode with a time step of $1e-05s$, chosen to capture the fast switching dynamics of the converter and the transients during fault conditions.

C. Integration with Typhoon HIL via FMU/FMI

Following the development of the Simulink model, integration with Typhoon HIL was performed to enable real-time testing of the system behaviour under fault conditions. The approach separated the MPPT control logic, implemented in Simulink with the Perturb & Observe algorithm, and the boost converter controller loop, from the electrical schema, which was migrated to Typhoon HIL. This strategy leverages Simulink's advanced control modelling and Typhoon HIL's real-time simulation capabilities.

The MPPT subsystem, utilizing PV voltage (V_{pv}) and current (I_{pv}) inputs to optimize the Boost converter's duty cycle, was exported from Simulink as a Functional Mock-up Unit (FMU) via the FMI standard. On the Typhoon HIL side, the FMU was imported into the schematic editor and connected to the rest of the system, as illustrated in Figure 4. During real-time simulation, Typhoon HIL sends measurement signals (e.g. V_{pv}, I_{pv}, V_{bus}) to the FMU, which computes the updated duty cycle and returns it to control the boost converter. This co-simulation configuration combines the advantages of both platforms and enables closed-loop real-time testing with realistic fault scenarios.

Furthermore, the same PV–Boost Converter circuit was implemented and simulated directly in the Typhoon HIL SCADA environment, operating in real time, as illustrated in Figure 5. The model replicates the electrical topology of the photovoltaic source, the controlled DC/DC converter, and the DC bus with its measurement points, allowing detailed observation of voltage and current dynamics under both normal and fault conditions. This implementation ensures consistency between the simulated configuration and the experimental setup used for validation.

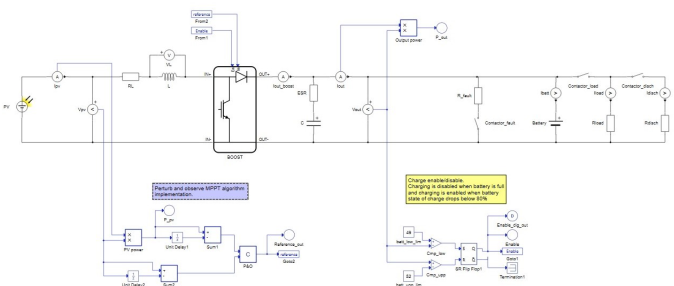

Fig. 5. Typhoon HIL Model

This configuration enabled comprehensive system monitoring and interaction through dedicated SCADA panels (Figure 6), providing clear visualization of both normal operation and fault scenarios with real-time responsiveness. The graphical interface displays key variables such as DC bus voltage, converter duty cycle, and current waveforms, enabling continuous supervision of the system during simulation. Through this interface, the user can manually trigger fault events, observe transient responses, and validate the performance of the implemented control and protection logic in real time. This real-time monitoring capability serves as a practical link between the simulated control model and the physical HIL implementation, ensuring that both environments operate in full synchronization.

The integration of the Simulink-based FMU into Typhoon HIL, complemented by the direct implementation of the circuit in the SCADA environment, demonstrates a robust and versatile validation workflow. By combining Model-in-the-Loop (MIL) simulations for early-stage algorithm verification with Hardware-in-the-Loop (HIL) testing for real-time performance

