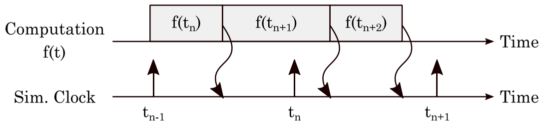
COURSE CONTENT FOR TRANSIT TRAINING

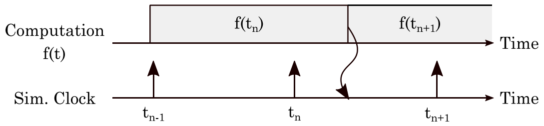
1.1 Introduction to Real-Time Simulations with Typhoon HIL: Voltage Source Converters Modelling and Real-time Machine-learning Applications

1.1.1 Introduction to real-time simulations

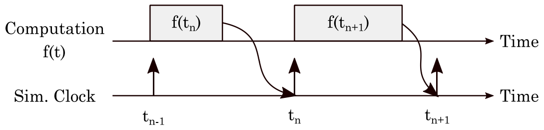
Real-time simulations are essential in various engineering fields, including electrical engineering, aviation, automotive, and robotics. In essence, a real-time simulation ensures that a given model operates at the same pace as the actual system it represents. This synchronization ensures that events within the simulation occur simultaneously with their real-world counterparts, allowing for proactive evaluation of system behavior and any implemented control or prediction systems. Figure 1 compares offline simulations with a real-time simulation.



(a) Offline simulation: Faster than real-time



(b) Offline simulation: Slower than real-time



(c) Real-time simulation: Synchronised

Figure 1. Comparison of offline simulations with real-time simulations.

Configuring models to run in real-time enables one to use *hardware-in-the-loop* (HIL) simulations to test controllers. It's possible to make design changes earlier in the development process, reducing costs and shortening the design cycle. This training introduces step-by-step modelling and simulation of Voltage Source Converters (VSCs) in the Typhoon HIL environment. In addition, some real-time machine learning applications are also given.

1.1.2 Modelling of Grid-Following Control for VSC

One of the common strategies to operate VSCs is following a grid voltage reference. This strategy is known as *grid-following* control. The implementation of this control strategy requires the connection of the VSC (and its filter) to an infinite bus, as depicted in Figure 2. As the VSC follows a voltage

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reference in this case, the control objective is the power injected at the Point of Common Coupling (PCC).

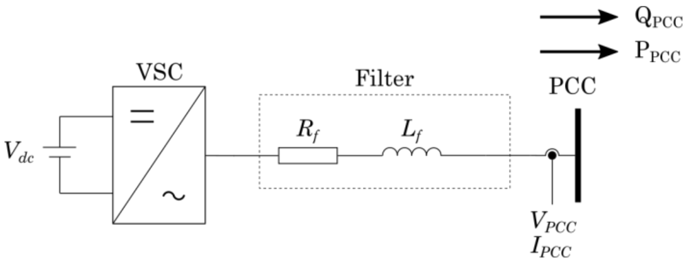

Figure 2. Circuit for the implementation of the grid-following control.

The implementation of the grid-following strategy in the Typhoon HIL Control Center environment requires the use of some common blocks in the Schematic Editor. These blocks can be found using the Library Explorer, by navigating through different categories, such as sources, signal processing, measurements, etc. Figure 3 depicts the electrical circuit implemented in the Schematic Editor.

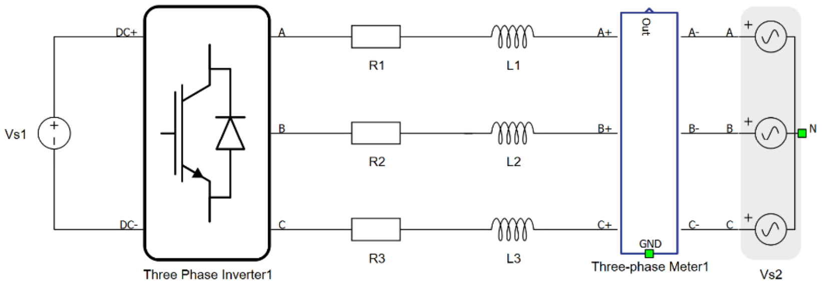

Figure 3. Voltage Source Converter implemented in the Schematic Editor of the Typhoon HIL Control Center.

