An Open-Source Industrial-Grade Collection of Renewable Energy Source Generic Models in Modelica Language

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Abstract

In a context of massive penetration of Renewable Energy Sources (RES) in the grid, it is of prime importance for Transmission System Operator (TSO) to correctly represent these components in their day-to-day dynamic simulations used to assess system stability, both in operational and planning situations. Well-parametrized generic Power Electronics Interfaced Resources (PEIR) models have emerged as a viable option for TSOs for large-scale stability situations, and are largely available in commercial power system software. However, despite previous efforts in the open-source community, especially in the Modelica one, there is a lack of a complete, up-to-date, and industrial-grade library. This paper presents the current status of the Dynaωo Modelica library for standard PEIR models that tries to fill this gap. The library's architecture and content, the implementation choices, and already existing industrial usages of the models are presented in detail, alongside validation cases and results.
Keywords: Western Electricity Coordinating Council (WECC), International Electrotechnical Commission (IEC), Power Electronics Interfaced Resources, Modelica, Dynawo

1 Introduction

Transmission systems are undergoing significant transformation due to the massive penetration of PEIR with the increased integration of RES and High-Voltage Direct Current (HVDC) connections.

Adding these new components to the system significantly impacts its dynamic behavior, which is crucial for accurately assessing system stability. The primary role of the electrical TSO is to ensure the security and stability of the system at all times through both preventive and corrective actions, supported by continuous monitoring and simulations. To achieve this, it is essential to accurately model and integrate these new components into time-domain simulations.

However, creating dedicated Root-Mean-Square (RMS) dynamic models for each new installation has proven to be a non-sustainable approach, due to the large number of new connections to the grid each year and the difficulty in obtaining open and transparent descriptions of the controls for intellectual property reasons. Two strategies are currently used by the different TSO across the world to tackle this issue: use black-box models directly provided by the Original Equipment Manufacturer (OEM) or/and require well-parametrized generic models allowing to correctly represent the installation behavior (EirGrid 2022; NGESO 2024; TenneT 2024).

Even if generic models can cover a large spectrum of phenomena, only adapting their parameters to the project-specific settings allows one to properly fit the response of many different installations. These standard models are mainly proposed by two entities: the IEC and the WECC. IEC 61400-27-1 international standard describes Wind Turbine (WT) and Wind Power Plant (WPP) models (61400-27-1:2020 2020). The WECC standard contains models for WPP, Photovoltaics (PV) and Battery Energy Storage Systems (BESS) installations (Pourbeik 2014).

A large part of these generic models is available in power systems commercial software such as DIgSILENT Power Factory, Siemens PTI PSS®E, or General Electric PSLF. However, in these environments, even if the general block diagram structures are visible and readable, the individual blocks and their implementation choices are hidden: this could lead to possible discrepancies in the results that are difficult to explain (Villena-Ruiz et al. 2019; Franke, Guironnet, and Cardozo 2024). On the other hand, Modelica is a high-level and open-source modeling language (Fritzson and Engelson 1998), (Mattsson, Elmqvist, and Otter 1998), which is particularly well-suited to offer transparent and unambiguous modeling of power system components in general (L. Vanfretti et al. 2013) and RES in particular.

Open-source implementations of WECC generic models have been proposed and released both in Dynaωo (Nuschke et al. 2021) and OpenIPSL (Fachini, Luigi Vanfretti, et al. 2021) Modelica libraries in recent years. Nevertheless, both efforts only cover part of the currently available WECC models due to the fast evolution of the standard. On the IEC side, the standard course of evolution is slower but the main previous work (Carbonell et al.

2023) focused on the implementation of the Edition 2020 Type IV model, which is not the mostly used by OEMs as of today from RTE's, the French TSO, experience. Recent contributions around Modelica and generic models were rather focused on improvements to the standard models, either to make them more adapted to weak grid conditions (Carbonell et al. 2023), to compare them and provide recommendations for further improvements (Franke, Guironnet, and Cardozo 2024) or to better match power hardware in the loop results (Fachini, Chang, et al. 2025), than on the completeness of the libraries. As a result, there is a lack of a complete, up-to-date and industrial-grade collection of generic RES models in Modelica. This paper tries to fill this gap by presenting the current status of the Dynaωo Modelica library which contains all the necessary standard models to cover all kinds of new RES installations that would like to connect to the grid. This open-source library will facilitate the collaboration between the different power system's stakeholders, offering a basis for discussions on the unavoidable implementation choices and easing the diffusion and usage of generic models in the academic and industrial communities.

The main contributions of this paper are thus the following:

- A presentation of a complete, up-to-date and industrial-grade Modelica collection of generic models for any kind of RES.
- A description of the modeling approach and the implementation choices done in the library.
- An introduction on the current and foreseen industrial usages of the RES models in RTE.

The paper is organized as follows. Section 2 presents the complete set of PEIR generic models available in the library as well as its global architecture. Section 3 and section 4 are dedicated to the IEC and WECC parts of the library, respectively. They provide an overview of the models, a description of the Modelica implementation, a focus on the newly implemented parts of the controls as well as on the final available models, and conclude with a models validation paragraph. Section 5 introduces two envisioned usages of the library from RTE's perspective. Finally, section 6 draws conclusions and presents potential next steps on this topic.

2 Library Content and Architecture

The Dynaωo Modelica library[1] contains at least one generic model for any kind of RES installation.

The models can be found under a PEIR package, as shown in Figure 1, containing both converter and plant models. Plant models are of prime importance for the TSOs as they are the ones that will be used in day-to-day operational and planning large-scale studies; converter models can also be useful if one wants to focus on the fast transient driven by the converter controls. For both packages, application-specific and non-specific models have been implemented.

