Simulating the Dynamic Coupling of Market and Physical System Operations

S. E. Widergren, *Sr. Member, IEEE,* J. M. Roop, R. T. Guttromson, *Member, IEEE,* & Z. Huang, *Member, IEEE*

Abstract—**As energy trading products cover shorter time periods and demand response programs move toward real-time pricing, financial market-based activity impacts ever more directly the physical operation of the system. To begin to understand the complex interactions between the market-driven operation signals, the engineered controlled schemes, and the laws of physics, new system modeling and simulation techniques must be explored. This discussion describes requirements for new simulation tools to address such market transaction control interactions and an approach to capture the dynamic coupling between energy markets and the physical operation of the power system appropriate for dispatcher reaction time frames.**

Index Terms—**adaptive systems, complexity theory, load modeling, power system simulation, power system economics**

I. INTRODUCTION

The restructuring of the electric power industry has seen the advancement of market-based signals into operational decision making of the power system. As time progresses, the number of business transactions increases and new market products bring new economic opportunities. These opportunities range from long term contracts, to participation in ancillary services, to demand response programs. Armed with advances in information technology and the pervasiveness of inexpensive communications alternatives, innovative organizations propose, test, and implement new financial products that offer incentives for market participants to behave in ways that improve the overall operational effectiveness of the power system.

The future energy system will apply the expansive capabilities of information technology to coordinate distributed energy resources (DER - including demand, distributed generation, and storage) with bulk transmission and generation resources to enhance system performance and reduce the impact of component failure (both technically and economically). To accomplish this transformation, the traditional paradigm of meeting all demand at a fixed cost at all times is giving way to more interactive, transparent mechanisms that recognize the value of an array of energy services to those participants with a need [1]. This entails the establishment of markets for the exchange of services, and the mechanism to obtain information to support good decision-making. Such exchanges of information and service will occur at all levels of the system: from the residential water heater to the turbines of major generating stations. The result is an economy of business transactions at a scale and pace unfamiliar to operational practices in place today.

The imagination of energy industry players (utilities, producers, system suppliers, marketers) are directed on what might be done in this information rich world, but the path forward is not clear. How should new markets be structured? How can we flexibly implement information exchange so it enables good decision-making and evolves with market and technology changes? What might the transition look like as existing mechanisms get replaced with new approaches over time? What regulation and policy constructs need to be put in place to assure reliable service and a resilient infrastructure for the security of the nation's economy?

To address these questions prior to implementation, analysis must be supported by simulation. To date, rigorous simulation of the technical aspects of running the system have been separated from market simulators [2][3][4]. In addition, a market-based framework moves the control paradigm away from centralized authority toward distributed, autonomous decision-making [5]. Properly designed, the result can provide greater efficiencies and reliability of operation, but it will also be a system with a different form of predictability, a system that behaves more with forecasted bounds such weather, a system that requires the application of complex system theory to discover emergent behavior and direct it in a beneficial manner.

The following material reports on an approach and the progress being made to address this gap in our simulation capability so we may better understand the issues posed by questions of market and physical system interactions.

II. POWER SYSTEM MODELING

Investigation of the interaction of energy markets and physical system operations covers a spectrum of time frames (from real-time system dynamics to the accrued impact of multi-year bi-lateral energy contracts). In addition, as one considers bulk generation and transmission to sub-transmission, distribution, distributed generation, and the loads, the entities of interest increase by orders of magnitude (Fig. 1). The extent of the system model forces simulation designers to organize their

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solution approaches around areas of analysis that constrain the time frames and number of components to be modeled.

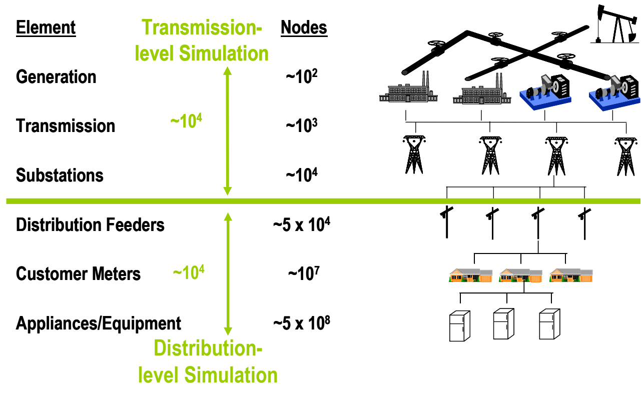

Fig. 1: Models must cover diverse scales (western US system example)

