An Overview of Co-Simulation Platforms for Transmission Planning

1 Background and Objective

The increased complexity of the power systems of today are challenging traditional modeling and simulation practices. A combination of economics, power electronics, control systems, communications, demand side participation and big data are now contributing actors in the operation of the power systems of today. These actors have been handled individually and separately in the past but are now communicating with each other ever more and these interactions call for a means to gather them together for analysis in order to derive a complete picture of the system. Whilst these changes raise new challenges they also offer new opportunities for enhancing the performance of power systems, particularly when coupled with the increasing computational resources available to planning engineers.

From the transmission planning and operation perspective the significant increase in installed capacity of distributed energy resources (DERs), observed in recent years around the world, is a particular challenge. Also, as generation is now moving into the distribution system, closer to the load, it is more important to capture the load generation dynamics in more detail than ever before, for example, embedded generation masking or shifting demand peaks or fault induced delayed voltage recovery. Adequate modeling of DERs in transmission-planning studies is needed to address challenges about ensuring adequate bulk system reliability in terms of voltage and frequency performance, ensuring efficacy and selectivity of transmission protection schemes under high levels of DERs, and to explore the contribution of new emerging technologies.

Moreover, emerging smart grid applications call for widespread communication networks and data handling capabilities that have not been considered in the past by leading planning study practices. Other drivers include the increased presence of hierarchical and distributed control using synchronized, distributed measurements (for example, phasor measurement units (PMUs)); the interaction between DER behavior and market economics; emerging markets that make use of DERs that offer ancillary services (for example, demand side response); and integration with other forms of energy systems (for example, gas and transport).

Today, transmission planning studies use positive-sequence models to simulate contingencies like three-phase transmission faults which represent worst-case events from a synchronous generator rotor angle stability perspective. Distribution loads are aggregated at the transmission or sub-transmission level and assumed to be balanced. Fault response of DER is assumed to be balanced and control loops with time constants shorter than a cycle are often ignored. Such balanced representation can fail to capture phase imbalances, or low voltages in individual phases, that may cause stalling of single phase induction motors and/or control responses from variable frequency drives or other converter interfaced components.

With increasing amounts of DERs, however, the assumption of balanced conditions and the described modeling approaches *may fall short* in adequately simulating the response of distribution grids with three-phase and single-phase inverter-based DER connected in various locations. Besides the continuous improvement of existing DER models, like the aggregate DER

(DER_A) model [1], co-simulation methods that simulate parts of the transmission system *and* the distribution grid, cycle *and* sub-cycle time frames, and/or balanced *and* unbalanced conditions is an evolving research area. While positive sequence platforms will continue to be used for performing interconnection-wide studies for a foreseeable future, transmission planners are interested in understanding state-of-the-art co-simulation platforms and potential use cases where they can provide deeper insights, as well as challenges in using these platforms.

In the context of the bulk transmission system, co-simulation can be used for studying the interactions between:

- Power system and communication system
- Power system and markets
- Power system and other infrastructure such as gas and water
- Transmission and distribution systems within a power system
- Transmission system and inverter-based generation connected to the transmission system

The focus of this white paper is studying the interactions between transmission and distribution systems within a power system and the interaction between transmission system and inverter-based generation connected to the transmission system. The aim of this white paper is to summarize the capabilities, development status, and application cases of reported co-simulation platforms. Hardware in the loop simulation is not considered here. It could be classed as a form of co-simulation, under certain circumstances where it entails synchronization of different software, but it contains a distinct and complex group of methods that emphasize real time simulation that for the purposes of this paper stand separate from the platforms investigated.

The white paper is organized as follows:

- Section 2 defines the different forms of co-simulation and disambiguates it from combined simulation.
- Section 3 describes the opportunities offered by the emerging co-simulation platforms.
- Section 4 provides a tabulation of the identified co-simulation platforms and their components, applications, and licenses.
- Section 5 summarizes these findings and draws concluding remarks on the state of co-simulation.
- Appendices provide more detailed information on each of the identified methods.