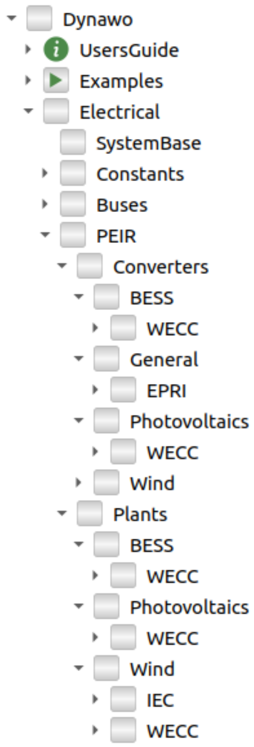

Figure 1. PEIR package in Dynaωo Modelica library.

- Application-specific models for BESS, PV and WPP described in IEC and WECC standards. The list in Table 1 will be presented in detail in the rest of this paper.
- Models with non-specific application "*General*" (i.e. could be used for PV, WPP or BESS components) from IEC and WECC standards or from projects related to grid following or grid forming converters. This part of the library is out of the scope of this paper.

These models have been developed by combining different individual modules available in the control part of the library under a dedicated PEIR package and physical electrical parts such as lines, transformers, and injectors.

PEIR	*Subtype*	*Available models*
Wind	Type III WT	IEC (61400-27-1:2020)
	Type III WPP	IEC (61400-27-1:2020), WECC
	Type IV WT	IEC (61400-27-1:2015/2020), WECC
	Type IV WPP	IEC (61400-27-1:2015/2020), WECC
PV	–	WECC
BESS	–	WECC

Table 1. Available PEIR models in Dynaωo Modelica library.

[1] https://github.com/dynawo/dynawo

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3 IEC Models

3.1 Overview and Modelica implementation

The IEC 61400-27-1 standard specifies generic and modular dynamic models suitable for power system stability studies. These models may be used to represent the dynamic behavior of WPP at their Point of Connection (PoC) to the transmission network and of WT at their output terminal. The overall structure of the WPP model proposed in the standard can be found in (61400-27-1:2020 2020).

- The **WPP control and communication** model, also known as Power Park Control (PPC), is in charge of controlling the active and reactive power (P,Q) of the whole plant at the PoC, by computing and sending appropriate orders to the WT. The ancillary services required by TSO, like primary voltage regulation or frequency sensitive mode are handled in the PPC. The PPC is mainly involved in slow dynamics (several seconds).
- The **WT** model is intended to represent an aggregation of a set of identical Wind Turbines. The WT is receiving an active power order p_{WTref}[2] and a voltage or reactive power order (depending on the chosen control mode) x_{WTref} from the PPC. These orders are used to compute reference active and reactive currents, which are then limited to respect the physical limits of the unit. These currents $(i_{\mathrm{pcmd}}, i_{\mathrm{qcmd}})$ are then injected based on the synchronization angle θ_{Pll} given by the Phase-Locked Loop (PLL). The control does not incorporate any inner current loop, so the converter is modeled solely as a current source. The WT control is involved in faster dynamics than the PPC (from ms to a few seconds) and is, for example, essential to represent the Fault Ride Through (FRT) behavior.
- **AUX** model is intended to represent auxiliary equipments which may be, for instance, STATCOMs or static VAR compensators. They have not been implemented at the moment but will be considered in future works.
- **Power Collection System (PCS)** represents an aggregation of the internal network between the WT and the PoC. In large WPPs, it is a crucial part of the model as there could be dozens of kilometers of cables in the real installation. The IEC standard does not specify a clear and unambiguous model for the PCS, even if it proposes a method to compute aggregated parameters based on the real installation complete internal network characteristics. In the Modelica implementation proposed in this paper, it has been decided to represent the PCS with a classical Π line model : $(R+jX)$ line impedance and $(G+jB)$ shunt admittance.

[2]All variables and parameters shown for the models are in per unit (pu). In Dynaωo library, a *Pu* is added to the variable and parameter names, it is removed in this article for better readability.

The overall Modelica implementation of the WPP models has been made to be as close as possible to what is specified in the standard. The only deviations at this level are the following:

- f_{sys} has been replaced by $omegaRef$ which is the notation used in Dynaωo for the system frequency (which means the rotation speed of the reference frame in which the phasors are computed).
- A measurement block has been inserted to obtain the WPP terminal complex voltage and current.
- An additional input $tanPhi$ has been considered for the WT model (in the standard $tanPhi$ is considered as a fix parameter).

3.2 Models description

3.2.1 Type IV Model

Type IV WT, also called full-converter WT, are interfaced to the grid with a AC/DC and then a DC/AC converter. This creates a decoupling between the mechanical system of the WT and the electrical system. Moreover, this type of WT has a very flexible control that can be used to offer support functions to the grid. The implementation of the Type IV model based on the Ed. 2020 of the IEC 61400-27-1 standard is presented in details in (Carbonell et al. 2023). A first version of the standard was published in 2015 which is still used by many vendors. Considering this, an implementation of the IEC Type IV Ed. 2015 has been added to the Dynaωo library. The main differences between the two editions of the standard are described below and summarized in Table 2.

- **Dedicated measurement module**: The 2020 version includes a dedicated grid measurement module that is used once for protection and once for control at the WT level and once for the PPC at the WPP level. In the 2015 version, there is no such centralized measurement module, and the filtering process is made independently in each control or protection sub-module. The centralized version used in the 2020 version avoids duplicating the declaration of the time constants and decreases the risk of inconsistencies.
- **WT electrical system**: The 2020 version includes an electrical system module to represent electrical components between the generator system (which is the output of the converter) and the point where the WT is connected. It would typically be used to represent the MV/LV transformer of the WT. In the 2015 version, this electrical system module is just a circuit breaker that will disconnect the WT based on the flag

F_{OCB} (Open Circuit Breaker). The 2015 version of this module can be extracted from the 2020 version just by setting $r_{\mathrm{es}} = x_{\mathrm{es}} = g_{\mathrm{es}} = b_{\mathrm{es}} = 0$. Considering this, the electrical system module is implemented for both versions.