The circuit in Figure 3 includes active components such as a DC voltage source, a three-phase inverter, and a three-phase voltage source; and passive components such as resistors and inductors. All these elements need to be initialized by defining their characteristic values. For control purposes, a three-phase meter is inserted at the PCC to measure voltages and currents at that point. Voltages and currents are transformed from the *abc*-frame to the *dq*-frame using '*abc to dq'* blocks. Reference currents in the dq axis are computed as:

$$i_{d,ref} = \frac{2}{3} \cdot \frac{P_{ref}}{V_d}$$

$$i_{q,ref} = -\frac{2}{3} \cdot \frac{Q_{ref}}{V_d}$$

Where P_{ref} and Q_{ref} are the active and reactive power references, respectively, and V_d is the direct voltage at the PCC. Current control is achieved using proportional-integral control:

$$m_d = \frac{2}{V_{dc}} \cdot (u_d - L\omega_0 i_q + V_d)$$

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$$m_q = \frac{2}{V_{dc}} \cdot (u_q + L\omega_0 i_d + V_q)$$

where m_d and m_q are the modulation indexes for the VSC, V_{dc} is the magnitude of the DC voltage source, u_d and u_q are the outputs of the PI controllers. Figure 4 shows the implementation of the current control.

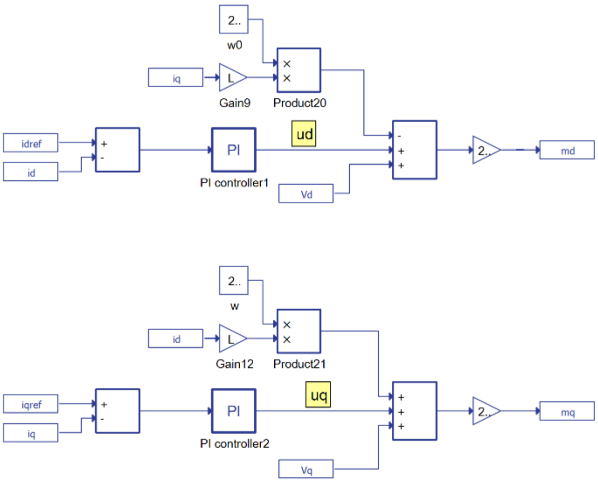

Figure 4. Implementation of the current control.

Modulation indexes are transformed back to the *abc*-frame and fed into the three-phase inverter. At this moment, the control loop is closed, and it is possible to perform the real-time simulation. Real-time simulations are launched from the HIL SCADA of the Typhoon Control Center. From the SCADA editor it is possible to configure some widgets that allow monitoring and control of the simulation in the real time. As an example, a simulation is performed in which the power references change over the time. Figure 5 represents the results in a Capture/Scope widget that allows monitoring of different variables of the model.