2 What is Co-Simulation?

The term "co-simulation" is somewhat loosely used and may be interpreted in different ways. A recent informational brochure from the North American Electric Reliability Corporation (NERC) [2] differentiates between "combined simulation" (referred to as combined modeling in [2]) and "co-simulation". Both combined simulation and co-simulation can be used to study the transmission and distribution system together. Co-simulation simulates multiple subsystems in parallel, where each of the systems are modeled/simulated using different methods and techniques. For example, an electrical power system could be simulated in parallel to a market system interfaced through communication links to study the interactions between these whilst capturing required level of detail for each. Combined simulation entails both the transmission and distribution system being modeled on the same platform and solved with the same solver. As such, unlike co-sim, no synchronization of solvers or information exchange is required as the combined system is solved as a single system [3].

These differences can be captured as in Figure 1.

A combined model of transmission and distribution was created using MATLAB/Simulink, with the Kundur two area system for the T and IEEE 34 node feeder for the D [3]. However, whilst this work was successful, it is not scalable, and the combined simulation of a bulk transmission system and distribution system is not presently feasible [3]. A focus upon co-simulation is recommended [2] [3]. Furthermore, it should be noted that co-simulation is more readily extendable to the simulation of other systems, for example, markets or communications—this is seen in the platforms described here. Hence, the focus here is upon co-simulation.

Co-simulation can entail modeling of multiple systems in a single platform/software or it can entail interfacing different software/platforms together where each software/platform is used to model a specific system. These different approaches are grouped into three broad types here as shown in Figure 2 and described as:

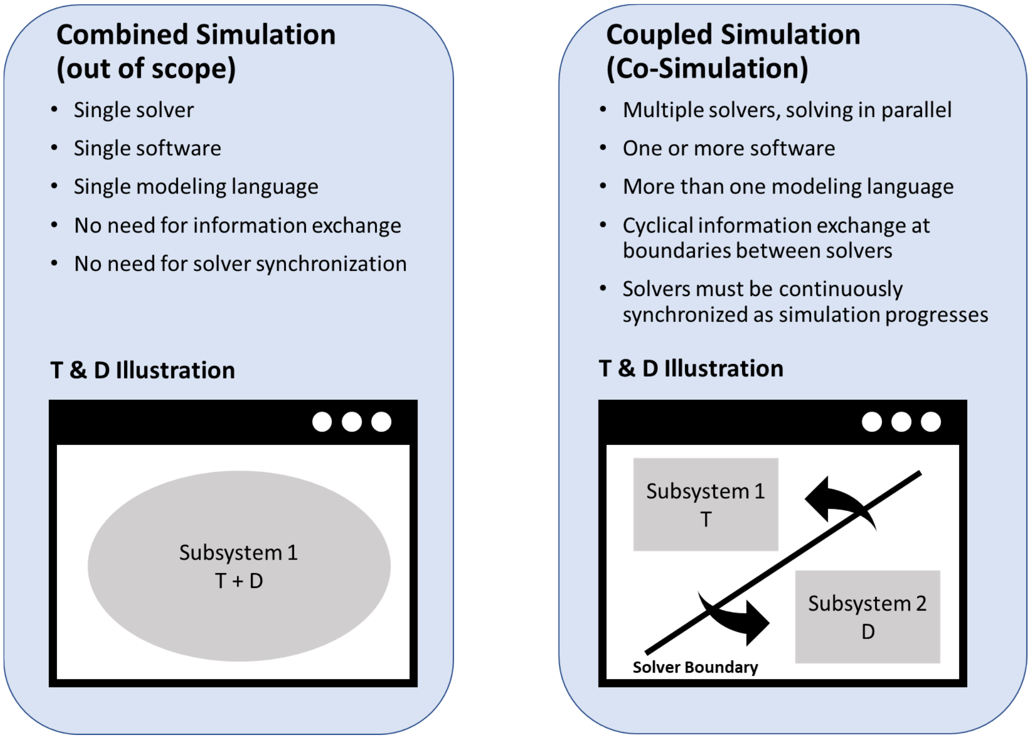

Figure 1. Comparison of Combined Simulation and Co-Simulation, information from [3] [2].