- **Reactive current injection**: The additional reactive current to be injected during fault differs between the two versions. In the 2015 version, it is proportional to the voltage measured at WTT terminal u_{WTT}, with a dead-band $[u_{\mathrm{db1}}, u_{\mathrm{db2}}]$: $i_{\mathrm{qv}} = K_{\mathrm{qv}}(u_{\mathrm{db1}} - u_{\mathrm{WTT}})$ when $u_{\mathrm{WTT}} \leq u_{\mathrm{db1}}$; while in the 2020 version, it is proportional to the derivative of u_{WTT} : $i_{\mathrm{qv}} = K_{\mathrm{qv}}(\Delta u_{\mathrm{db1}} - \Delta u_{\mathrm{WTT}})$ when $\Delta u_{\mathrm{WTT}} \leq \Delta u_{\mathrm{db1}}$. This derivative is computed with a time constant t_{Uss}, if t_{Uss} is very large this becomes equivalent to the 2015 version, while if t_{Uss} is small the converter will inject reactive current only with fast variations of voltage.

- **Over-Voltage Ride Through (OVRT)**: In addition to the Under-Voltage Ride-Through (UVRT) operation, the 2020 version also includes an OVRT operation. This aims to adapt the reactive current order if voltages exceed a given parameter U_{qRise}. The control path for additional reactive current in the case of OVRT is the same as in the case of UVRT but with the opposite reaction, considering that this path reacts to voltage variations (see previous point). This part of the control is not present in the 2015 version, which means that there is no particular operation in case of over voltages.

- **WPP description**: The 2020 version includes a full description of WPP including PPC with its two main control blocks (active and reactive power controls) along with the communication and measurement modules. Two variants are proposed for the communication module : a linear one consisting of lead-lag transfer functions applied to every communicated variable, and a pure delay one. At this time, only the linear variant has been implemented but the pure delay variant could be developed in the future to better observe some dynamics. In the 2015 edition, a draft version of PPC active and reactive control blocks was proposed in the standard, but without any general structure to build the full WPP model. The choice made in the Dynaωo implementation is to use the structure proposed in the 2020 version and put into it the 2015 control blocks to build 2015 WPP models.

Additionally, it is important to keep in mind that there are two variants of Type IV WT : Type IV A and IV B, the only difference being that Type IV B includes an additional module giving a simplified representation of the mechanical part.

	2015 version	*2020 version*
Measurement	Electrical quantities independently filtered.	Centralized measurement module.
Electrical system	Not in the norm but added in the Modelica implementation.	Classical PI-system between converter and WT terminal.
UVRT reactive current injection	Included and proportional to the voltage u_{WTT}.	Included and proportional to the derivative of the voltage u_{WTT}.
OVRT reactive current injection	Not included.	Included.
WPP	No main structure in the norm but modeled in Dynaωo based on the 2020 structure with the 2015 control blocks.	Full description of WPP including PPC with P and Q/U controls, communication and measurement modules.

Table 2. Summary of the main differences between 2015 and 2020 versions of the IEC 61400-27-1 standard and additional Modelica implementation

3.2.2 Type III Model

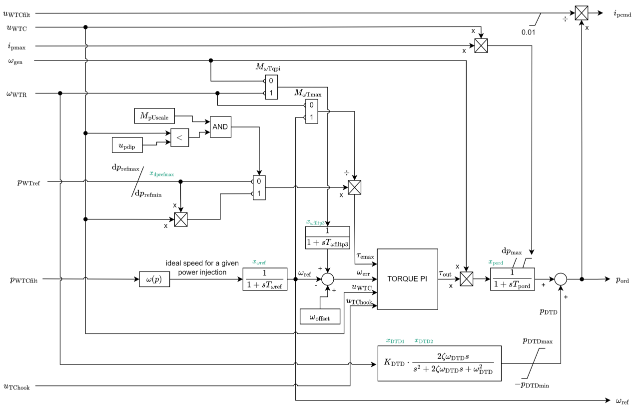
The Type III model represents a wind power plant with Doubly-Fed Induction Generators (DFIG). It shares many of its sub-models with the Type IV model. The differing models are presented in more detail below:

- **Active power control** of the wind turbine control, including its sub-model, the **Torque PI controller** (see Figure 2). Its general behavior is influenced by an $\omega(p)$ lookup-table that provides the angular velocity at which the turbine should rotate when it is injecting a certain active power. The specific implementation choices in these controllers, especially integrators, limiters and their interactions, are delicate and can have a large influence on model behavior.

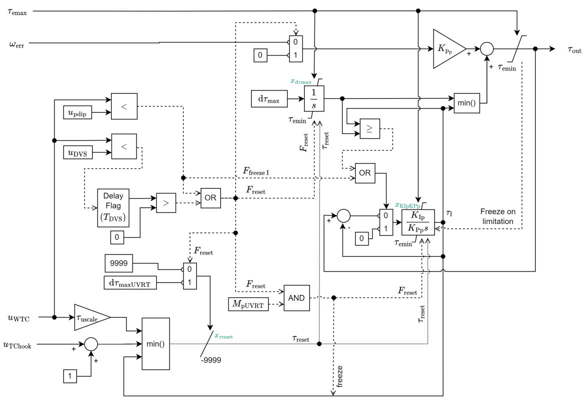
- **Two-dimensional aerodynamic** model (see Figure 3). It models the energy conversion from available wind power p_{avail} to what the wind turbine passes on to the mechanical rotor. This is influenced by the rotor blades' pitch angles θ and the turbine's angular velocity ω_{WTR}.

- **Pitch angle control** (see Figure 4). It uses two PI controllers to control the pitch angle, one associated with rotor speed $\omega_{\mathrm{WTR}} - \omega_{\mathrm{ref}} + K_{\mathrm{PX}}(p_{\mathrm{ord}} - p_{\mathrm{WTref}})$ and one with generator power $p_{\mathrm{ord}} - p_{\mathrm{WTref}}$.