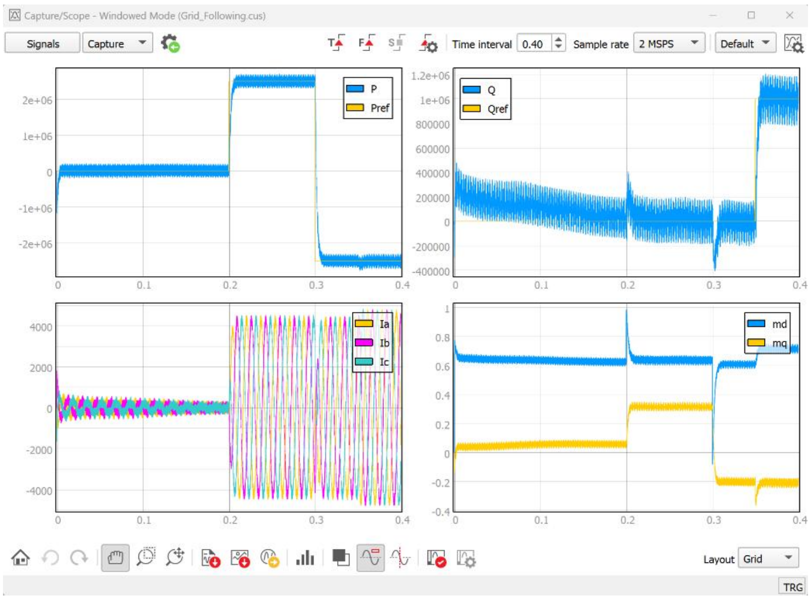

Figure 5. Capure/Scope widget showing the results of the real-time simulation.

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As depicted in Figure 5, power delivered by the VSC matches power references over the simulation. Some other variables are depicted such as the *abc* currents at the PCC and the modulation indexes of the VSC in the *dq*-frame.

One of the advantages of real-time simulations is that the simulation can interact with the real world by using analog and/or digital inputs and/or outputs. To illustrate this possibility, in this training we extract the *abc*-currents at the PCC to visualize them in an oscilloscope. The configuration of the inputs and outputs of the model is directly performed from the HIL SCADA. Figure 6 depicts the experimental testbed used to show extraction of signals from the real-time simulator.

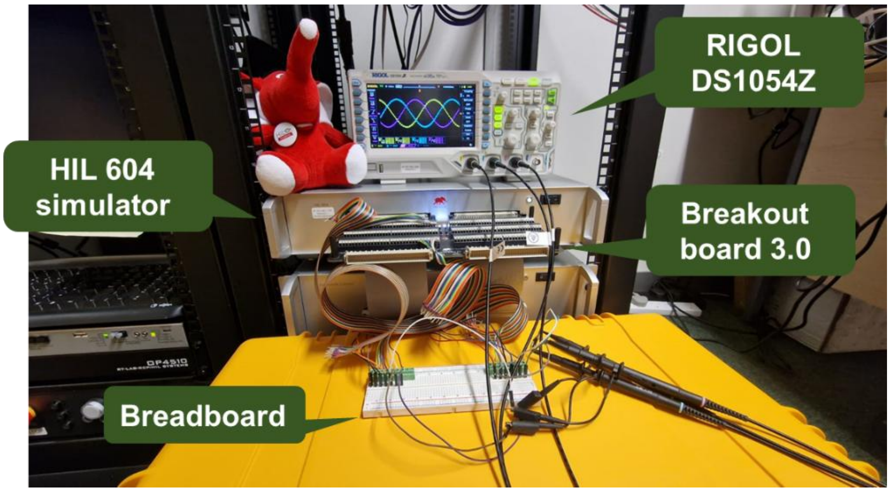

Figure 6. Experimental testbed used to extract signals from the real-time simulator.

1.1.3 Modelling of Grid-Forming Control for VSC

The second control strategy implemented during the training was *grid-forming* control. This control strategy makes the VSCs to emulate the grid, so the variables that are controlled in this case are the voltage magnitude and its frequency at the PCC. Figure 7 shows the isolated circuit used for the illustration of grid-forming control.