To address the interaction of market and physical system interaction, the problem is divided along the traditional lines of bulk system level / wholesale market operation and distribution / retail market level operation. Within these areas, the time frames of interaction focus primarily on the longer term dynamic operation of the system in the order of seconds to minutes. However, by decoupling the distribution level modeling from the transmission level modeling, we can also adapt the simulation techniques to address different time frames (such as the multi-year impact of retail contract choice on the distribution system, versus the influence of price responsive demand on daily operation scenarios at the transmission level. Still, the boundary issues between these levels must be carefully addressed to simulate equivalent behavior from simplified models depending upon the transmission or distribution level issue under investigation.

A. Distribution Feeder Modeling

Classical power system load models look at the probabilistic behavior of load averaged over different times of day and various times of the year. These models also reflect aggregated contributions from many different types of appliances and equipment used in industry, commercial buildings and homes. The advent of demand management systems that controlled specific types of appliances, such as water heaters, began to change these models [6]; however, to study the impact of demand response programs, detailed equipment and human behavior modeling is necessary to include in the simulation.

Such detailed load modeling has been done for residential neighborhoods [7][8]. Fig. 2 shows the pulsed nature of appliance load on the distribution system over the course of a day. Only as the number of homes increases do we begin to see the diversity usually represented in traditional load models. To simulate the interaction with market signals, the load models need to include price responsive controllers. Such controllers may adjust thermostat set-points or directly curtail energy delivery to an appliance, thus altering the nature of these pulses. In addition, human behavior patterns may change to move load to shoulder or off-peak time periods if given the right financial incentive.

At the head of the distribution feeder, a simplified model of the rest of the power system is represented. Typical voltage and frequency profiles can be used as input to the feeder. However, in order to represent demand response to spot market or time of day rates across significant regions of the transmission system, simplified equivalent models of such feeders are necessary. Regional dependencies on climate and personal behavior in addition to the nature of retail power contracts impact how these reduced order models are constructed. An approach to creating such a simplified model for heating, ventilation, and air-conditioning (HVAC) systems is reported in [9]. Important to the realization of these equivalent models is the ability to capture the complex behavior that emerges from large populations of appliances under price responsive. For example, a high real-time price signal may result in a relatively quick reduction of load on a feeder; however, it also has the side effect of reducing the diversity of the load, such that after prices are relieved or consumer discomfort sets in, the rebound need for electricity may exceed the original peak.

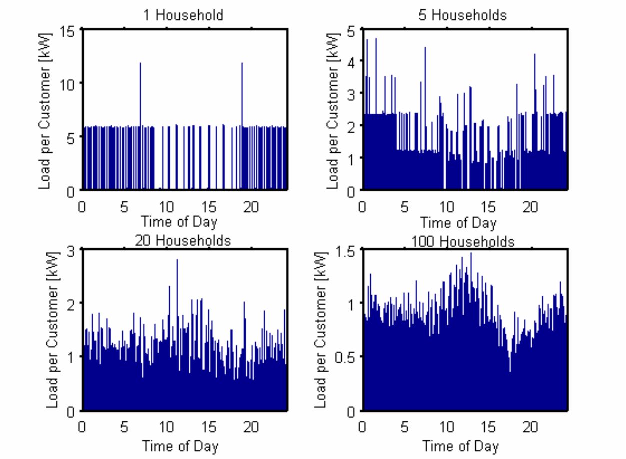

Fig. 2: Load diversity as household loads increase

B. Transmission Level Modeling

Given a reasonable equivalent for price response demand at the distribution feeder, traditional steady-state load models can be replaced in transmission level analysis tools. To study the interaction of bulk power markets dynamics with physical system operations, modeling the slow moving dynamics of the power system in quasi-equilibrium is adequate. In these scenarios, daily, hourly, and perhaps short period ancillary service markets set generation schedules that then impact the flow of energy in the system.

