Model Portability for EMT Studies of IBR

As inverter-based resources (IBR) appear in greater numbers on the bulk electric system (BES), NERC has encouraged utilities to perform electromagnetic transient (EMT) studies of IBR [1]. This creates a new burden on the engineers to create and maintain robust EMT models of many IBR plants, along with extensive BES network models for EMT. Network models for power flow (PF) and positive sequence phasor domain transient (PSPDT)[1] applications are maintained in tool-specific file formats that have become de facto standards. However, PF and PSPDT models don't have enough detail for EMT studies, so their de facto standard file formats don't suffice for EMT. As with all power system studies, the EMT model provides the foundation for all processes and results, and building the model can be the most time-consuming phase of an EMT study. This white paper summarizes approaches to reduce the effort and increase the quality of EMT model-building.

Currently, engineers must assemble, verify, and fill gaps in EMT model components manually, which is both time intensive and error prone. This process is semi-automated, based on PSSE files [2], with specific gaps in zero-sequence data, geographic information, transformer and bus mismatches, boundary identification and equivalencing, validating solutions, dynamic load modeling, and synchronizing updates [3]-[4]. Instead of storing links to a PSCAD model, we store links to a standardized model. This approach has shown success with Common Information Model (CIM)-based EMT model building in France [5] and is more suitable for diverse stakeholders at a continental level compared to proprietary solutions used in countries like Japan [6].

Figure 1 shows how the *CIM Network and Dynamics* schema [7] can support a framework for building and maintaining EMT models for IBR studies. The *Planning Tool Export* comes from PF, PSPDT, and/or short-circuit (SCKT) native file formats. The *Asset and Settings Data* may define control and protection settings, line construction, transformer test reports, etc., for more EMT details. At present, *User Edits* are necessary to complete the EMT model, but with appropriate extensions, CIM could lessen the need for such manual interventions.

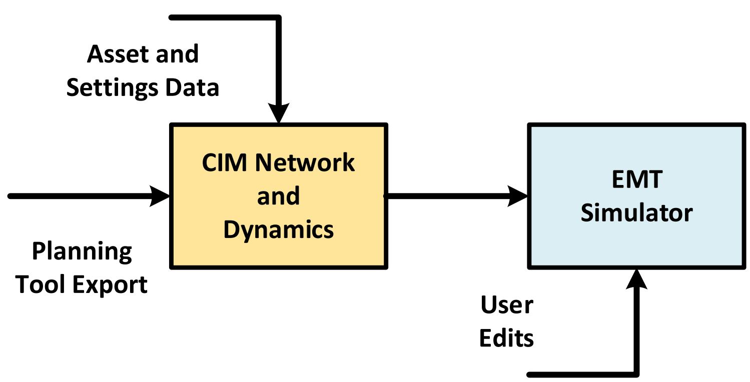

Figure 1: Collecting power system data into a model for electromagnetic transients [8]

[1] A more precise term for "stability" analysis, under consideration by the NERC EMT Task Force and the IEEE P2800.2 Working Group.

Simulation results from a preliminary CIM-based framework have been obtained using the Alternative Transients Program (ATP) with two medium-scale BES networks [9]:

- **IEEE118** – representative of the Midwestern United States circa 1962, with 56 machines aggregating steam and hydro generators, 14 solar generators, and 5 wind generators. Includes 193 buses considering generator step-up (GSU) transformers [10].
- **WECC240** – representative of the Western Electricity Coordinating Council (WECC) system, with 49 machines aggregating steam and hydro generators, 25 solar generators, and 10 wind generators. Includes two series capacitors, two aggregations of distributed energy resources (DER), and 243 buses [11].

Data and script files for these examples are available to licensed ATP users [12].

The rest of this white paper presents some heuristics to get started with a CIM-based EMT modeling framework, based on PF and/or PSPDT data, i.e., no zero-sequence or asset-based information. Minimum extensions for transformer saturation and IBR plant models are then presented.

Balance-of-Network Model Components

EMT supports frequency-dependent and unbalanced line models, which require data on the conductors, bundling, tower cross section, and midspan sags for overhead lines, or geometric and materials information for underground lines. However, frequency-dependent models are not needed for IBR studies, as the frequency range of interest is rather low among other EMT applications. Unbalanced line models are not needed for IBR studies because the dynamics are primarily positive sequence; it's necessary to represent single-line-to-ground faults (SLGF) accurately, but this can be done without using unbalanced line models. For EMT studies of IBR, it's sufficient to use balanced (or transposed) line models with 60-Hz resistance, inductance, and capacitance values.