- **Generator system models** (see Figure 5). Two generator system models have been implemented: **III-A**



(a) Active power control model



(b) Torque PI control model

Figure 2. IEC Type III Wind Turbine control models.

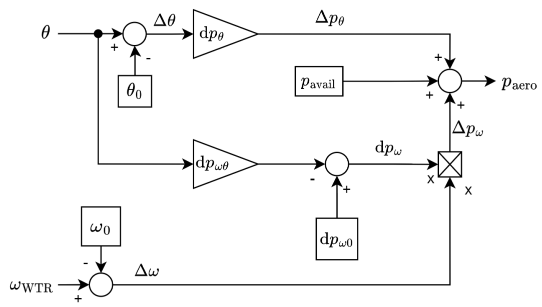


Figure 3. IEC Type III Two-Dimensional Aerodynamic Model.

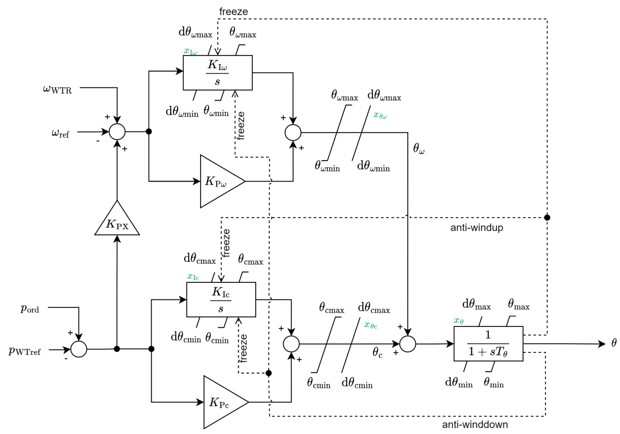


Figure 4. IEC Type III Pitch Angle Control Model.

with an explicit model of the current control loop and **III-B** with a simple model of a crowbar-circuit.

All the figures are extracted from (*COLib, a collaborative open-source dynamic simulation library for power systems* 2025).

3.3 Models validation

The 2015 version of the Type IV model has been validated by comparing the results with the detailed 2020 version. For the Type III model, in-depth comparisons against the results obtained with the DIgSILENT PowerFactory (DIgSILENT 2024) models have been done. Indeed, a structured qualitative validation procedure has been conducted for the components implemented in OpenModelica (Fritzson, Pop, et al. 2020) as follows:

- Set up the model with inputs and outputs in both simulation environments.
- Define test cases with varying input signals.
- Run the simulations and visually compare output signals using OMPython[3] and powfacpy[4].

[3]https://github.com/OpenModelica/OMPython
[4]github.com/FraunhIEE-UniKassel-PowSysStability/powfacpy

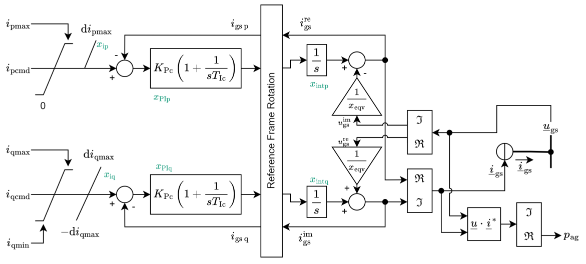
Exemplary results are presented in Figure 6 showing a test case of the validation of the P control model. Several step variations of the input voltage at the converter u_{WTC} are performed, and it is seen that the outputs of the P control model, active power order of the WT p_{ord} and the active current command i_{pcmd}, in OpenModelica and DIgSILENT PowerFactory are identical. In Figure 7, several step variations are done on the input active current command i_{pcmd} of the Type III-A generator system model. The real active current injection i_{gsre} is observed at the output. A perfect match is observed between both implementations.

Figure 8 displays the response of the complete wind turbine model in a Single Machine Infinite Bus (SMIB) configuration to a change of the active power reference setpoint P_{ref} ($= p_{\mathrm{WTref}}$). The responses of both models are very similar, even if not completely identical. All these results allow to validate the WT Type III Modelica implementation.

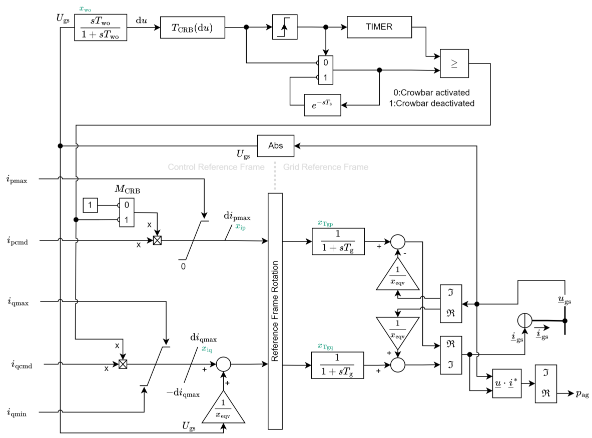
4 WECC Models

4.1 Overview

WECC generic models represent second generation generic renewable energy systems that are interfaced with the grid through power electronics converters, like PV, Wind Turbine Generator (WTG), and BESS. These models are used in transient stability studies where the electric



(a) Generator System A



(b) Generator System B

Figure 5. IEC Type III Wind Turbine Generator Systems.