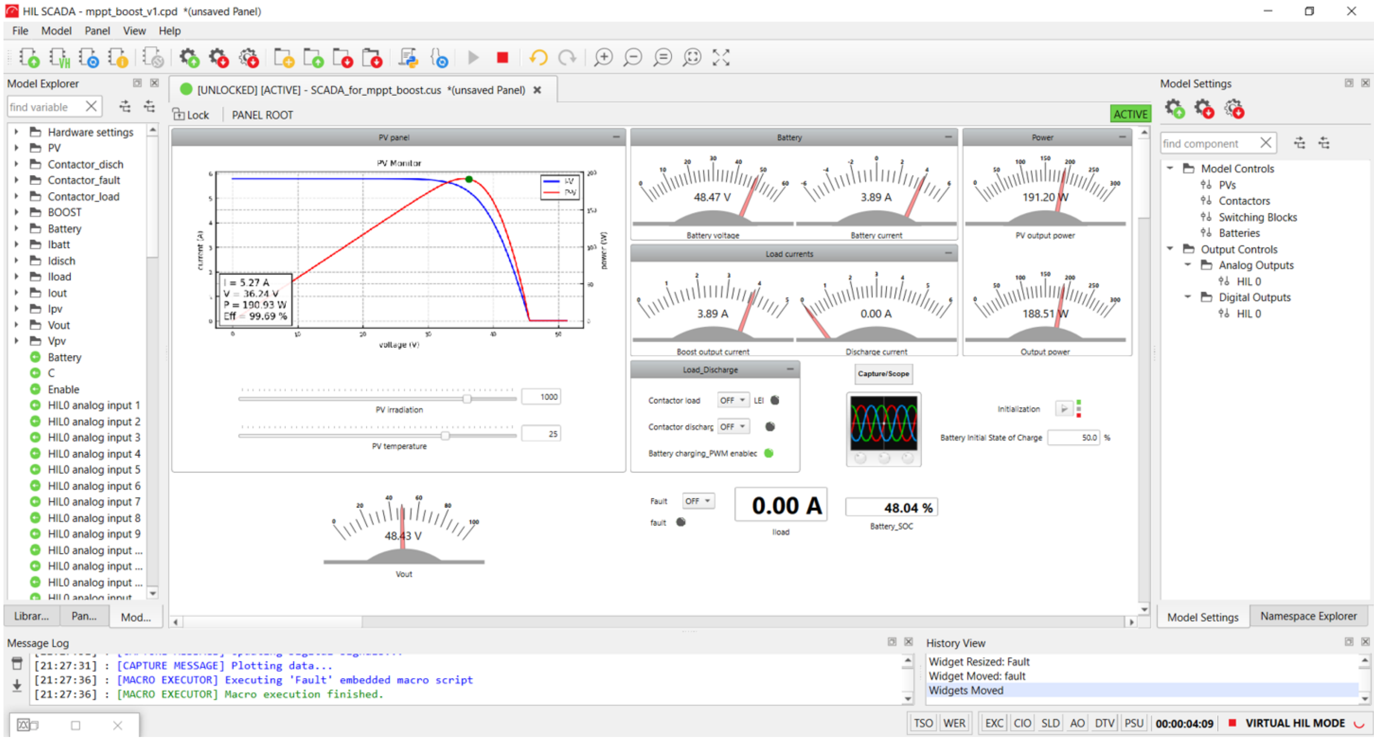

Fig. 6. Typhoon HIL SCADA Environment

assessment, this methodology bridges the gap between theoretical design and practical implementation.

V. Simulations and Results

In this study, we evaluated three representative short-circuit scenarios, each applied at a different point of the LVDC system to capture the impact of fault location on system behavior. The fault impedance was assumed negligible (0.0001 Ω) in all cases, and the faults were applied in steady-state conditions. The scenarios are summarized below.

- **Scenario 1 — Short-circuit at the PV output**
  The fault is applied on the line between the positive terminal of the PV array and the input of the Boost converter, more precisely between the output of the inductor L1 and the switching diode. In this scenario, the fault current is supplied by the PV panel at the value of the short circuit current Isc and, depending on the architecture, the output capacitor of the converter may also contribute. This setup simulates a wiring fault on the PV side, such as a damaged or loose cable shorting the input side of the Boost converter before protection devices engage.
- **Scenario 2 — Short-circuit applied to the DC bus before the load**
  The fault is applied directly on the main DC busbar, before the power reaches the resistive load. In this case, all available sources: PV through the boost converter, possibly a battery, and bus capacitance, contribute to the fault current. This situation simulates a critical system level fault, which bypasses the load entirely and tests the maximum short-circuit current that the system can deliver. It reflects a worst case fault in the distribution panel.
- **Scenario 3 — Short-circuit at the DC/DC converter output**
  The fault is applied immediately at the output terminals of the boost converter, before the energy is distributed across the DC bus. The current is supplied primarily by the Boost converter and the local bus capacitance, and its magnitude depends on the converter's current limiting capabilities. This scenario is useful for evaluating the converter's response and the effectiveness of its integrated protections in the event of a localized fault on its output cables.