The CIM *ACLineSegment* class has positive sequence parameters *r*, *x*, and *bch* in SI units, zero-sequence parameters *r0*, *x0*, and *bch0* in SI units, and a parent class *Conductor.length* attribute in meters. Per-unit impedances from PF or PSPDT models must be converted to SI units for CIM. Both line charging parameters, *bch* and *bch0*, must be specified as non-zero. The zero-sequence data may be available from SCKT network models. If not, it can be estimates as follows for transmission lines:

$$L = x/(length * \omega) \tag{1}$$

Where ω is 377 for 60-Hz systems. If *bch* > 0, estimate the capacitance and surge impedance as follows:

$$C = bch/(length * \omega) \tag{2}$$

$$Z = \sqrt{L/C} \tag{3}$$

Otherwise, assuming a typical overhead line surge impedance, then estimating *bch* as follows:

$$Z = 400 \tag{4}$$

$$C = L/Z^2 \tag{5}$$

$$bch = C * length * \omega \tag{6}$$

Check the positive sequence (line mode) propagation velocity, which must not exceed the speed of light:

$$v = 1/\sqrt{LC} \leq 3e8 \tag{7}$$

If *v* is 50% or less of 3e8, then the line is probably underground cable, not overhead.

If *Z<100* in (3), assume the line is underground cable and estimate zero-sequence parameters by:

$$r0 = r \tag{8}$$

$$x0 = x \tag{9}$$

$$b0ch = bch \tag{10}$$

Otherwise, assume overhead line and estimate zero-sequence parameters as follows, using either the PF/PSPDT value for *bch*, or the value estimated from (6):

$$r0 = 2r \tag{11}$$

$$x0 = 2x \tag{12}$$

$$b0ch = 0.6 * bch \tag{13}$$

If the line is known to have bundled sub-conductors, then *Z=300* may be used in (4). If the branch consists of two or more lines in parallel, the surge impedance, *Z*, should be reduced accordingly. If the original PF/PSPDT model included line charging data for the branch, then (7) should still help distinguish between overhead and underground lines. If the original data did not include line charging data, then it's probably an overhead line. Cable line charging values are relatively high and more important, hence more likely to have been maintained in PF/PSPDT models.

Most of the EMT line models for IBR studies should include traveling wave behaviors; the tool may refer to these as Bergeron, Clarke, Karrenbauer or distributed transposed models. However, if the line is so short that its travel time is less than the simulation time step, a single pi section may be used to represent it. The CIM-to-EMT exporter could make this choice based on a user-supplied Δt.

Figure 2 shows important considerations for transformer modeling. Legacy PF models can still represent three-winding transformers with separate two-winding transformers in a star equivalent (Figure 2 left) because legacy PF tools only represented two-winding transformers. One of the legacy two-winding transformers is likely to have negative reactance, which is okay for PF simulations but not for EMT. Furthermore, the star point is retained in such legacy PF models with a base voltage of, typically, 1 kV or 0.1 kV. In preparing such models for EMT, the two-winding transformers must be reaggregated into correct three-winding models.

To represent the transformer zero-sequence behavior for EMT, it's essential to correctly specify the delta or wye connection type for each winding. It's also important to correctly specify any neutral impedance, or ungrounded connection, for wye windings. This data is typically not included with PF or PSPDT models.

Transformer saturation can also be important to model in EMT studies of IBR, because under dynamics conditions, saturation may increase the reactive power[2] demands on generators. For IBR studies, this can be modeled with sufficient accuracy by a two-slope characteristic (Figure 2 right). It's possible to use more points and slopes, but the data is not readily available.

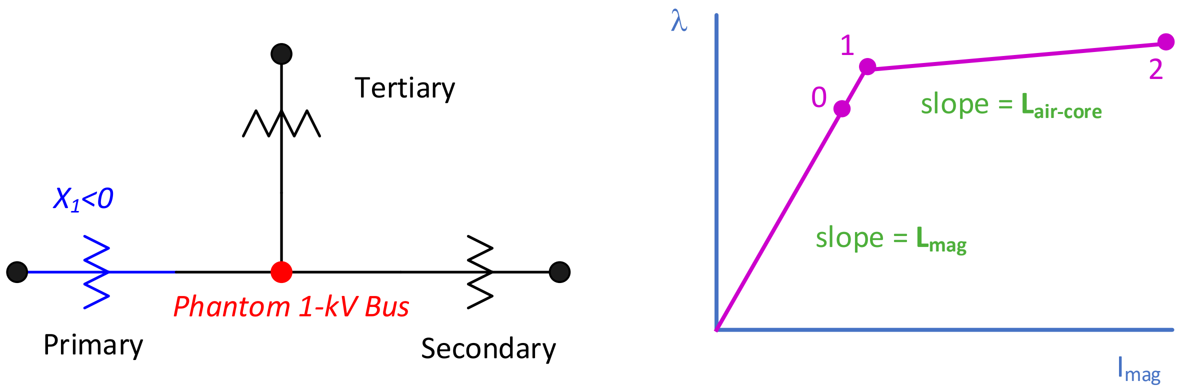

Figure 2: Three-winding transformer star equivalent (left) and saturation characteristic (right) for EMT [9]