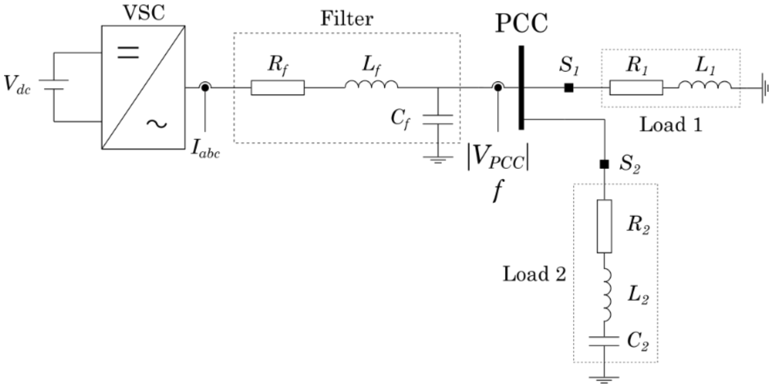

Figure 7. Circuit for the implementation of the grid-forming control.

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Figure 8 shows the implementation of the electrical circuit for the grid-forming control. It includes '*Triple Pole Single Throw Contactor*' blocks to perform switching of the loads.

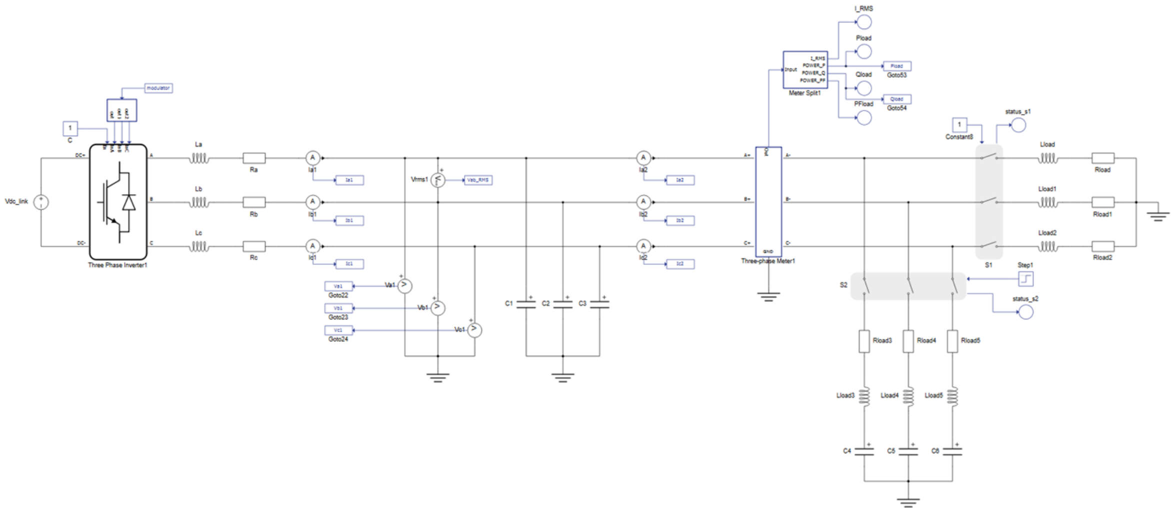

Figure 8. Circuit implementation for grid-forming control in the Typhoon HIL Control Center.

Although current and voltage measurements are like those of the grid-following approach, the control scheme of the system is slightly different. It includes two cascaded PI controllers to perform the outer control (voltage) and the inner control (current). Figure 9 shows the Implementation of the voltage and current control for the grid-forming approach.

