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Conference Paper · January 2016

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A Reusable and Extensible Web-Based Co-Simulation Platform for Transactive Energy Systems

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Keywords: Co-simulation, web-based platform, high-level architecture, model-based integration, smart grid

Abstract

Rapid evolution of energy generation technology and increasing usage of distributed energy resources (DER) is pushing utilities to adapt and evolve business models that are aligned with these changes. Energy pricing is becoming rather competitive and transactional, needing utilities to increase flexibility of grid operations and incorporate transactive energy systems (TES). However, a huge bottleneck is to ensure stable grid operations while gaining efficiency. A comprehensive platform is therefore needed for grid-scale multi-aspect integrated evaluations. For instance, cyber-attacks in a road traffic controller's communication network can subtly divert electric vehicles in a particular area, causing surge in the grid loads due to increased EV charging and people activity, which can potentially disrupt, an otherwise robust, grid. To evaluate such a scenario, multiple special-purpose simulators (e.g., SUMO, OMNeT++, GridlabD, etc.) must be run in an integrated manner. To support this, we are developing a cloud-deployed web- and model-based simulation integration platform that enables integrated evaluations of transactive energy systems and is highly extensible and customizable for utility-specific custom simulation tools.

1. INTRODUCTION

Utilities and power grids are undergoing major evolutionary changes today [1] [2] with a continual increase in the use of distributed energy resources (DER) and a rapid acceleration in green energy generation. Today, consumers (both residential and industrial) are increasingly equipping themselves with alternate energy sources, such as photovoltaic and even alternate power lines. This has led to a significant increase in market competition in pricing and alternative mechanisms for power delivery. Several new players have emerged in all aspects ranging from energy generation, transmission, distribution, and even storage. The entire landscape is getting chaotic and as such ensuring safe and reliable grid operations while maintaining a profitable business is becoming rather difficult. Another effect of the ongoing grid transformation is the need to increase communication and control efficiency and security. Multiple players in the area and ever-growing number of edge devices are hugely increasing attack surfaces, both physical and cyber. For these reasons, incorporating transactive energy systems (TES) into the grid is highly challenging.

An apparent need for enabling the transactive energy systems is to be able to perform comprehensive evaluations of newer business models, grid operations including the impact of communication mechanisms in an integrated manner. The integrated evaluations should be able to flow the effects of changes in one domain, such as business models and regulatory changes, to other domains such as the physical grid or the cyber infrastructure. The integrated modeling and simulation should be run in a parallel, logically coherent manner so that multiple aspects of grid operations are synchronized with regard to the logical time and causalities. A large number of sophisticated special-purpose simulation tools, both open-source and commercial, exist in the power domain. Additionally, most utilities use or develop highly customized analysis tools. The problem is that these tools remain largely disconnected and need to be used separately for analyzing the aspects they were designed for. As mentioned above, the effective migration to transactive energy require us to study different aspects of the problem together i.e. we need to integrate these different simulation tools in a semantically coherent manner.

However, multiple challenges make the task of implementing grid-scale multi-aspect integrated evaluations difficult. Existing special-purpose tools not only differ in the modeling and implementation languages, but are also deeply different in the underlying model semantics and computational models. Another critical difference is the time and space granularity these tools operate in. For example, distribution planning tools – such as Gridlab-D [3] or OpenDSS [4] – do not support high resolution transient analysis. On the other hand tools specifically designed for high resolution physics-based transient analysis such as SGRS [5] are not well-suited for large-scale distribution planning. Additionally, there are tools that attempt to do both, such as SimScape [6] or Dymola [7], but are not scalable due to computational inefficiencies that result from mixing higher and lower time-resolution models.

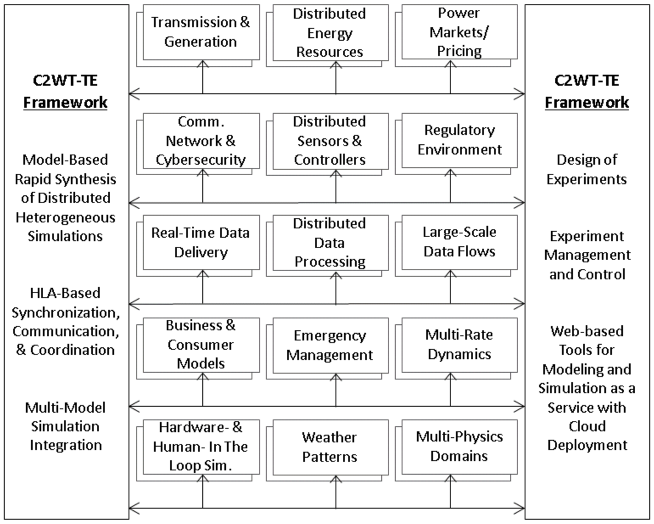
Another key challenge arises from the need to maintain coherence between the physical powerflows and the transactional market dynamics. Moreover, humans play a critical role in the overall equation, so the various human aspects such as consumer behavior models, trust, security, safety, business models and workflows, regulatory and legal requirements, and organizational policies. Furthermore, to support evolution and avoid lock-ins, the platform for integrated evaluations must be open and flexible so that it can be adapted and customized for utility-specific needs.