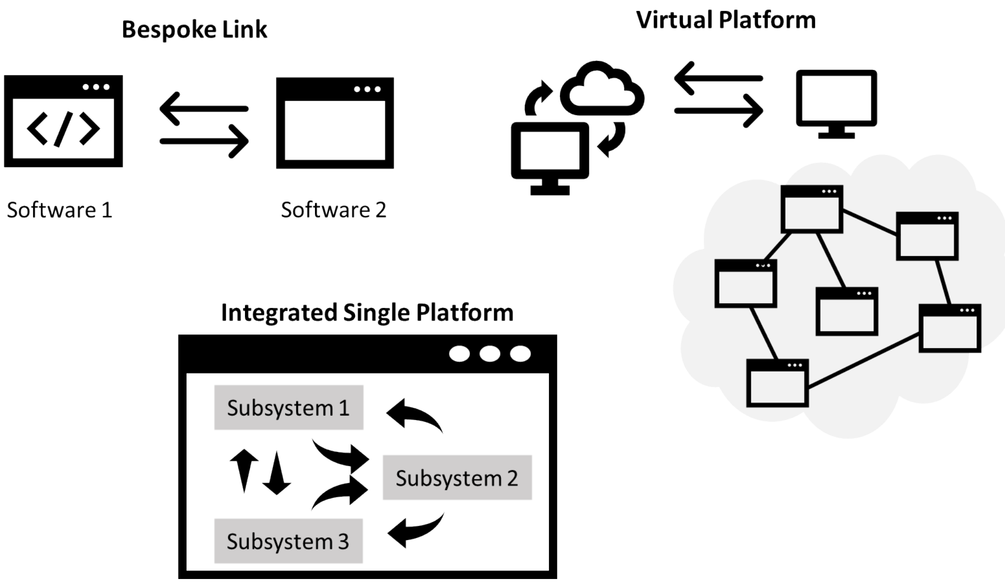

Figure 2. Summary of co-simulation approaches

1. Virtual Platform
   A platform that can connect multiple simulators, potentially cloud based or on a single computer (for example, HELICS™).
2. Integrated Single Platform
   A single software that is an integrated platform that supports multiple simulators with different modeling environments (for example, DIgSILENT PowerFactory).
3. Bespoke Link
   A dedicated link, communication socket or interface between two specific software applications (for example, TDCOSIM with OpenDSS and PSS/E).

In all these cases, creation of an interface between each of the multiple systems can be challenging due to the differences in the modeling details and the diversity in the input/output data that needs to be exchanged between the different platforms through the interfaces. In addition, scalability with optimum computing speed is hard to achieve for these co-simulation platforms.

The nature of the power systems is changing in the components it hosts from the conventional sense. With increasing penetration of distributed energy resources (DERs) with dedicated local controls, increased number of sensors and wide area measurements, system services derived through market forces and so on, the burden is increasing in terms of modeling and analysis and may no longer be feasible to study the aspects individually. In the context of a smart grid, communication, transmission and distribution system, system integrity protection and control, market modeling all need to be considered.

A large number of very mature software exist for each of these elements where the traditional studies operate. Co-simulation is a means to make use of the existing software and find a way to capture a complete picture of system behavior by providing ways for them to speak to each other and exchange valuable information. As already discussed this could be achieved in one of three different ways and is an active research topic to ascertain the necessity, need, and use cases. Increased computational capabilities, capacity, and storage has made larger and more demanding simulations and parallel processing possible, thus making co-simulation viable. In the past, although recognized that aggregate models are approximate (for example, load modeling) the technological capabilities were insufficient to consider capturing all the modeling detail under a single umbrella (either as a single software or combination of multiple software). This along with the fact that transmission systems, distribution systems and generation systems are becoming more fast, flexible and variable makes a compelling case to go ahead with co-simulation studies for assessing reliability and resiliency of the system.