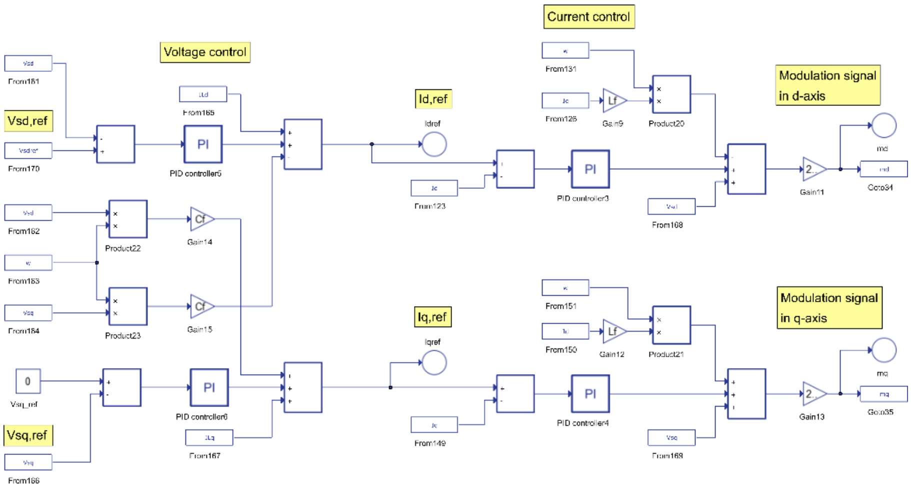

Figure 9. Implementation of the voltage and current control for the grid-forming approach.

The references for the control system are generated through the droop equations, which aim to mimic the behavior of conventional synchronous generators. The equations representing droop are detailed in the following:

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$$\omega_{set} = \omega_{nom} + m_p \cdot (P_{Load} - P_{set})$$

$$V_{set} = V_{nom} + m_q \cdot (Q_{Load} - Q_{set})$$

Where ω_{set} and V_{set} are the reference frequency and voltage magnitude, respectively. Subindex '*nom*'

Represents nominal values, and m_p and m_q are the droop coefficients for the active and reactive power, respectively. The implementation of the droop equations in the Typhoon HIL environment is depicted in Figure 10.

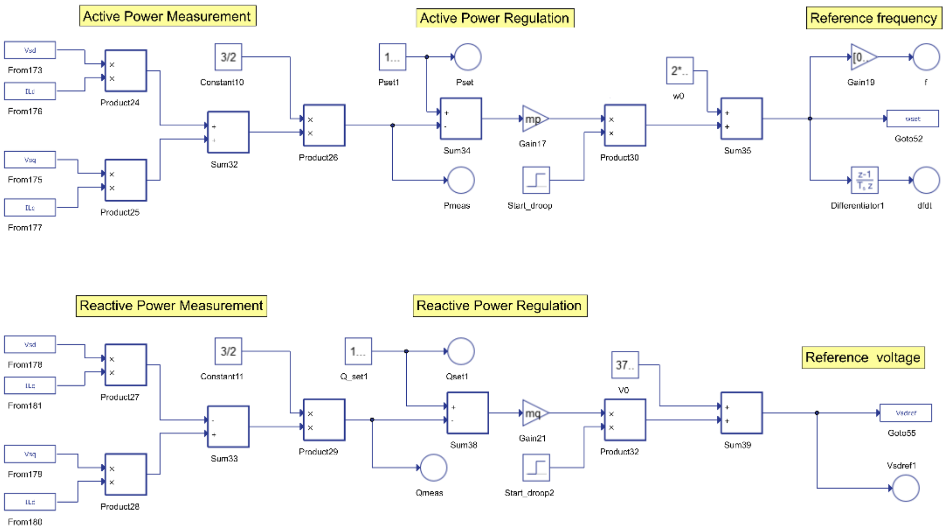

Figure 10. Implementation of the droop equations in the Typhoon HIL environment.

The effects of modifying droop coefficients was assessed in simulations. First, the VSC fed only Load 1 (switch S1 closed and S2 opened). After reaching the steady-state, at t = 0.5 seconds, switch S2 closes and the inverter feeds the two loads simultaneously. Figure 11 shows the evolution of the active power and frequency measured at the PCC.