These three scenarios were selected for their practical relevance: they illustrate different fault contributions, from local PV faults to severe DC bus and Boost converter output faults, and are commonly used as benchmarks for validating DC protection strategies.

The simulations corresponding to the three short-circuit scenarios were carried out using the Typhoon HIL simulation environment, specifically through the TyphoonSim interface. At this stage, the models were implemented and tested in software-in-the-loop mode, allowing the evaluation of fault dynamics under idealized conditions, without hardware-in-the-loop.

Figure 7 presents the simulation results for the three short-circuit scenarios, showing the time evolution of input and output currents (I_{in}, I_{out}) and DC voltages (V_L, V_{dc}).

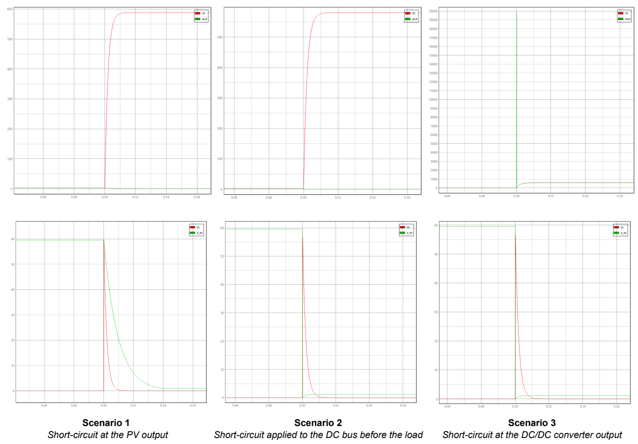

Fig. 7. Simulation results of the input and output currents I_{in}, I_{out}, and the PV and DC bus voltages V_L, V_{dc}, for the analyzed fault scenario

Subsequently, the same circuit was implemented and executed in real-time within the Typhoon HIL SCADA environment, resulting in the graphs shown in Figure 8. These real-time traces confirm the transient behavior observed in the offline simulations, showing a sudden increase in current immediately after the fault initiation and a rapid voltage drop on the DC bus.

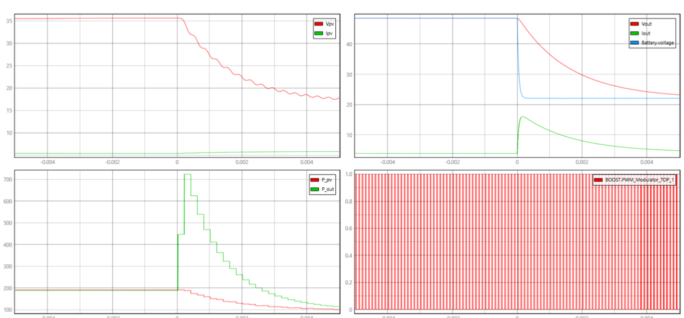

Fig. 8. Simulation results of fault operation in Typhoon HIL SCADA

VI. Conclusion

This study has demonstrated that co-simulation using MATLAB/Simulink and Typhoon HIL provides a robust framework for measuring and validating short-circuit currents in LVDC microgrids. The results of the “Cottage in the Sun” case study demonstrate the framework’s capability to safety and realistically simulate severe fault scenarios – at the PV output, the DC bus and the converter output - providing crucial data for validating the coordination and fault response strategies of protection devices.

These results highlight the need to implement fast protection devices to limit the fault current and safeguard critical components of the microgrid. By addressing fault conditions at multiple points in the system, the co-simulation approach ensures a comprehensive evaluation of dynamic short-circuit behavior.

While simplified modeling approaches trade computational efficiency for dynamic accuracy [12], the co-simulation framework presented in this work delivers detailed system dynamics with real-time validation. This integrated approach provides a more comprehensive basis for evaluating short-circuit behavior and developing reliable protection strategies in LVDC microgrids.

Furthermore, the integration with Typhoon HIL SCADA highlights the scalability and practical relevance of the proposed methodology. Beyond offline modeling, this real-time validation workflow bridges the gap between theoretical analysis and hardware-based testing, paving the way for more reliable and deployable protection strategies in LVDC microgrids.

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