Co-simulation allows different domains to interact through the course of a simulation, typically by exchanging values dynamically that define boundary conditions for other simulators. This may make use of simulators across a variety of computation platforms and languages.

Research (both academic and industrial) interest in this topic has resulted in the development of various co-simulation platforms. This white paper looks at these reported co-simulation platforms (research grade and commercial) and discusses their proposed application cases. This paper should act as a quick reference to the readers and includes information collected from various open sources as a mere 'statement of facts' without an assessment from EPRI on the performance comparison of one over the other.

3 Opportunities for Co-simulation in Transmission Planning

Transmission planners have begun to look at the aggregate impact of loads and DERs at the bulk transmission level using commercial tools that are not part of any co-simulation framework. However, with increasing DER penetration, the underlying dynamics at the distribution level may need to be captured in more detail as compared to the level of detail afforded by an aggregated representation. This includes the DER and dynamic distribution system level load interactions which may not be studied in depth using aggregate representations. Co-simulation provides an opportunity to capture in detail these distribution level dynamics and their possible impact on the transmission system. Alternatively, in the absence of measurement data, co-simulation platforms can also provide a base to test the behavior of aggregate models to verify the level to which the increased complexity and more nuanced distribution system dynamics are captured.

Some of the key questions that have been discussed in the literature where co-simulation may find further applications include:

1. Are aggregate models still sufficient to capture new dynamics or do transmission system planners need to include detailed distribution system models? If yes, what are the indicators that a detailed model is required?
2. Given the increasing role that the demand side and distribution-embedded generation are expected to play in delivering system services, do transmission planners need to capture any limitations that the distribution network may place on the provision of these services? Or would this completely fall under the purview of distribution system planning and just knowing the limitation at the substation interface would be sufficient?
3. Is a combined use of a positive sequence simulator and an electromagnetic transients program (EMTP) the path to be

taken by transmission planning engineers to perform studies for a grid with increasing penetration of fast acting inverter based resources, especially when connected to weak parts of the network?

4. To what degree do planners need to capture the complexity of scheduling new service providers, for example, battery charging cycles, availability of demand side resources, limitations on the number of uses in a given period or capacity of other systems (for example, district heating or gas networks)?
5. Can existing methods capture the impact of very high level DERs, storage and flexible demand?
6. Is there a need for the system planners to capture the increasing interdependency between the power systems and other systems, for example, gas, transport, heating and water when considering system services?
7. How existing technologies interact with new ones and whether assets at the distribution level negatively impact controls at the transmission level and if yes, what are the communication requirements for that?

4 Overview of Co-Simulation Platforms

Many co-simulation platforms have been developed or explored by the power system community and these are in various levels of maturity. These are summarized in Table 1. This table has been adapted from and has overlap with NERC [4]. This white paper can be used as a companion document to NERC's "White Paper: Beyond Positive Sequence" [4] wherein further exploration of the need and applicability of beyond positive sequence tools for transient stability studies are elaborated. For further information and references see Section 5.

Table 1. Summary of Co-Simulation Platforms and Capabilities

Name	Creator/Lead	Platform	Main Components	Status	Capabilities	Application Cases	License
GridSpice [5] [6] [7]	Stanford University	Cloud based virtual platform	**MATPOWER** – bulk power system simulation and analysis **GridLAB-D™** – distribution system simulation **Python™** – scripting	No active development in the last two years.	Steady-state simulation only; no dynamic simulation capabilities. Models transmission, distribution and markets.	Smart grid applications with modeling for volt/var control, demand side response, EVs and storage.	Open source
FNCS **Framework for Network Co-Simulation** [8] [9] [10]	Pacific Northwest National Laboratory (PNNL)	Local virtual platform	**PowerWorld** – bulk power system power flow **MATPOWER** – wholesale markets **GridLab-D™** – distribution system simulation **GridAPPS-D™** – advanced distribution management system **Energy Plus™** – whole building energy simulator **FESTIV** – Energy scheduling tool **GridDyn** – power-grid simulator **VOLTTRON** – agent based platform for managing physical devices **ns-3** – discrete event communication system simulator	Still in early stages of development.	Steady-state simulation only; no dynamic simulation capabilities. Communication network modeling. Market modeling.	T+D+ comms + market. Well suited for hierarchical and/or distributed control. Demand side response.	Open source