EMT saturation models are generally defined in characteristics of instantaneous flux linkage, λ, vs. instantaneous magnetizing current, I_{mag}. The CIM *TransformerCoreAdmittance* class has a *b* attribute for magnetizing susceptance, and a *g* attribute for core losses, both in SI units. If these are not available from PS/PSPDT data, then typical non-zero values should be assumed, e.g., 1% magnetizing current and 0.25% core loss current, then convert those to SI values. Use the secondary, or lowest-voltage winding, excluding the tertiary, for connecting the saturation branch. The short-circuit inductance, *x*, between primary and secondary windings is also needed, with *x* in ohms referred to the secondary winding. The secondary winding's rated voltage, *u*, should be expressed in peak volts, not rms volts. The steady-state magnetizing current, I_0, should be expressed in peak amps, not rms amps, referred to the secondary winding. From this information, we can estimate the slopes and point **0** in Figure 2 (right) as follows:

$$L_{mag} = b/\omega \tag{14}$$

$$L_{air-core} = 2x/\omega \tag{15}$$

$$\lambda_0 = u/\omega \tag{16}$$

Then we choose a typical "knee voltage", V_{knee_pu}, for the transformers, typically 1.05 to 1.15 per-unit. This defines a straight-line extrapolation from point 0 to point 1 in Figure 2 (right). Then determine points **1** and **2** as follows:

$$I_1 = V_{knee\_pu} * I_0 \tag{17}$$

$$\lambda_1 = V_{knee\_pu} * \lambda_0 \tag{18}$$

$$\Delta I = 1000 \tag{19}$$

[2] It's not strictly correct to view transformer saturation current in terms of reactive power, but the practice is widespread.

$$I_2 = I_1 + \Delta I \quad (20)$$

$$\lambda_2 = \lambda_1 + L_{air-core}\Delta I \quad (21)$$

EMT saturation models typically take points **1** and **2** for input, with the origin implied. The steady-state solution may use point **0**, which will be consistent with points 1 and 2 after time-stepping begins.

Plant Model Components

Figure 3 shows the rotating machine connected to a single-machine infinite bus (SMIB) test system at extra-high voltage (EHV). The plant is connected at a point of common coupling (PCC). The generator model in *dq* axis form, a single inertia, *J*, and typical control systems are highlighted in orange. PSPDT models, and the CIM for Dynamics schema, include these items. The plant also minimally includes a generator step-up (GSU) transformer, highlighted in green. The GSU data is generally available in PSPDT models, but the delta winding connection should be specified for EMT. The CIM already supports the items in Figure 3[3].

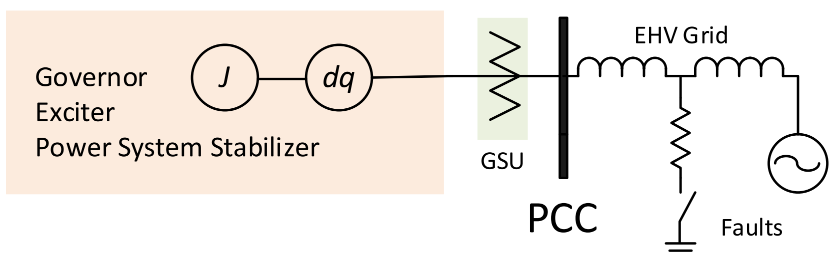

Figure 3: Rotating machine plant model components connected to a SMIB test system [13]

Figure 4 shows an IBR plant model connected to the SMIB at a PCC. The balance-of-plant model, highlighted in green, includes more components than in Figure 3, but they are all supported in CIM. The IBR-specific components, highlighted in orange, are not presently supported in CIM. Extensions to enable this support will be discussed next.

The *Exact or Generic Controls* in Figure 4 may comprise a real-code dynamic link library (DLL) as defined in [14], with an example in [15]. It may also comprise a Western Electricity Coordinating Council (WECC) generic model, which is already supported in CIM. Other options include custom user-models, which would be specific to the EMT tool and not addressed in this white paper. Figure 5 summarizes the DLL interface, which may be incorporated into the CIM by reference, especially if the DLL interface is formalized as an IEEE standard. The orange-highlighted converter bridge and passive filter components in Figure 4 might be specified in a tractable number of attributes for a new CIM class, as discussed later. EMT tools generally have their own inverter bridge modeling

[3] One of the early EMT applications was to perform sub-synchronous resonance (SSR) studies of generators in series-compensated BES. For SSR studies, the single inertia, *J*, had to be replaced with a multi-mass rotational system. That data was not available in PSPDT models, which is still usually the case.

options, including average sources for either exact or generic controls, or pulse-width-modulated (PWM) switching topologies for exact controls.