Power system simulation tools currently exist that provide reasonable representations of system behavior for these slow dynamics. Called dispatcher or operator training simulators (DTS/OTS), these tools are built around a power flow solution engine that assures Kirchhoff's current and voltage laws are satisfied at each step in time (on the order of 2 to 20 seconds, depending upon the nature of the study) [10]. In between these time steps, the dynamic aspects of power system equipment, particularly generators and their controls, but also transformer taps, capacitor banks, and the gross operation of protection relays are modeled. Fig. 3 depicts a simplified view of the major components in a DTS/OTS. The generation and load models interact with the power flow engine. They are influenced by the area control algorithms used by a region to balance its supply, demand, and inter-area transfers in real-time. They are also influenced by maintenance schedules and by reliability criteria for secure operation as may be directed through SCADA measurements and the results of on-line network analysis tools.

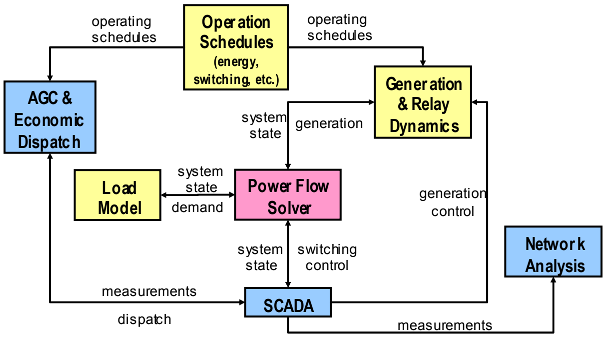

Fig. 3: Block diagram of the power system components of a DTS/OTS

Energy markets interact with the DTS/OTS through the schedules for generation and load influenced by the price signals that the power producers, load serving entities, and consumers receive from wholesale and retail markets (see the *Economics & Market Modeling* section below).

III. ECONOMICS & MARKET MODELING

Consistent with the division of simulation between transmission and distribution, are the corresponding economic market models for wholesale and retail energy. The boundary between these financial domains must also be carefully considered. Retail energy providers, otherwise known as Load Serving Entities (LSEs), aggregate individual commercial or residential demand into load blocks that can be traded at the wholesale level to match bulk generation with load.

A. Retail Market Modeling

The economic simulation approach is based upon agent-based computational economic (ACE) modeling [11]. Using this technique, consumers, LSEs, distribution system operators, and the market instruments they use to contract for services are modeled as software agents (Fig. 4).

A variety of different auction forms are options for any market at all levels within a grid. These include call auctions, blind auctions, English auctions, Dutch auctions and double discriminatory auctions [12]. These may work well at the bulk power level, but for the residential customer, at the distribution level, where a single, regulated distribution company distributes power to many customers, this market form is unlikely what the residential customer will face. What most customers face is a fixed-price contract. Some utilities have experimented with alternative contracts, such as time-of-use (TOU) rates or real-time pricing (RTP).

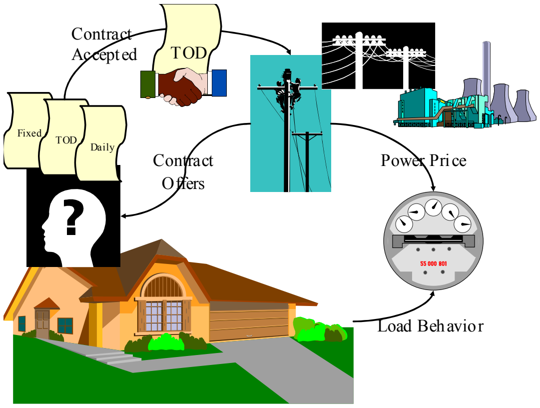

Fig. 4: Customer, LSE, distribution company interaction – agent-based computational economics

The behavioral element critical in any modeling of market behavior is the mechanism by which the actors formulate bids or offers. We have explored genetic algorithms (GA) and a more human psychology defensible approach to consumer behavior – the modified Roth-Erev method (MRE) [13]. The application of the MRE method to the retail level relies on a fitness measure that, for the residential customer, depends on household type, the history of utility expenditures relative to income, and the level of service implied by different characteristics of the household.

At the core of the strategy for constructing a price-responsive retail electricity market that includes households is the decision to adopt a specific type of contract that has advantages to both the consumer and the distribution utility. The advantages to the utility come from sharing the risk of wholesale price fluctuations that affect the utility's costs; the advantages to the user come from being able to manage better its utility bills and, with that better management, reduce utility costs in its budget.