Name	Creator/Lead	Platform	Main Components	Status	Capabilities	Application Cases	License
HELICS™ **Hierarchical Engine for Large Scale Infrastructure Co-Simulation** [11] [12] [13]	Pacific Northwest National Laboratory (PNNL)	Local, federated virtual platform	**PowerWorld** – bulk power system power flow **MATPOWER** – wholesale markets **GridLab-D™** – distribution system simulation **GridAPPS-D™** – advanced distribution management system **Energy Plus™** – whole building energy simulator **FESTIV** – Energy scheduling tool **GridDyn** – power-grid simulator **VOLTTRON** – agent based platform for managing physical devices **ns-3** – discrete event communication system simulator **OpenDSS** **PSLF** **InterPSS** **Built in comms simulator** **Python™, C, Java™, Matlab®, Julia, FMI** – scripting	Under active development.	Developed as generic federation platform for cyber-physical systems. Tools provided to enable user to integrate new simulators into the HELICS™ themselves. With power systems as a demonstration. Draws on experience from FNCS and other co-sim developments by partners to develop new generalizable platform.	Design: Predictive State Estimation & Machine Learning Control. DSM and market interactions (T+D+market).	Open source BSD style license
IGMS [14] [15]	National Renewable Energy Laboratory (NREL)	Local, virtual platform	**FESTIVE** – wholesale markets, UC and AGC **MATPOWER** – bulk AC power flow **GridLAB-D™** – distribution system simulation	On-going development.	Steady-state simulation only; no dynamic simulation capabilities. Semi-automated data import from PLEXOS, SynerGEE & CyME.	Analysis of distributed PV support and grid operations. Smart grid storage, PV, DR. Co-simulation with Hardware via PHIL.	Open source
T&D dynamics analysis tool [16] [17]	Illinois Institute of Technology (IIT)	TS3ph with socket communication with CAPE	**TS3ph** – A new solution technique that solves the transmission-distribution system equations simultaneously **CAPE** – protection engineering tool	On-going development in the last three years.	Proprietary. Dynamic simulation only. T + D + protection. Unbalanced three phase modeling and a single phase induction motor model.	Protection and dynamic studies, e.g. fault induced delayed voltage recovery.	Commercial License

Name	Creator/Lead	Platform	Main Components	Status	Capabilities	Application Cases	License
TDCOSIM [18] [19] [20]	Argonne National Laboratory (ANL)	Bespoke interface between PSSE and OpenDSS	**Transmission simulator** – PSSE™ **Distribution simulator** – OpenDSS	Recently released	Steady-state, dynamic and quasi static simulation capable.	DER Impact assessments (short and long term).	Open source
Three-phase Dynamic Analyzer (TPDA) [21]	Virginia Tech	Local, dedicated tool	TPDA uses a sequential or partitioned method for solving the DAEs; the differential equations are solved using the trapezoidal method as implemented in the ode23t function of MATLAB® while the Distributed Engineering Workstation (DEW®) software is used to solve the algebraic equations.	Existing	Capable of simulating combined transmission and distribution networks due to its ability to model three-phase unbalanced networks. Capable of performing dynamic simulations.	DER impact studies.	Proprietary
PSSE Sincal [22]	SIEMENS	Local, dedicated tool	**PSSE™ Sincal**	Existing	It can model and simulate multi-phase radial as well as meshed networks, which are applicable to both T&D networks. Capable of steady-state, dynamic, and EMT simulations. It comes with a comprehensive library of T&D components and controls. Unclear on the scalability of the tool.	T&D dynamic simulations or static studies.	Commercial License
DIgSILENT PowerFactory [23]	DIgSILENT	Local, dedicated tool	**DIgSILENT PowerFactory**	Existing	T&D combined tool. Both steady state and Dynamic simulations (RMS balanced/ unbalanced, EMT).	T&D dynamic simulations or static studies.	Commercial License