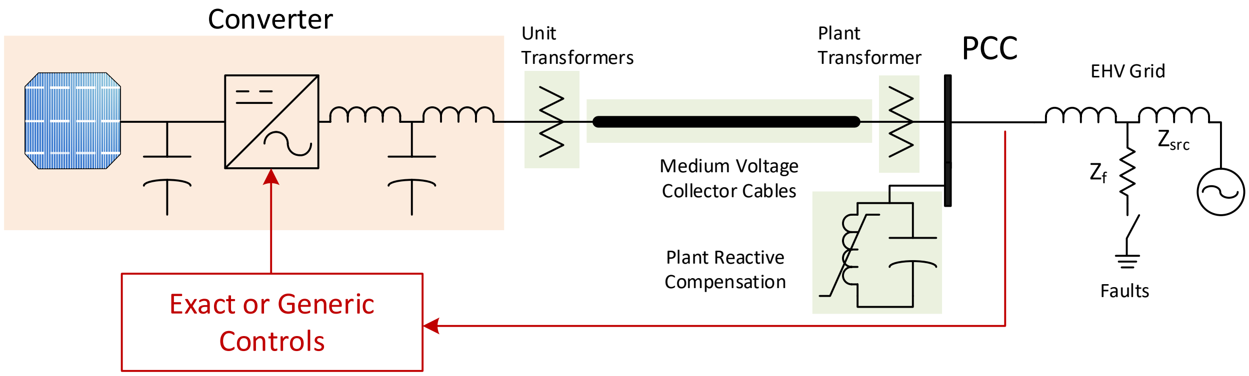

Figure 4: IBR plant model components connected to a SMIB test system

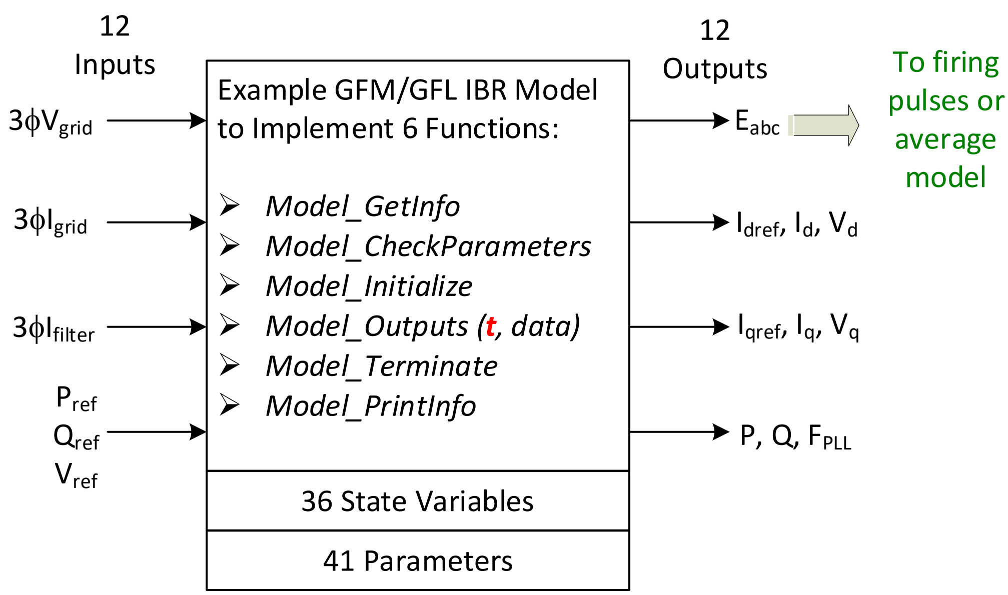

Figure 5: DLL specification for exact IBR control code modeling [13]

CIM for Dynamics and EMT

Figure 6 shows the current CIM Dynamics support for WECC models, including some of the newer distributed energy resource (DER) aggregation models, in the form of a unified modeling language (UML) schema. In CIM, the inverter is called a *PowerElectronicsConnection*, which is part of the *Wires* package. It has a *Terminal* for connection to other grid components, e.g., the *Unit Transformers* from Figure 4. A similar pattern is used for connecting exciter, governor, and power system stabilizer dynamics to a *SynchronousMachine* instead of *PowerElectronicsConnection*. No further extensions are needed to support EMT studies with WECC models, as demonstrated in [9].