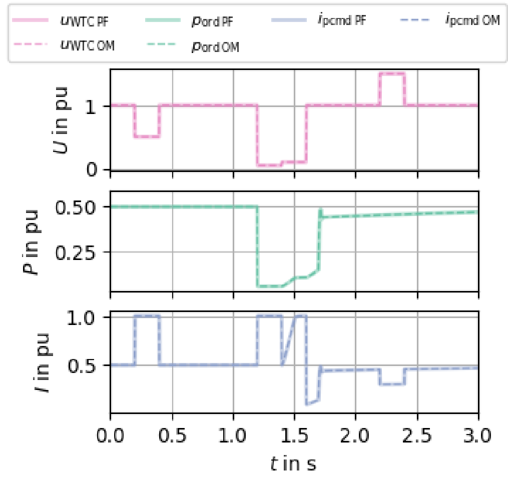


Figure 6. Voltage at converter terminal u_{WTC} variation (pink) for IEC Type III P Control Model. Active power order p_{ord} (green) and active current command i_{pcmd} (bleu) are observed. The dashed lines correspond to DIgSILENT PowerFactory (PF) simulations and the straight lines correspond to OpenModelica simulations.

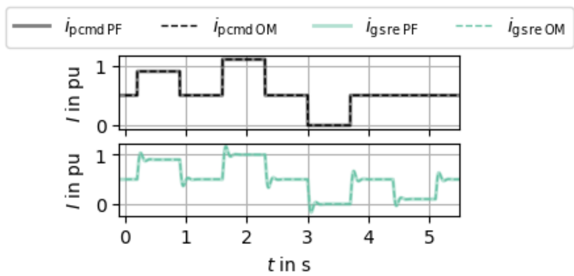


Figure 7. Active current command i_{pcmd} variation (black) for IEC Type III-A generator system model. Real current i_{gsre} (green) is observed. The dashed lines correspond to DIgSILENT PowerFactory (PF) simulations and the straight lines correspond to OpenModelica simulations.

controls and converters are modeled along with the plant controls.

The WECC RES models are implemented by combining the different individual blocks (REPC_*, REEC_* and REGC_*) that represent the controls of an installation as seen in the Figure 9a for PV plants for example. These three control systems and the mechanical system models are presented below :

- The plant control - **Renewable Energy Plant Controller** (REPC_*) models - sets the main controls of the plant : voltage or reactive power control and frequency-dependent active power. The REPC_A model is available in Dynaωo and could be used for PV, WTG, and BESS.

- The electrical control - **Renewable Energy Electrical Controls** (REEC_*) models - includes the local inverter functionalities such as FRT characteristic with fast reactive current injection, local voltage and reactive power control, and current limitation with respect to the priority given to active or reactive current. This control system calculates the active and reactive current set-points *idCmd* and *iqCmd*. Three models are available in Dynaωo : 1) the REEC_A model that is recommended for WTG and now for PV, 2) the simple REEC_B model that was recommended for PV, 3) and the REEC_C model that is recommended for BESS where the State Of Charge (SOC) is modeled allowing negative current (i.e. consumption).

- The generator/converter control - **Renewable Energy Generator/Converter** (REGC_*) models - is the last part of the control and interfaces with the network. It enables the conversion of the current setpoints calculated by the REEC part into the final currents (or voltages) delivered to the network. Three models are available in Dynaωo : 1) the REGC_A for current source models, 2) the REGC-B, and 3) REGC-C for voltage source models. All these three blocks could be used for PV, WTG, and BESS models.

- The **WTG mechanical side models** for Type III and Type IV WTGs. All mechanical models introduced in the WECC are available in Dynaωo : the drivetrain shaft dynamics models WTGT_A used for Type

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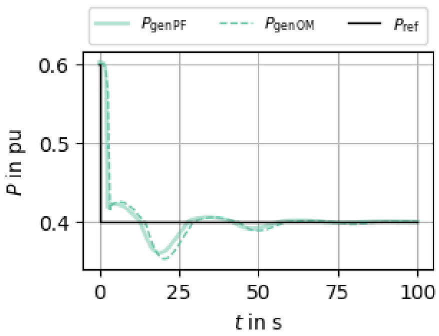


Figure 8. SMIB test comparison of the full IEC Type III-A WT model: Reference power step P_{ref} (black) from 0.6 to 0.4 pu. Generated active power P_{gen} (green) is observed. The dashed line corresponds to DIgSILENT PowerFactory (PF) simulation and the straight line corresponds to OpenModelica simulation.

PEIR	***Model combination***			
	Plant Control	***Electrical Control***	***Generator Control***	***Mechanical Controls***
Wind (Type IV)	REPC_A	REEC_A	REGC_A (_B or _C)	optional WTGT_B (or _A)
Wind (Type III)	REPC_A	REEC_A	REGC_A (_B or _C)	WTGA_A, WTGQ_A, WTGP_A (or _B), WTGT_A
PV	REPC_A	REEC_A (or _B)	REGC_A (_B or _C)	-
BESS	REPC_A	REEC_C	REGC_A (_B or _C)	-

Table 3. Possible combinations for PEIR WECC models in Dynaωo Modelica library.

III WTGs and WTGT_B used for Type IV WTGs. These models represent the rotor speed changes and resulting torsional oscillations after faults or sudden wind speed changes. The pitch controller (WTGP_A and WTGT_B), the torque controller (WTGQ_A), and the aero-dynamics (WTGA_A) models are used to properly model a Type III WTG.

Table 3 presents the current list of possible model combination in Dynaωo Modelica library for PV, WTG Type III, WTG Type IV and BESS. Noting that the new models introduced by the WECC standard, such as REEC_D, REEC_E, REPC_C and REPC_D, are currently being implemented, and will be completing the current list.

4.2 Modelica implementation

As shown in Figure 9b, the implementation in Dynaωo Modelica library follows the same structure as presented in (Ellis, Behnke, and Elliott 2013) for the **IBR level control** where the three control blocks are interconnected and receiving measurements from the network. Inside each of these blocks, the controls are described through a *block-diagram* approach following the latest version of the *Model User Guide for Generic Renewable Energy System Models 2023* (Ramasubramanian 2023).