Name	Creator/Lead	Platform	Main Components	Status	Capabilities	Application Cases	License
OpenDSS [24]	Electric Power Research Institute (EPRI)	Local, dedicated tool	Three phase RMS simulation for both T and D	Existing	Can handle steady state, harmonics both T and D three phase. Has dynamic module which many users have adapted for their own use.	T&D dynamic and static studies. Harmonic studies. DER long range planning studies, hosting capacity studies. Large-scale modeling for hardware-in-the-loop simulations. Microgrid power flow and protection studies. Aggregated/disaggregated load simulations.	Open source

5 Summary and Conclusions

With increasing amounts of DERs the assumption and the traditional modeling approaches used in transmission planning studies *may fall short* in adequately simulating the response of distribution grids with three-phase and single-phase inverter-based DERs connected in various locations. Co-simulation methods that simulate parts of the transmission system *and* the distribution grid, cycle *and* sub-cycle time frames, and/or balanced *and* unbalanced conditions is an evolving research area. Transmission planning practitioners are interested in understanding co-simulation application cases as well as a particular co-simulation platforms' user-friendliness and scalability. Hence, the object of this report was to summarize the capabilities, development status, and application cases of reported co-simulation platforms. This report focused on "co-simulation" as a means to simulate multiple subsystems in parallel, where each of the systems are modeled/simulated using different methods and techniques; a detailed discussion of "combined modeling" was outside the scope of this report.

It was found that there are a wide range of approaches for co-simulation; however, all of them are in R&D stage with different levels of maturity. Besides the overview and discussion of co-simulation platforms presented in section 3, it is not possible at this time to compare the performance of the reported platforms as the maturity and use cases of the reported tools vary significantly. In fact, many of the tools currently available are primarily used by their respective developer to address their particular research needs.

The co-simulation platforms available have looked at modeling of transmission and distribution systems, protection, market modeling and communication. The research community is looking at a number of application cases as listed in Section 3.

To date, we did not identify a single tool that may emerge as a promising candidate for industry wide adoption. But we expect the existing tools will contribute to increasing the maturity of the concept of co-simulation and also the industry's understanding of its potential application cases in the coming years. At a high level, we believe co-simulation could provide the following two benefits in the future:

1. Verification of aggregate and simplified models of new emerging resources that can be used in traditional transmission planning software.
2. Increased accuracy of modeling bulk power system voltage and frequency performance and operation of transmission protection schemes under high levels of new emerging resources for certain events and conditions.

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7 APPENDIX – Further Review of Platforms

7.1 GridSpice

Virtual platform for modeling, analysis, and optimization of the Smart Grid. It is an open source, cloud-based platform for modeling and simulations of the smart grid. Per [5],Stanford reported this is still in early development stages and is being tested for various academic/ industrial applications.

In 2014, Stanford reported the 2014 version as complete, no apparent development since then [6].

It is a flexible framework that runs industry standard simulation tools as separate but synchronized processes on a cluster. Each subsystem runs as a process in a simulator designed for that purpose while GridSpice synchronizes the boundary states for the loosely coupled processes.

The research team behind GridSpice is adding several applications to the platform, such as energy storage and electric vehicles, along with standardizing the software to comply with Common Information Model (CIM). The early-stage GridSpice platform has been incorporated into GridLAB-D™ with modules added to support co-simulation with Matpower, distributed computing and Python scripting.

The cloud-based architecture allows GridSpice to parallelize large simulation jobs across many virtual machines using a pay-as-you-go model. A variety of application cases have been published in the open literature looking at the applications of GridSpice. Of particular relevance here, GridSpice has been used to explore the creation of a platform that can perform studies that combine generation, transmission, distribution and markets.