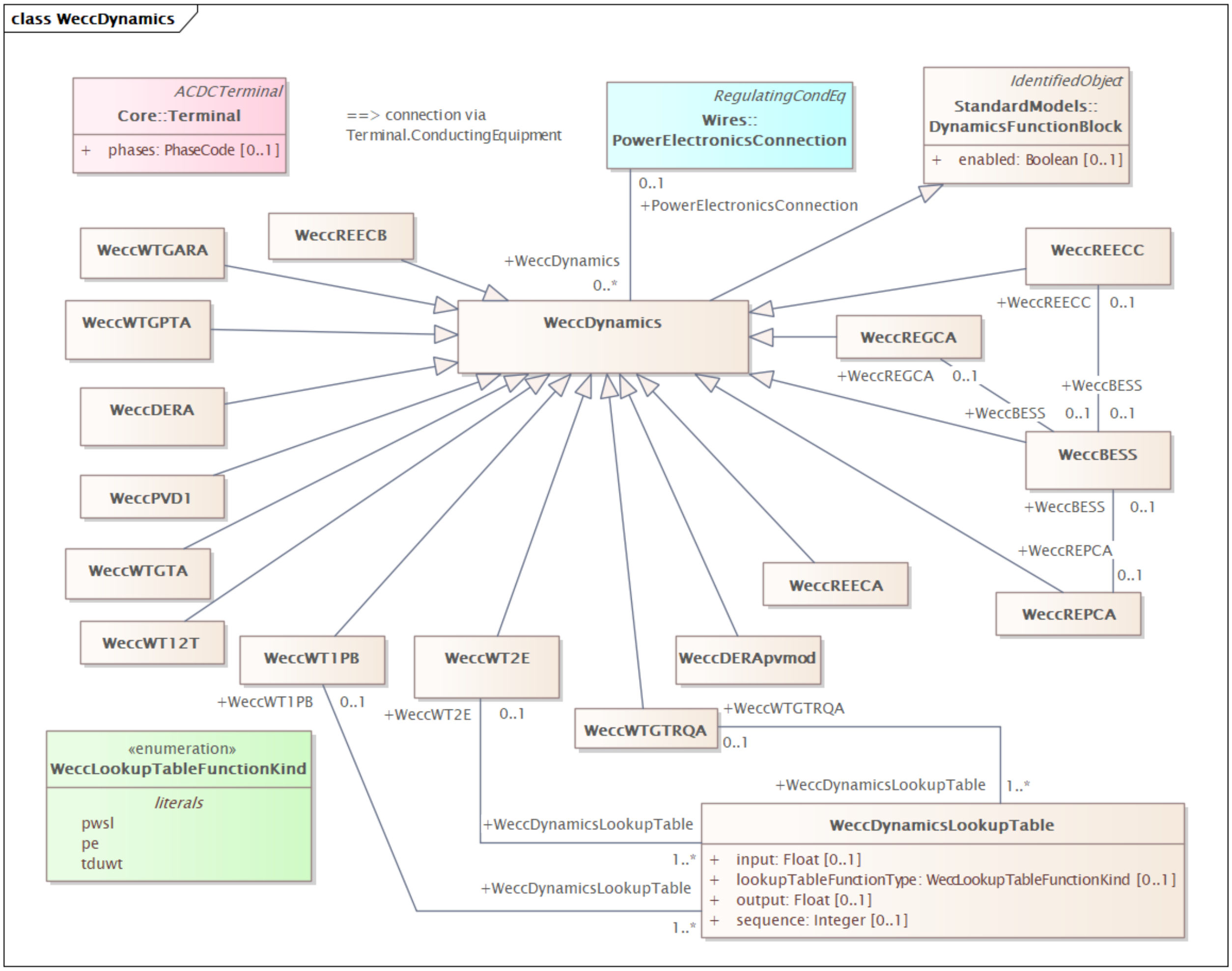

Figure 6: CIM Dynamics UML for the WECC Generic IBR Models

CIM Extensions for Transformer Saturation

Figure 7 shows UML for a *TransformerSaturationCurve* with attributes defined in Table 1. It uses a well-established pattern in CIM, by associating an optional *TransformerSaturationCurve* to the *TransformerCoreAdmittance*. There will be two instances of CurveData for each saturation characteristic, defining points **0** and **1** of Figure 2 (right) with equations (17), (18), (20), and (21).