In the Dynaωo Modelica implementation, each IBR is connected to the grid through a **terminal**. The following blocks, shown in Figure 9b represent the connection between the IBR and the network :

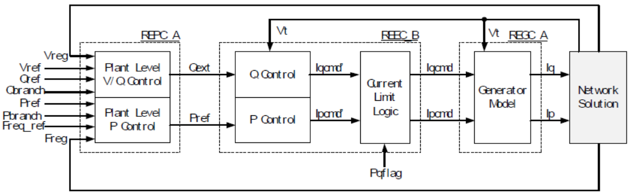
- The current **injector**, where the interface to the grid is a current source, calculates the real and imaginary currents that IBR model will inject. The dq transformation is done inside this block and is described through *equation-based* approach. For voltage source models, the dq transformation is done inside the REGC model.
- The **PLL** is added in all the models to calculate the voltage phase θ needed for the dq transformation. This block is described in a *block-diagram* approach. In the WECC standard, the PLL is neglected for the REGC_A and REGC_B models and only represented for the REGC_C model. In Dynaωo, the PLL was initially added in all models to overcome some numerical issues by adding some dynamics to the voltage phase instead of calculating it instantaneously.
- A classical Π **line** is modeled to represent an aggregation of the Inverter-Based Ressource (IBR) unit transformer and the step-up transformers and is connected to the Point of Common Coupling (PCC).
- Finally, the **measurement** block calculates variables needed for the plant control : the complex voltage and current, and the active and reactive power at the PCC. Note that the other variables needed for the PLL, the electrical control, and generator controls are measured at the injector level.

4.3 Models description

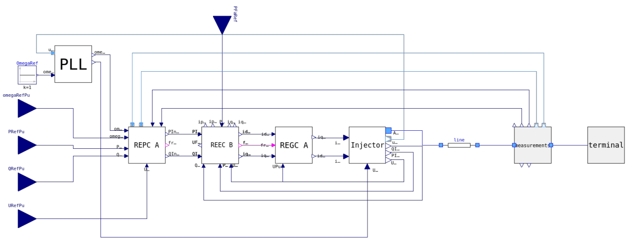
The first WECC generic models implementation in Dynaωo has been presented in (Nuschke et al. 2021), where REPC_A, REEC_A, REEC_B, REGC_A, and WTGT_A are described for PV and WTG modeling. This paper will focus on the new models added such as the REEC_C model enabling the representation of BESS, and the voltage-source models REGC_B and REGC_C for voltage-source interface with the grid.

4.3.1 Electrical control REEC_C model

The REEC_C model is quite similar to the REEC_A model; thus, in Dynaωo Modelica library, these models share the same base-model. Here, some of the differences are highlighted. Table 4 summarizes the key point differences.



(a) WECC PV current source model *(Ellis, Behnke, and Elliott 2013)*



(b) WECC PV current source model implementation in Dynaωo Modelica library

Figure 9. WECC PV current source model.

- The **reactive current injection** during fault is different. The REEC_C injects reactive current actively when the voltage at the injector is different than the reference voltage, unless the gain is set to zero or the deadband is extremely wide. However, the REEC_A has a switching logic between different states in normal operation state, during and after voltage dips, for the reactive current injection mainly related to Type III and Type IV WTG.

- The **d-axis current limits** are different. The minimal d-axis current *idMin* in REEC_A is 0, while the REEC_C model takes the negative value of *idMax*, enabling the charging and discharging of the battery. The limits of the d-axis and q-axis are calculated in the *CurrentLimitsCalculationC* model (equation-based block in REEC_C) depending on the state of charge of the battery, the P/Q priority flag and the Voltage Dependent Limitations (VDL) look-up tables.

- An additional path exists in REEC_C for the **state of charge** and includes an integrator block with a time constant t_{battery}, that represents process of charging and discharging. $SOC0$ is the initial state of charge of the battery and is a parameter in per unit given by the user, having a value between 0 and 1. $SOCMax$ and $SOCMin$ are, respectively, the maximum and minimum allowable state of charge.

  Values of the active current maximum and minimum limits are conditioned by the SOC. When the maximum state of charge is reached, the minimal active current is forced to zero, the battery cannot store anymore energy. When the minimum state of charge is reached, the battery cannot inject energy anymore. When $SOCMin < SOC < SOCMax$, the active current limits values will depend on the P/Q priority and the VDL look-up tables as explained in (Ramasubramanian 2023).

	REEC_A	*REEC_C*
Reactive current injection	Switching logic for current injection during and after fault.	Active injection of reactive current.
d-axis current limits	$idMin = 0$	$idMin = -idMax$ when not fully charged
SOC	Not included.	Included.

Table 4. Summary of the main differences between REEC_A and REEC_C

4.3.2 Generator control models

All REGC_* models have common parts, such as the inputs and the calculation of the reference q-axis current $iqRef$; this is implemented in a base common model for REGC. Here are some differences between the three models. Table 5 summarizes the key point differences.

- The **inner-current control-loops** : The REGC_B was proposed to remediate the numerical instability issues of the REGC_A in weaker networks by having a voltage source interface. However, the inner-current control-loops are still neglected, as in REGC_A. The REGC_C includes a generic representation of the inner-current control-loops with PI controllers on the d and q axes.

- The **interface with the grid** : In REGC_A, a current-source interface, the outputs of the block are the reference d-axis $idRef$ and q-axis currents $iqRef$ that will be connected to the injector block. In both REGC_B and REGC_C models, a voltage source behind an impedance ($RSource$, $XSource$) is added, with values in per unit, to emulate the source impedance of the Voltage Source Converter (VSC).

  In the Dynaωo Modelica implementation, a *VSourceRef* block is implemented, taking as an input the d-axis and q-axis current references along with the measured voltage dq components $udInj$, $uqInj$ and calculating the d-axis and q-axis voltage references following Listing 1. Then a dq to RI transformation is done, resulting in the real *urSource* and imaginary *uiSource* voltage components that will be interfaced with the grid (Listing 2).