To address these challenges, we are developing an open platform called Command and Control Wind Tunnel for Transactive Energy (C2WT-TE) [8] [9] [10]. This platform will be completely web-based and provide model-based integrated simulations as a cloud-deployed service. The platform being designed allows for rapid synthesis of distributed heterogeneous simulations. Starting from the component models for certain aspects in the power grid domain and web-based integration models of the composed system-of-systems, the platform automatically composes the runtime artifacts, execution scripts, and deployment and monitoring configurations needed to run integrated simulations on the cloud. The platform is also being designed for flexibility and customization by its users for their own, for example utility-specific, needs.

2. GRID-SCALE MULTI-ASPECT INTEGRATED EVALUATIONS

Enabling utilities to implement effective integration of transactive energy systems in the power grid requires integration of power domain models of generation, transmission, and distribution with a number of transactive aspects such as distributed monitoring and control, digital information storage and communication networks, real-time data analytics, cyber defense equipment and measures, security, market-based energy pricing, and safety and reliability measures and control. These aspects have been modeled and analyzed for several decades now but these analyses are largely performed separately for each of the concerns. Effective methods are needed to integrate traditionally disjoint analysis methods into comprehensive, system-of-systems evaluations. Notice that these aspects go well beyond analysis of Cyber-Physical Systems (CPS) [11] because, in addition to the multiple interacting domains of mechanical, electrical, cyber, thermal, and electronic, smart grids with transactive energy systems also need integration all of the human aspects listed previously as well as the transactional market dynamics of supply and demand.

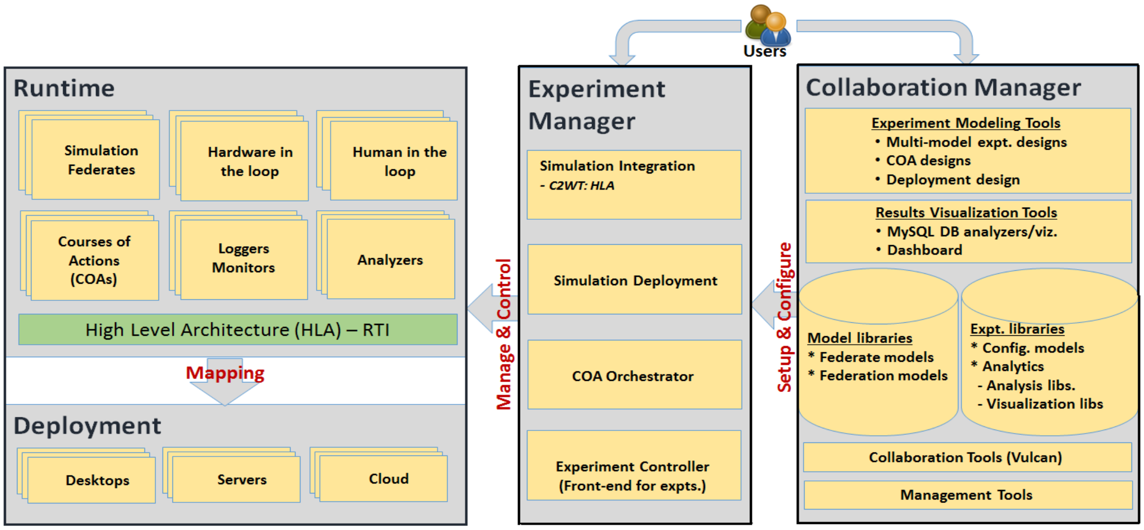
A notional architecture of the C2WT-TE platform is shown in Fig. 1. It shows the various aspects of smart grid operations such as transmission and generation, DER, power markets, business and regulatory models, multi-physics-, multi-rate-, and multi-scale dynamics, and hardware- and human-in-the-loop evaluations. It illustrates the integration bus that ties the diverse aspects of the grid operation with key technological enablers in the architecture such as model-based rapid synthesis of distributed, heterogeneous simulations, web-based and cloud-hosted modeling and simulation as a service, integrated simulations using with synchronization, communication and coordination among integrated components, and a rich experimentation and analysis tool-suite.