Table 1: CIM Attributes for Transformer Saturation Curve

Name	CIM Type	Description
Curve		
xUnit	UnitSymbol	A (current)
y1Unit	UnitSymbol	Vs (flux linkage, choosing Vs over Wb)
CurveData		
xvalue	Float	Instantaneous current, Imag
y1value	Float	Instantaneous flux linkage, lambda

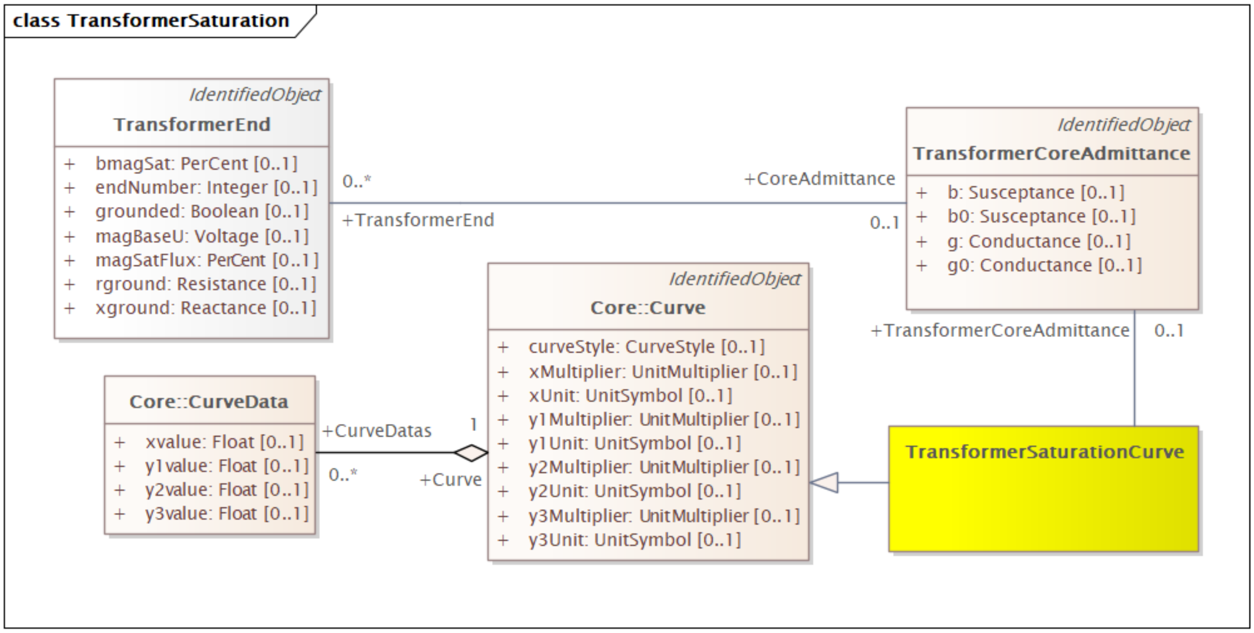

Figure 7: CIM extension UML for transformer saturation added to Wires:TransformerCoreAdmittance

CIM Extensions for Exact IBR Control Code

Figure 8 shows two new IBR class associations on a UML diagram, with new attributes as defined in

Table 2, to complete representation of the orange highlights in Figure 4 for CIM. Both are optional associations to *PowerElectronicsConnection*, and they inherit from *PowerSystemResource* and *IdentifiedObject*. The *name* and *mRID* attributes of *IdentifiedObject* support unique and persistent identifiers for the new classes.

The IEEECigreDLL attributes can specify the location and vintage/version of a DLL, which is assumed to comply with a standard interface specification for the DLL. There should be no attempt to model details of the DLL interface in CIM. Instead, the specification should be incorporated by reference. Model builders and EMT tool vendors would be responsible for using the specification to connect the DLL to the inverter bridge, and other components, at simulation time[4].

[4] CIM for Dynamics already represents *RemoteSignals* as needed for *SynchronousMachine* control. Extensions may (or may not) be required for IBR plants, but this topic is not addressed here.

Table 2 includes a starting point for attributes of *InverterBasedResourcePlant*, primarily focused on the passive filter components in Figure 4. This list would be refined in collaboration with EMT tool vendors and other interested parties. For example, *switchingFrequency=0* implies use of an average source model, but the CIM working groups generally prefer a more explicit Boolean attribute for such choices. It's expected that a tool-neutral set of attributes can be developed for InverterBasedResourcePlant, based on experience with other use cases that were successfully represented in CIM.

Table 2: CIM Attributes for two new IBR Plant Classes

Name	CIM Type	Description
IEEECigreDLL		
vendorName	String	Name of the model provider
firmwareVersion	String	Version of the hardware provider's firmware
firmwareInstalled	DateTime	Date and time of the firmware installation at the IBR plant
uri	String	Location of the DLL, either a universal resource locator or network-accessible filename.
InverterBasedReourcePlant		
dcLinkVoltage	Voltage	Voltage of the DC bus, if applicable
dcLinkCapacitance	Capacitance	Capacitance (plus-to-minus) of the DC bus, if applicable
acFilterRgrid	Resistance	Grid-side resistance of the AC tee filter
acFilterLgrid	Inductance	Grid-side inductance of the AC tee filter
acFilterCapacitance	Capacitance	Shunt capacitance of the AC tee filter
acFilterRbridge	Resistance	Inverter bridge-side resistance of the AC tee filter
acFilterLbridge	Inductance	Inverter bridge-side inductance of the AC tee filter
switchingFrequency	Frequency	Pulse-width modulation (PWM) switching frequency