Listing 1. d-axis q-axis voltage references

```
udSourceRef = udInj + idRef * RSource -
    iqRef * XSource
```

	REGC_A	*REGC_B*	*REGC_C*
Current loop control	Not included.	Not included.	Included.
Interface with the grid	Current source interface.	Voltage source interface.	Voltage source interface.

Table 5. Summary of the main differences between REGC_A, REGC_B and REGC_C

```
uqSourceRef = uqInj + iqRef * RSource +
     idRef * XSource
```

Listing 2. Real and imaginary voltage components

```
urSource = udSourceRefTe * cos(theta) -
     uqSourceRefTe * sin(theta)
uiSource = udSourceRefTe * sin(theta)+
    uqSourceRefTe * cos(theta)
```

4.4 Model Validation

4.4.1 BESS model

The REEC_C model in Dynaωo is integrated in the BESS model. This model has been validated against results found in (Pourbeik and Petter 2017) for a SMIB test case, in OpenModelica (Figure 10) and in Dynaωo engines.

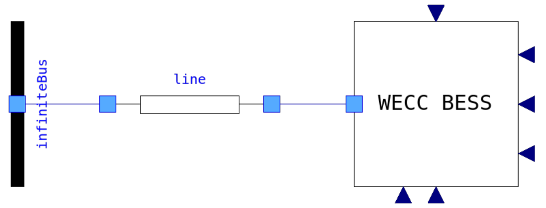


Figure 10. BESS SMIB test case in OpenModelica.

The BESS model comprises the REPC_A, REEC_C and REGC_A control models. It is connected to an infinite bus through an impedant line ($X_{\text{line}} = 2.0661 \cdot 10^{-6}$ pu, base $Sn_{\text{ref}} = 100$ MVA). The initial operating point for the battery is : $P = 0.5$ pu , $Q = 0$ pu (base $SNom = 6$ MVA) - as shown by the plot in Figure 11 - and $U = 1$ pu (base $UNom = 225$kV).

At t = 1 s, a voltage dip ($U = 0.55pu$) is applied at the infinite bus to mimic a three-phase short-circuit in the external network and is then removed at t = 1.5 s (fault clearing). At the fault insertion, the fast reactive current injection starts acting and the reactive current rapidly reaches its maximum value as seen in Figure 11 for *iqCmd*. This value is maintained until the fault clearance. On the active side, it is the normal control path that reacts to the fault by increasing the active current reference to try to maintain the active power despite the voltage dip. However, this increase is limited by the maximum current limitation and the reactive current increase (Q priority). P and Q in Figure 11 confirm this behavior and allows validating the model implementation thanks to a perfect match with the reference results (Pourbeik and Petter 2017).

The active power P plot in Figure 11 also demonstrates that the BESS is able to discharge (producing active power), which is the expected behavior as the initial state of charge $SOC0 = 0.5$ is between the accepted range $[SOCMin = 0.2$, $SOCMax = 0.8]$. The discharge time is much longer than the simulation time considered here.

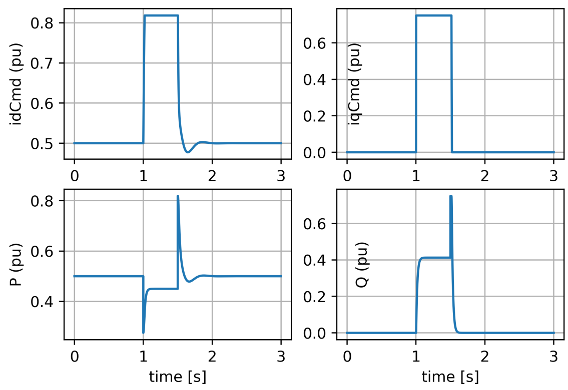


Figure 11. Validation results for a voltage dip - WECC BESS. On the top left, the active current *idCmd* is plotted, on the top right, the reactive current *iqCmd*. On the bottom left, the active power P is plotted and on the bottom right, the reactive power Q. The values are in per unit base $SNom$, $UNom$. Reference results are found in (Pourbeik and Petter 2017).

5 Applications

5.1 Models Validation and Operational Stability Assessment

The Modelica IEC and WECC models presented in the previous sections are used in the model validation process introduced into the French Connection Network Code (CNC) in February 2024 (RTE 2025). Indeed, for each new PEIR installation connected to the grid, the CNC requires the tuning of a generic dynamic model. One of the main criteria for grid code compliance is that the dynamic responses of the tuned generic model closely match those of the proprietary model used by the producer during simulation performance tests and those of the installations during real field tests. To assess the accuracy of this tuning, RTE has defined a set of standardized tests (e.g., three-phase faults, active/reactive power setpoint changes, voltage dips or surges at the point of connection) and associated compliance criteria (Cardozo et al. 2023) and developed an open-source tool (Marin et al. 2024) named DyCoV[5]. Its purpose is to automate the comparison process between:

[5] https://github.com/dynawo/dyn-grid-compliance-verification

1. Signals generated using the tuned generic IEC or WECC model, implemented within the Dynaωo Modelica library,

2. Reference signals obtained from the proprietary model used by the producer, typically simulated in a commercial tool, and from real field tests.

These comparisons are performed over the full set of standardized tests. The overall function of DyCoV is illustrated in Figure 12. The input format are Dynaωo parameters (*par*) and dynamic data (*dyd*) files to describe the tuned generic model and *csv* or comtrade files for the reference signals. In short, DyCoV applies consistent signal processing techniques to both sets of signals, enabling meaningful comparisons. The tool then computes a set of Key Performance Indicators (KPIs), such as the Maximum Error (MXE), Mean Error (ME) and Mean Absolute Error (MAE) between two signals during a disturbance. Finally, DyCoV generates a detailed *pdf* report that includes the test conditions, signal comparisons, computed KPIs, and an evaluation of compliance against RTE's predefined thresholds.