GridSpice simulations can be managed through a representational state transfer (REST) application programming interface (API), or through a python library which allows the user to run programs that interface with disparate data inputs, for example, EMS and DMS, and post-processing tools with applications in grid control and optimization. The GridSpice framework and GridLab-D™ are available open source under the BSD license.[1]

GridSpice was used to demonstrate the application of an integrated volt/var control and distributed demand response scheme, as reported by Anderson and Narayan in [7]. The integrated volt/var scheme uses distributed demand response capacity on distribution networks to improve the reliability and efficiency of the distribution network.

7.2 FNCS

FNCS, pronounced "Fee - nix", is a federated co-simulation platform that merges communication (data) simulators with distribution and transmission simulators [8].

PNNL has been working on FNCS since 2011. FNCS was built primarily with the idea of integrating distribution network models, transmission network models and communication network models to produce a holistic view of the grid. FNCS performs synchronization and inter-simulator message delivery. FNCS capabilities have been tested for smart grid applications that calculate electricity clearing prices and co-simulation of transmission, distribution and communications network simulators. FNCS allows co-simulation of both transmission and distribution level power grid simulators with the communication simulator [8].

In a federated environment, each simulator runs its own process where FNCS performs the synchronization and inter-simulator message delivery. In 2017, FNCS was incorporated into GridAPPS-D™ as well as into Trans-active Energy System Platform (TESP).

FNCS has been widely referenced in literature with applications including integrated control of T and D and power grid and communication network interactions. The nature of FNCS lends itself to fields or studies where the handling of sensor data, control implementation and external inputs to these controls are key [9]. Examples include, integration of demand response and retail markets, integration of system operator commands and demand side response, and applications where fast communication is needed - like wide area control and PMU applications, hierarchical controls or distributed control.

1 **BSD licenses** are a family of permissive free software licenses, imposing minimal restrictions on the use and distribution of covered software [source wikipedia]

7.3 Hierarchical Engine for Large-scale Infrastructure Co-Simulation™ (HELICS™)

PNNL, under The Grid Modernization Lab Consortium Program, is leading the development of HELICS™ with multiple partners (NREL, Sandia NL, Argonne NL, Oak Ridge NL, Lawrence Livermore NL, Idaho NL).

The goal of HELICS™ [10] is the study of smart grid applications through a platform that brings information and communication technologies together with power systems [24]. The vast number of sensors and resulting data that underpins the smart grid must be processed either locally or centrally before the required decisions can be made. It is the proper simulation of this essential sensing and processing that motivates the creation of HELICS™, as failure to properly assess these disparate processes and alternative methods for performing them (for example, centralized vs decentralized consensus) could lead to sub-optimal or event flawed design of smart grid applications. This work has an initial focus upon power systems but has the goal of offering a broader multi-disciplinary platform for co-simulation [11] [12].

The core philosophy of HELICS™ revolves around making use of domain-specific tools for the simulation of each process which FNCS can then help integrate. This has been demonstrated for several power system applications Large-scale DER-Market Interactions, Novel T&D control architectures and hybrid communication design [12].

7.4 The Integrated Grid Modeling System (IGMS) for Combined T&D simulation

IGMS is a parallel, modular co-sim framework that is well suited for high performance computing (HPC) architectures [13]. It supports a very large number of highly distributed energy sources, wholesale market simulation and end-to-end T&D Modeling capability.

Features include detailed multi-period wholesale markets (including locational marginal prices), generator/ reserve dispatch, bulk AC transmission, full unbalanced 3-phase power flow for distribution feeders and end user loads and building models.

Example applications include

- Analysis of distributed PV support and grid operations
- Smart grid storage, PV, DR
- Co-simulation with Hardware via PHIL
- Connect to advanced DMS/EMS systems

IGMS offers a number of advanced feature including: automated output processing and visuals, Semi-automated data import from Plexos, SynerGEE & CyME – development to date. Next steps will include scale-testing (run time for 10-1000+ feeders), high – penetration of PV scenario development, DGPV for Grid Operations Research [14].