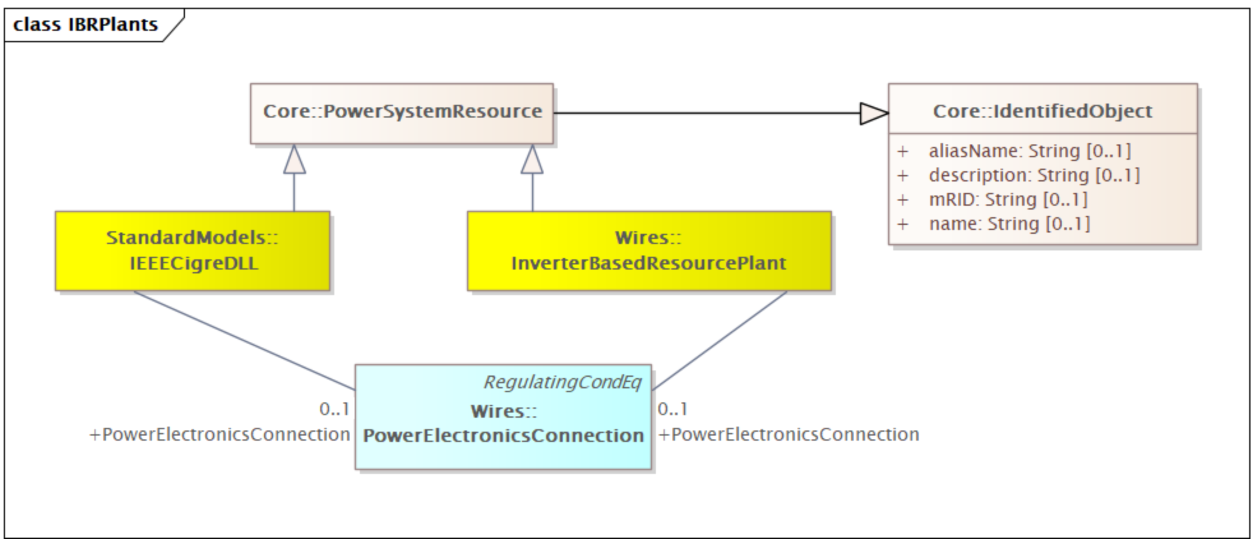

Figure 8: CIM extension UML for plant parameters and DLLs added to Wires:PowerElectronicsConnection

Future Work

A CIM-based framework with automation can provide more benefits with future work:

- A CIM-based framework can support automated IBR model validation using scripts and single-machine infinite bus (SMIB) test systems [13]. The support for different test systems and EMT tools could be broadened.
- Interoperability tests for PSPDT, SCKT, and EMT models should be sponsored by the CIM Users Group. These interop tests have been essential in fixing gaps and errors in the CIM UML, and in promoting or enabling acceptance by utilities and tool vendors.

- Standardization of asset-based information for transformers and lines. Distribution utilities have already done much of this work through asset management and geographic information systems, which reduces the time to build and validate network models for planning and distributed energy resource interconnection studies.
- Adoption of node-breaker modeling for EMT and protection system design. This enables more accurate simulation of fault events and protection system response. The bus-branch model, currently used for many PF, PSPDT, and SCKT models, only represents the system state before and after contingencies.
- CIM fragments for IBR balance-of-plant models, shown in Figure 4, could help regularize the treatment of network subsystems. IEC Working Group 13 has worked sporadically on this concept, but not completed it. IBR plant models provide another use case for CIM fragments.
- Formalizing the DLL interface as an IEEE Standard will foster its adoption in CIM by reference, along with other benefits of standardization.

References

[1] NERC, "Reliability Guideline: Electromagnetic Transient Modeling for BPS Connected Inverter-Based Resources—Recommended Model Requirements and Verification Practices," North American Electric Reliability Corporation, Atlanta, Mar. 2023. [Online]. Available: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline-EMT_Modeling_and_Simulations.pdf

[2] P. Zhao *et al.*, "Rapid Modeling of Large-Scale Power System Based on PSCAD," in *2019 IEEE Asia Power and Energy Engineering Conference (APEEC)*, Mar. 2019, pp. 167–171. doi: 10.1109/APEEC.2019.8720692.

[3] M. Abdelmalak *et al.*, "PSS/E to RSCAD Model Conversion for Large Power Grids: Challenges and Solutions," in *2021 IEEE Power & Energy Society General Meeting (PESGM)*, Jul. 2021, pp. 01–05. doi: 10.1109/PESGM46819.2021.9637930.