An example of such a report, focusing on an active power setpoint test, is shown in Figure 13 and Figure 14. On Figure 13, the reference signal from the proprietary model is plotted in orange and the tuned generic model, in blue. The event simulated is a step order in active power at t = 20 s. It can be seen that both models are settling around the same point in time at t = 20.93 s. However the reaction time is very different as the reference model reacts with a pure delay. This validation methodology aligns with the principles of the IEC standard (61400-27-1:2020 2020).

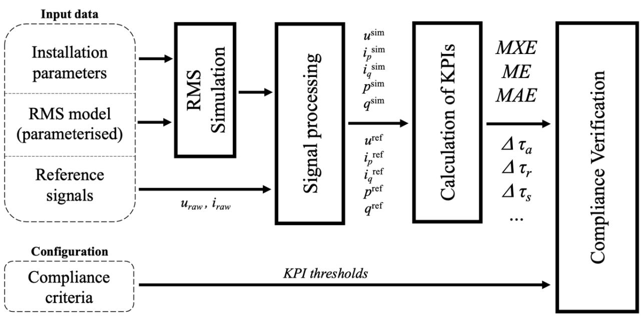


Figure 12. Functional diagram of DyCoV, RTE's dynamic grid compliance verification tool

Crucially, from a Modelica perspective, DyCoV relies entirely on the open-source implementation of IEC and WECC generic models developed within the Dynaωo library. All simulations and compliance assessments are therefore performed using transparent, reproducible, and openly available models.

The validated tuning of the generic models are then stored to complement RTE's historical dynamic data base for time-domain simulations and stability assessment in

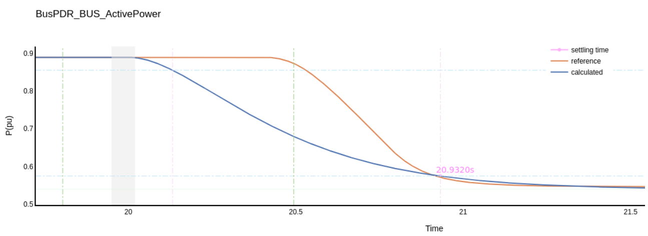


Figure 13. Extract of a DyCoV report. Generic WECC tuned model in blue and proprietary model in orange.

Compliance thresholds on the curves:

	Pre-event			Event		
	MXE	ME	MAE	MXE	ME	MAE
P	0.05	0.02	0.03	0.05	0.02	0.03

Compliance checks on the curves:

	Pre-event			Event			
	MXE	ME	MAE	MXE	ME	MAE	Compl.
P	0.000829	0.000829	0.000829	0.191	0.0841	0.102	False

Figure 14. Extract of a DyCoV report. KPIs calculated based on Figure 13.

order to be used in the near future in the operational evaluation of transient, voltage, or small-signal stability.

5.2 Prospective studies

Another interesting usage for standard IEC and WECC models are prospective studies. Indeed, TSOs can construct a set of parameters for these models that fulfills the minimal requirements from their CNC and then use this set of parameter as default value for the future units.

Such a strategy allows the TSOs to conduct stability studies in prospective situations and to anticipate future issues as well as to easily test the impact of modifications in the CNC, such as a change in the dynamic performance requirement for primary voltage regulation for example.

6 Conclusion and Perspectives

This paper presents the current status of the Dynaωo Modelica library for PEIR components. It notably introduces the library's architecture and content then details the IEC and WECC models available with a special focus on the recently added parts. Models introduced can be simulated in OpenModelica and Dynaωo engines. Amongst the different features of the library, it is important to notice:

- *its completeness*: at least one model is available for any kind of RES installation, and a special effort is done to try to follow the standard evolution.

- *its transparency*: it is an open-source library, thus including the implementation choices for each and every individual block.

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- *its industrial quality*: it is already used in the network connection procedure by RTE and so in the associated discussions with stakeholders.

The next efforts will concentrate on two different parallel axes. On the one hand, there are still evolutions on the standard and especially on the WECC side that introduce new and improved control modeling options. It is necessary to keep working on the library to support the newest versions of the models: one key point will be the implementation of newly proposed *Grid Forming* standard models. On the other hand, the industrial usages of the models will increase on RTE side with expected use in operational stability studies and the continuation of exchanges with stakeholders in the connection process. This will help improve the overall quality of the library and make it even more robust.

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Glossary

BESS Battery Energy Storage Systems. 1, 2, 5–7, 9

CNC Connection Network Code. 9, 10

DFIG Doubly-Fed Induction Generators. 4

FRT Fault Ride Through. 3, 6

HVDC High-Voltage Direct Current. 1

IBR Inverter-Based Ressource. 7

IEC International Electrotechnical Commission. 1–3, 6, 9, 10

KPIs Key Performance Indicators. 10

MAE Mean Absolute Error. 10

ME Mean Error. 10

MXE Maximum Error. 10

OEM Original Equipment Manufacturer. 1, 2

OVRT Over-Voltage Ride Through. 4

PCC Point of Common Coupling. 7

PCS Power Collection System. 3

PEIR Power Electronics Interfaced Resources. 1, 2, 9, 10

PLL Phase-Locked Loop. 3, 7

PoC Point of Connection. 3

PPC Power Park Control. 3, 4

PV Photovoltaics. 1, 2, 5–7

RES Renewable Energy Sources. 1, 2, 6, 10

RMS Root-Mean-Square. 1

SMIB Single Machine Infinite Bus. 5, 9

SOC State Of Charge. 6, 8

TSO Transmission System Operator. 1–3, 10

UVRT Under-Voltage Ride-Through. 4

VDL Voltage Dependent Limitations. 8

VSC Voltage Source Converter. 8

WECC Western Electricity Coordinating Council. 1, 2, 5–7, 9–11

WPP Wind Power Plant. 1–4

WT Wind Turbine. 1, 3–5

WTG Wind Turbine Generator. 5–8

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