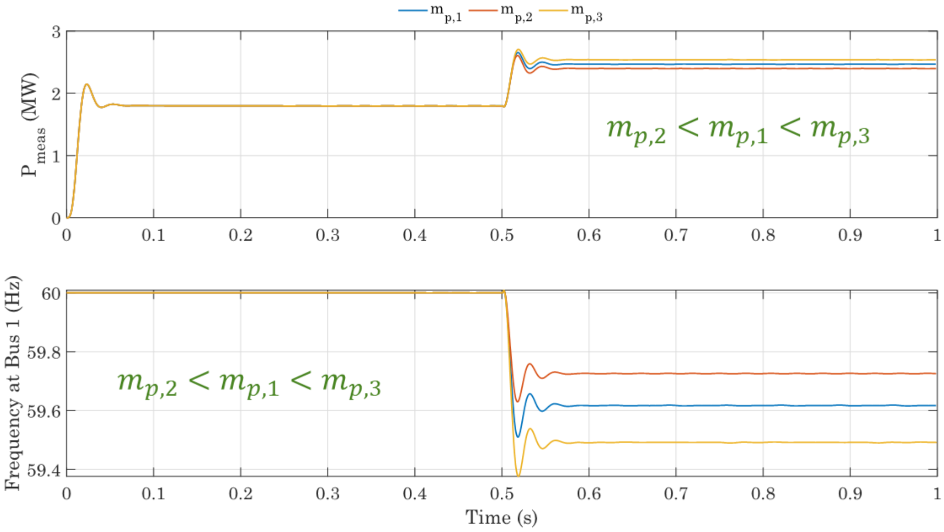

Figure 11. Simulation results for the grid-forming control: assessment of the droop coefficient values.

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As depicted in Figure 11, droop coefficients affect the behavior of the system, from the most aggressive ($m_{p,3}$) to the mildest case ($m_{p,2}$).

1.1.4 Real-time machine-learning applications with Typhoon HIL

The final part of the training gives an overview of real-time machine-learning applications with Typhoon HIL. To this end, the training introduces an example which demonstrates the use of Artificial Neural Networks (ANNs) in a microgrid. The microgrid is an IEEE34 bus network with distributed generation (DG), and the ANN is used for islanding detection. The network is depicted in Figure 12, where it is possible to identify different elements such as transmission lines, constant impedance loads, three-phase two-winding transformers, and an averaged wind power plant.