7.5 TS3ph – Dynamics and Protection simulation platform

Illinois Institute of Technology developed the 'High Fidelity, Faster than Real-Time Simulator for predicting power system dynamic behavior' with critical contributions from Electrocon International, Argonne National Laboratory, Alstom Grid and McCoy Energy as well as Commonwealth Edison and AltaLink [15] [16].

TS3ph offers faster than real-time dynamics simulation achieving 1.68 speedup during a mix of stable and unstable dynamics for a 20 second simulation. An industry standard simulator was used in the benchmarking process to verify the accuracy of the faster-than-real-time simulator [17].

These simulations can include unbalanced three-phase network modeling, which is reported as a major breakthrough, for transmission dynamics analysis enabling investigation of network imbalances and impacts on future devices. Sources describe a range of challenges including computational complexity, weak scalability and memory bandwidth limits for large sparse matrices.

This three phase modeling is achieved through a TS3ph-CAPE co-simulation framework. CAPE and TS3ph continue to execute on their respective operating platforms and linked. CAPE runs in server mode whereas TS3ph connects as a client, which allows the use of the existing protection settings database. This combination allows a transmission planning engineer to simulate relay responses based on the currently deployed field settings and makes the study of power swings and frequency related issues easier.

Finally, a single-phase induction motor has been modeled, with stall capability, which is important for fault induced delayed voltage recovery studies of long-term voltage collapse.

7.6 T&D Co-Simulation Tool (TDCOSIM)

TDCOSIM is an open source tool from Argonne National Labs [17]. A python interface is used to combine PSS/E as the T-Simulator and OpenDSS as the D-Simulator [18].

The tool has the capability of running balanced positive sequence dynamic simulations on the transmission system while adding three phase distribution system feeders on identified load buses. Additionally, on the distribution system, impact and behavior of distributed PV sources can be studied using a python based DER dynamic model [19]. The simulation package also has the capability to run longer time frame quasi-static simulations to evaluate the impact of detailed distribution system models on the transmission system.

7.7 DIgSILENT PowerFactory

DIgSILENT PowerFactorySingle offers a multiple domain co-simulation tool for T and D dynamic studies in a single software. Single/multiple domain co-simulation supports root-mean-square (RMS) balanced/unbalanced and/or electro-magnetic transient (EMT) modeling.

This enables simulation in parallel of different subsystems which form a coupled problem. Within the single/multiple domain co-simulation, multiple simulation units can be included, and the associated power system model of each unit is referred to as a Region. The regions/ simulation units are typically connected at the user defined borders, regions are physically separated regions of the power system. Co-simulation domains are assigned individually for each region.

Boundary objects are PowerFactory grouping objects which specify a topological cut through the power network. Boundary objects cut the power network via all AC line elements separating one region from all other neighboring regions [22].

7.8 OpenDSS

OpenDSS [25] has traditionally been an open source electric power distribution system simulator (DSS) designed to support DER integration and modernization. The solution capabilities include unbalanced, multi-phase power flow, quasi-static time series (QSTS), fault analysis, harmonic analysis, dynamic (electro-mechanical) analysis, linear and non-linear analysis. DER models include PV systems, energy storage, smart inverters, wind systems, demand response, microgrids and DER short-circuit.

OpenDSS provides solutions for enhancing performance in the form of parallel processing using actors, multi-threading circuit processing, multi-core management and fast power flows. Solution interfaces include distribution system scripting language, full graphical user-interface, co-simulation capabilities and integrated SDK for customized development. Recent advances in OpenDSS also allow modeling of associated transmission system networks in three phase and interface with the corresponding distribution system feeders.

OpenDSS also comes with a set of complementary tools to facilitate the input/output of information to the simulation platform. Scripting tool, OpenDSS has a graphical interface called OpenDSS-G.

OpenDSS example applications include: Long-range planning studies of DER, distribution system loss/ efficiency studies, DER interconnection screening, hosting capacity for PV generation impacts, large-scale modeling for hardware-in-the-loop simulations, microgrid power flow and protection studies, aggregated/ disaggregated load simulations [23].

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Note

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