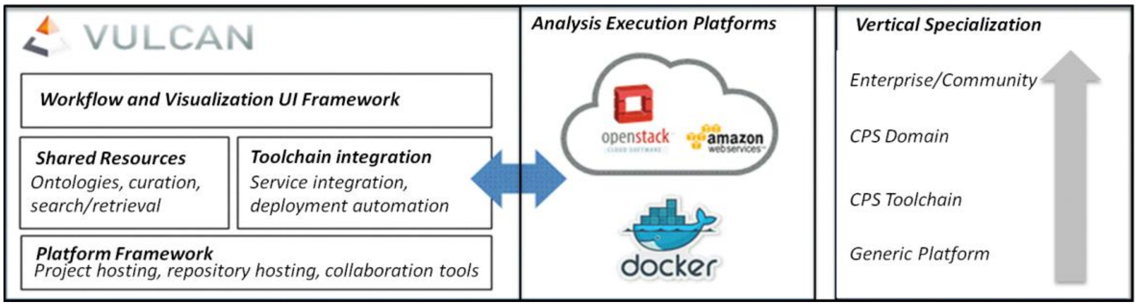
1. C2WT-TE Platform Notional Architecture

3. THE C2WT-TE PLATFORM

The functional architecture of the C2WT-TE platform is shown in Fig. 2. The foundational element of this architecture is a High-Level Architecture (HLA) [12] – based *runtime* that enables integrated heterogeneous simulations. The platform allows d*eploying* the integrated components (called *simulation federates*) on several computation platforms such as *desktops*, *servers*, or *cloud*. Other components such as *Loggers*, *Monitors*, and *Analyzers* can also be supported. The platform also enables support for *Hardware-in-the-loop* and *Human-in-the-loop* integrated simulations. Furthermore, the *COA Orchestrator* supports creation of a number of Courses of Action (COA) [13] (or task plans) that enable what-if analysis over a federated simulation as well as gaming strategies with one another to determine the optimal task plans in different situations, e.g. amidst various cyber-attacks.



2. C2WT-TE Functional Architecture



3. Vulcan Framework for Project Collaboration

Modeling, configuration, and control of experiments are supported by the *Experiment Manager*. Web-based modeling and simulation is enabled by the *Simulation Integration* and *Simulation Deployment* modules. The major component *Collaboration Manager* supports user groups, roles and privileges, projects and tasks, and provides a web-based platform for multi-user collaborative modeling and experimentation. In the next sections, we describe three key technologies that bring this unique platform to fruition.

3.1. Vulcan Framework for Project Collaboration

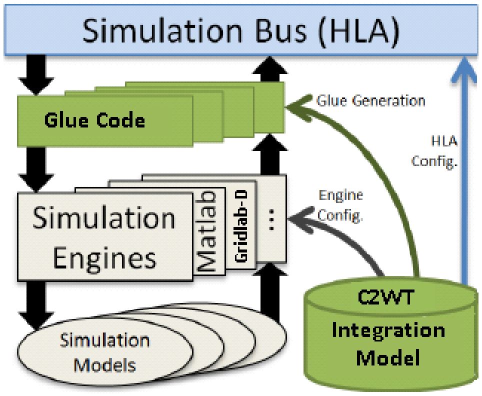
The key characteristic of a web-based integrated simulation platform is the ability to manage tools, libraries, and models in version- and access-controlled repositories as well as to collaborate with other users and providers on models and experiments. The Vulcan Framework [14] for Collaboration, Management, and Execution is shown in Fig. 3 with the key services it provides. In addition, it supports rich definitions of user roles and privileges allowing for fine-grained access control of models, experiments, analysis tools, and results. It also hosts code repositories, issue-tracking, and communication tools for users to facilitate collaborative development of models and experiments.

3.2. Web-based Generic Modeling Environment

WebGME [15] [16] has been recently developed at our institute and provides a highly scalable, web-based multi-user modeling and metamodeling environment with full version control and traceability. Requiring only a web-browser, it supports rich Domain-Specific Modeling Languages (DSMLs) for rapid synthesis and configuration of applications [17] [18].