A major challenge is the development of a "fitness measure" that triggers a switch from one sort of contract to another. In most applications of ACE models, this fitness measure is the gain to the player – in the work we have studied so far, this is the cost of power subtracted from revenues for the aggregator (LSE) and sales minus cost for the generators. The agents that accept new contracts have to migrate from the current pattern of use under the old contract to the new pattern of use under the new contract aided by incentives – in the form of technology to manage loads and lower power bills.

Residential customers are modeled to review their bills and determine if a contract change is in order (Fig. 5). Incentives are also modeled for utilities to offer alternative contracts. The idea is to play out the resulting dynamic in the simulator to gain insight into the viability and stability of various contract offerings.

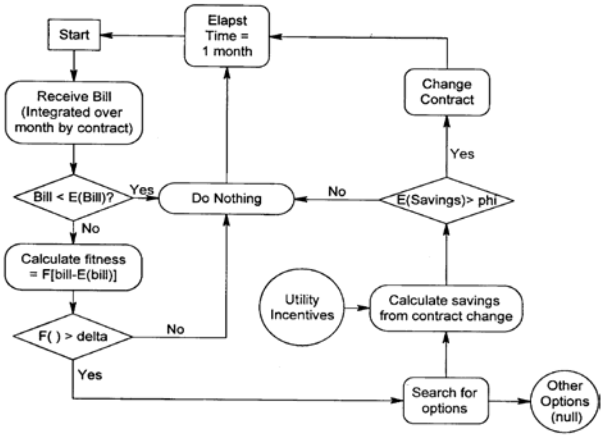

Fig. 5: Decision logic for residential contract choice flow diagram

B. Wholesale Market Modeling

The ACE technique is also applicable for wholesale energy market modeling. Software components representing the decision making processes and success measures of various organizations are simulated using the agent-based approach. A significant issue in constructing these entities is that organizations do not fall into neat categories, but they combine various combinations of functions and responsibilities. They also reorganize by division and mergers. To address this problem, agent templates are constructed based upon function and area of responsibility. NERC has experienced this problem within their own industry standards and guidelines efforts. The NERC Functional Model Review Task Group of the Planning Reliability Model Task Force has documented what they refer to as the Functional Model [14]. The Functional Model serves as a good guide for identifying the fundamental areas from which organizations can be constructed.

Using the terminology from the NERC Functional Model, the simulation needs to include wholesale short-term, mid-term, and futures markets involving market players (Generator Owners and LSEs) and the market regulatory and administrative functions (Market Operations, Balancing, Interchange and Compliance Monitoring). In addition, energy schedules must be coordinated with transmission providers, balancing authorities, and regional reliability entities (e.g., ISOs, RTOs). Long term, bi-lateral energy markets that involve much the same players must also be modeled.

The generators have characteristics based on fuel supply, fuel costs, capital costs, return on investment, and operating and maintenance costs for the various types of equipment in operation. These costs must be covered over some interval of time, and these costs provide a basis for a bidding strategy in the bulk market. The costs vary depending on where in the life-cycle of the plant the generator is currently operating, how fuel costs vary, and economic considerations – covering marginal costs over some periods of time is adequate, so long as other costs are recouped over the appropriate accounting period. As with the LSEs, the generators' performance in the bulk market needs to be translated into a fitness measure that is part of the learning process that conditions the bid strategy in the bulk market.

A long-term, bi-lateral power market operates without direct supervision on the part of the ISO. The initial simulation design proposes that this market be structured so that LSEs can purchase long-term contracts directly from the generators. While the ISO is not directly involved in this market, as part of the routine completion of a contract the generators and LSEs alert the ISO that there is a future commitment to transfer power from a specific generator to a specific LSE. These contracts provide both the generators and the LSEs a vehicle for hedging to cover power needs (in the case of the LSE) or costs (in the case of the generators).

Transmission system simulation requires that each LSE and each generator is located at a specific site and connected through a grid. The restrictions on the flow of power through the grid, from a market perspective, give rise to scarcity of transmission assets that imply a higher cost for the use of this transmission asset compared to one that is underutilized. Location dependent pricing (e.g., locational marginal prices, zonal prices, or flow gates) are essential for consideration of markets for transmission services, which also require simulation.