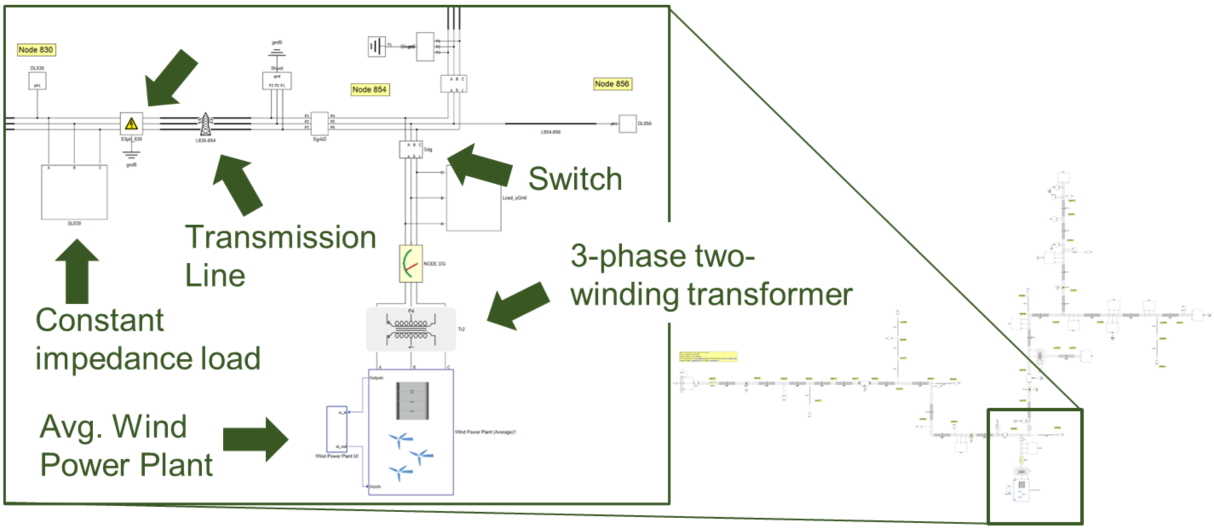
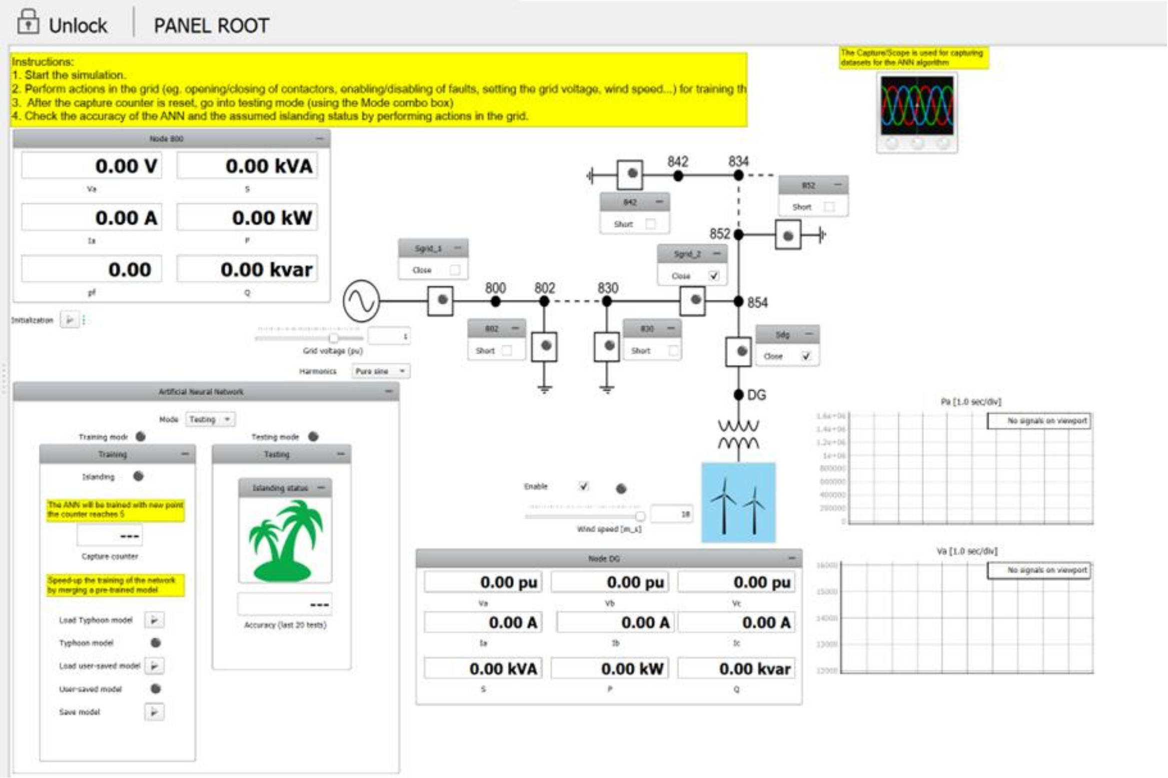


Figure 12. IEEE34 bus network with a connected wind power plant.

The most interesting part of this model appears when the user compiles the typhoon schematic editor (.tse) file, and the HIL SCADA is launched. This example comes with a predefined SCADA panel that the user can modify as they require. Figure 13 depicts the SCADA panel of this example.

The panel incorporates different sections for monitoring and control of the system. The one-line diagram displays the state of contactors and faults in the grid. The user can perform several actions like opening/closing contactors and enabling/disabling faults by using the dedicated checkboxes. For its part, the ANN section has two modes of operation: training and testing. In the training mode, with each action performed in the grid, a capture function is performed to capture relevant signals and the capture counter increases by 1. After the sixth action is performed, the ANN is trained. In the testing mode, by performing various actions in the grid, the user can see the response of the ANN. The islanding status flag and the accuracy based on the previous 20 tests is depicted also in real-time.