3.3. Command and Control Wind Tunnel (C2WT)

C2WT [9] [10] [19] is the result of almost 10-years of research work at our institute and represents a robust model-based integration tool-suite that supports rapid synthesis of distributed system-of-systems simulations. The conceptual architecture of C2WT is shown in Fig. 4. Central to distributed simulation is a simulation bus based on the HLA IEEE-standard that provides services to manage distributed simulations such as time synchronization, communication, coordination, and data-exchange. The framework provides support for a number of simulation tools such as SUMO [20], CPN Tools [21], Matlab/Simulink [22], OMNeT++ [23], etc. for use in distributed simulations. Using the data models and integration models designed in the C2WT modeling language the framework automatically generates glue code for wrapping simulation tool specific models as HLA compliant federates.



4. C2WT Distributed Simulation Framework

C2WT-TE weaves the above three technologies in a single cloud-hosted, web-based integrated simulations platform. The multi-model integration also supports multi-scale and multi-rate dynamics of integrated components. Once fully developed, the platform will be hosted on the CPS-VO [24].

4. EXPERIMENTS

The C2WT-TE platform enables comprehensive HLA-based simulations and has been used in the past for several experiments. We have previously published [8] [25] two complex experiments in the power domain that were conducted using C2WT-TE. Here we describe a new experiment that we plan to demonstrate at the TES 2016 conference and targeted specifically toward evaluating challenges that arise due to integration of physical, cyber, and transactional domains.

First, consider a power generation and distribution scenario consisting of multiple communities' micro-grids receiving power from centralized distributors. These micro-grids contain their own de-centralized low-scale power generation and storage facilities such as photovoltaics and fuel cells, and other Community Energy Storage (CES) devices [26].

Each community implements a reactive demand controller which must select from the available generation sources to meet the current load of the community according to the aggregate load profiles of the attached charging stations and houses, taking into account the current output of its local generation and storage facilities. The controller determines from which generator companies to draw power based on the current available excess power the generator company is producing, as well as the current price of that power.

Each generator implements a reactive price controller which senses the current aggregate load of the communities drawing power from it and compares it to the generator's power generation profile. The price controller attempts to set the price to match the current load of the connected communities to the current power being produced by the generator according to its generation profile.

Because this is a large, distributed system, the pricing signals sent out from the generator and the load signals sent out by communities must travel through a communications network which alters their timing characteristics, delaying and possibly reordering the sensor data packets. This communications network also acts as another vector for faults to occur and propagate, as well as for attacks.

Because these communities are each operating independently, but are indirectly affecting each other through their connections to the generators and through the communications network, the behavior of this system is difficult to mathematically/formally analyze but amenable to simulation. Similarly, the generators operate independently but affect each other through their pricing mechanisms. As one generator lowers its price, the communities connected to other generators may switch away from the other generators, which will in turn cause a higher load on the generator with the lowest price (driving its price up) and a lower load on the higher priced generators (driving their prices down).

Similarly, the entire stability of the grid will need to be shown through (a) secure and reliable communication networks, requiring tightly integrated network simulators, and (b) the switching characteristics of the communities between the generators, requiring the use of a transient simulator in addition to the steady state simulator used for the behavioral simulation.

5. CONCLUSION AND FUTURE WORK

With major transformation across all aspects of the power grid and rapid evolution of green generation technologies and market-based supply and demand, utilities are facing a paradigm shift in integrating transactive energy systems. Growth in local distributors and prosumers, and increasing needs of coordinated communication and control across the grid, has made it even more challenging to ensure stable and profitable grid operations. For this reason, an open platform is sorely needed that can enable stakeholders to evaluate complex business models, power grid and cyber infrastructures in a tightly-coupled integrated manner. The C2WT-TE technology being developed will provide a flexible and customizable platform for quick and efficient large-scale system-of-systems evaluations. The web-based and standards-based approach used in the platform coupled with a flexible and customizable design allows for greater ease of use as well as large-scale adoption. As the technology matures, we plan on making the platform available [24] to the larger transactive energy community.

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Biography

Himanshu Neema is currently working as a Senior Engineer at Vanderbilt University and holds a MS degree in Computer Science. His primary research interests include Modeling & Simulation, Model-Integrated Computing, Distributed Simulations, Smart-Grids, Transactive Energy, Artificial Intelligence, Semantic Web, Big Data, Cloud Computing, Constraint Programming, Resource Allocation, and Planning & Scheduling. He has 18+ years of experience in research, development, and managing of software applications.

William Emfinger is currently working as Post-Doctoral Researcher at Vanderbilt University and received a PhD in Electrical Engineering from Vanderbilt University in 2015. He received a B.E. in Electrical Engineering and in Biomedical Engineering from Vanderbilt University in 2011. His research interests include distributed, real-time cyber-physical systems, their modeling, analysis, and development, with a focus on space systems.

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