[4] J. Thapa *et al.*, "Plug-and-Play Regional Models for Real-Time Electromagnetic Transient Simulations of Large-Scale Power Grids: A Case Study of New York State Power Grid," *IEEE Access*, vol. 11, pp. 87600–87614, 2023, doi: 10.1109/ACCESS.2023.3305394.

[5] F. Martin, C. Y., "Automation of model exchange between planning and EMT tools," presented at the International Conference on Power System Transients (IPST), Seoul, 2017. Accessed: Dec. 20, 2023. [Online]. Available: https://www.ipstconf.org/papers/Proc_IPST2017/17IPST099.pdf

[6] T. Noda, T. Tadokoro, and T. Dozaki, "Automatic Generation of Power System Simulation Data Cases From Utility Databases: Introducing a new technology," *IEEE Electrification Mag.*, vol. 11, no. 4, pp. 79–85, Dec. 2023, doi: 10.1109/MELE.2023.3320521.

[7] ENTSO-E, "Common Grid Model Exchange Specification (Dynamics)." Accessed: Apr. 11, 2024. [Online]. Available: https://cgmes.github.io/dynamics/#dynamics

[8] McDermott, Tom, "CIM for Bulk Power System EMT." Accessed: Sep. 25, 2024. [Online]. Available: https://openei.org/wiki/File:CIM_EMT_Article.pdf

[9] M. Ramesh and McDermott, Thomas E., "Transmission System Transient Models from the CIM," presented at the IEEE PES General Meeting, Seattle, Washington, Jul. 24, 2024. Accessed: Sep. 25, 2024. [Online]. Available: https://emthub.readthedocs.io/en/latest/_static/24PESGM2411.pdf

[10] I. Peña, C. B. Martinez-Anido, and B.-M. Hodge, “An Extended IEEE 118-Bus Test System With High Renewable Penetration,” *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 281–289, Jan. 2018, doi: 10.1109/TPWRS.2017.2695963.
[11] H. Yuan, R. S. Biswas, J. Tan, and Y. Zhang, “Developing a Reduced 240-Bus WECC Dynamic Model for Frequency Response Study of High Renewable Integration,” Piscataway, NJ: Institute of Electrical and Electronics Engineers (IEEE), NREL/CP-5D00-79181, Jan. 2021. doi: 10.1109/TD39804.2020.9299666.
[12] T. McDermott, *temcdrm/emthub*. (Sep. 25, 2024). Python. Accessed: Sep. 25, 2024. [Online]. Available: https://github.com/temcdrm/emthub
[13] PNNL, “i2x/emt-bootcamp at master · pnnl/i2x,” GitHub. Accessed: Dec. 20, 2023. [Online]. Available: https://github.com/pnnl/i2x/tree/master/emt-bootcamp
[14] “Joint IEEE TASS Task Force and Cigre B4.82 Working Group: Use of Real-Code in EMT Models for Power System Analysis".” Accessed: Dec. 20, 2023. [Online]. Available: https://www.electranix.com/ieee-pes-tass-realcodewg/
[15] EPRI, “Code Based Generic Inverter Based Resource Model.” Accessed: Sep. 25, 2024. [Online]. Available: https://www.epri.com/research/products/3002028322

Scope from EMT TF WI3 Meeting Minutes

White paper "Resources for EMT modeling of bulk power systems" (Tom M. responsible person: due by end of Q3 2024)

Abstract:

With EMT studies, there is not always a one size fits all representation for modeling general power system equipment. Many of the commercially available tools which are used for automated creation of EMT models have a default method of modeling equipment and will generate a usable model. For example, these tools will typically import steady-state and dynamics data from a phasor domain tool and will generate a EMT model that can run time domain simulations at a given simulation time-step. However, because of limitations of data available in the source databases, such models will not include many system modeling details that are typically important for EMT level simulation, such as:

- *Correct zero sequence impedance of transmission lines or cables*
- *Frequency dependent impedance of transmission lines or cables*
- *Mutual coupling between transmission lines*
- *Transformer winding configuration and grounding information*
- *Transformer saturation characteristics*
- *Custom or user-defined representation for load or generation*

It is necessary for the study engineer to ensure that power system equipment is modeled appropriately for the phenomena of interest under evaluation. Providing a complete and detailed discussion on power system modeling for EMT is outside the scope of this document.

Topics to cover include:

a. Real code models for IBRs
b. Resources for obtaining "missing" EMT model data e.g.,
    i. Transformer winding configuration and grounding information
    ii. Transformer saturation characteristics
        - What are rules of thumb/guidance for determining saturation characteristics? (e.g., selection of knee point, selection of excitation current, selection of air-core reactance)
c. When and why is the missing data important?
    i. E.g., do you always need frequency dependent transmission lines?