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Instructions:
1. Start the simulation.
2. Perform actions in the grid (eg. opening/closing of contactors, enabling/disabling of faults, setting the grid voltage, wind speed...) for training th
3. After the capture counter is reset, go into testing mode (using the Mode combo box)
4. Check the accuracy of the ANN and the assumed islanding status by performing actions in the grid.

The Capture/Scope is used for capturing datasets for the ANN algorithm

Node 800

Va: 0.00 V
S: 0.00 kVA
Ia: 0.00 A
P: 0.00 kW
pf: 0.00
Q: 0.00 kvar

Grid voltage (pu): 1
Harmonics: Pure sine

Artificial Neural Network

Mode: Testing

The ANN will be trained with new point the counter reaches 5

Capture counter: ---

Speed-up the training of the network by merging a pre-trained model

Accuracy (last 20 tests): ---

Wind speed [m_s]: 10

Node DG

Va: 0.00 pu
Vb: 0.00 pu
Vc: 0.00 pu
Ia: 0.00 A
Ib: 0.00 A
Ic: 0.00 A
S: 0.00 kVA
P: 0.00 kW
Q: 0.00 kvar

Figure 13. SCADA panel of the IEEE 34 node islanding with implemented ANN example.

1.1.5 Contribution to development of low carbon technologies, sustainability and circularity

The topic of this training is closely related to low-carbon technologies, sustainability and circularity. On the one hand, electronic converters serve as an interface between renewable generators and electrical power systems. On the other hand, the gradual shift from conventional generation to renewable generation makes it necessary for renewable sources to provide ancillary services. In other words, in addition to generating the necessary energy, renewable generators must emulate the behavior of conventional synchronous generators, which naturally respond to imbalances between generation and consumption. To achieve this goal, it is necessary to change the approach to inverter control from *grid-following* to *grid-forming*.

Secondly, the training aims to provide a first contact with real-time simulations, illustrating step-by-step how to set up and launch such simulations. The *hardware-in-the-loop* methodology is key to validate control strategies in early stages of development, reducing costs and duration of the design stage.

Finally, there is no doubt about the ability of artificial intelligence techniques to find complex relationships between variables in a system. This training shows some of the possibilities offered by the Typhoon HIL simulator to implement machine-learning techniques applied to electrical power systems in the real time.

1.1.6 Highlight on application in industry

The content of this training can be useful for industries in different aspects. On the one hand, a real-time simulation tool has been presented that can be used by industries in sectors such as energy, automotive, aerospace, etc. Typhoon HIL software has a wide variety of examples that can be modified as required by the user for each application. As discussed throughout the training, real-time simulations can reduce costs and development times at the product design stage.

On the other hand, an example based on machine learning has been shown, which is intended to serve as an inspiration for industries to improve their monitoring and control processes. Nowadays, industries have a large amount of data that can be used to detect possible failures before they occur, allowing preventive maintenance instead of corrective maintenance.

In addition, a highly topical subject was discussed, such as electronic converters, which are used to connect the most developed renewable generation technologies to the grid: wind and solar photovoltaic generation. These devices offer greater flexibility than conventional synchronous generators so power system engineers can use the material in this training to test different VSC operating strategies and their impact on power grids.

1.1.7 Contribution to development of skills and competences

This training program develops a broad set of skills in three key areas: real-time simulations, voltage source converter modelling and real-time machine-learning applications. Participants gained in-depth knowledge of real-time systems and their applications, enhancing their analytical and problem-solving skills. Hands-on experience in modeling and simulation of power supply converters provided practical engineering knowledge and insight into power electronics optimization. In addition, the integration of machine learning with real-time systems enabled participants to make data-driven decisions and enhance their technical competence, making them valuable in technology-driven industries. Overall, this multidisciplinary training prepares individuals for advanced positions in engineering and applied sciences.