IV. COMPUTATIONAL FRAMEWORK

The complexity of the market and physical operation of our electric power system is reflected in the complexity of the computational framework needed for its simulation. Depending upon the topic of analysis, the simulation environment must be configured accordingly. This framework requires great flexibility to add and delete components as well as incorporate components that may be developed by independent entities. In the initial simulation environment under construction, we incorporate a DTS/OTS from one organization, a power flow solver for distribution system simulation from another, and market-based agents from a third.

A. Simulation Scenario

To achieve the formidable objectives of integrating great numbers of components from different sources that may use various programming technologies (compilers, tool sets, graphics packages, etc.) across multiple computing platforms, the design of this framework must consider the specification of a common set of simulation services, and investigate the ease of integration, flexibility, and system performance. Examples of the challenges to be addressed include the sharing of common information between components in a distributed environment (e.g., power system and market information models, time, weather, system frequency), the ability to adjust simulation step size for coordination by each component, the ability to archive an integrated configuration of components, and to reconstitute a configuration across multiple processors from an archive.

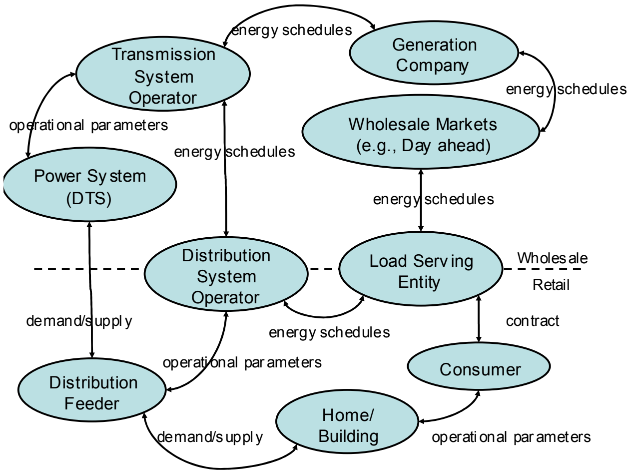

Fig. 6: Simulation components and their general interactions

To make the generalized aspects of the simulation environment tangible, a specific scenario was developed that links components of interest and describes their initial interactions. Fig. 6 illustrates the types of entities to be modeled in this scenario. The distribution utility is represented here as a combination of the Distribution Feeder, the Load Serving Entity (LSE), the Distribution System Operator, and the customer. The LSE and the generators interact in the bulk power market, where deals are struck for future (day-ahead) power. Although not shown in the figure, the LSE and generators are allowed to contract directly. The generators, in turn, provide power to the transmission grid, which then delivers power to the distributor, under distribution operations control. The transmission system operator coordinates transmission flows based on bulk market transactions. The initial simulation work is to flesh out these components and integrate them into an interactive system.

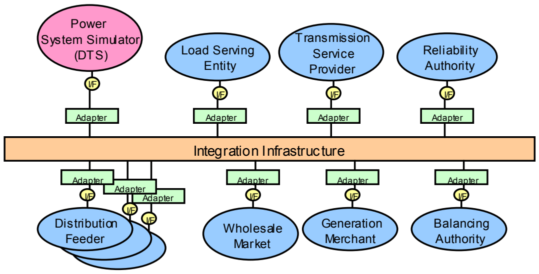

Fig. 7: Simulation integration framework

B. Component-Oriented System Designs

Fig. 7 depicts the software framework envisaged for designing, implementing, and integrating the simulation components. The Power System Simulator (DTS/OTS) is an off-the-shelf, hardened set of software. The Distribution Feeder component results from the work being done to create equivalent models of distribution feeders from a detailed distribution system simulator developed earlier [7]. The other components are agent-based components. They are integrated together using a J2EE framework [15] that supports the exchange of messages between components. J2EE is an open specification for component-oriented system architecture [16]. It supports a flexible, distributed computing environment. Well defined interfaces allow integrators to "connect" components into the system and replace them with other components as long as the interface contracts remain honored. The adapters in the figure represent conversions that are necessary to "hook-up" a software component into the framework.

The J2EE compliant message-based integration framework consists of a set of services needed to integrate the various simulation components needed for an analysis, and enable these components to exchange simulation data and control. Specifically, the design of the simulation environment must support services such as,

- **Configuration and execution management**: organize and track the various components that make up the system, the ability to start/pause/stop the simulation, the messages being exchanged, and the publish/subscribe topics the components use to organize their interaction.
- **Activity logging**: store a history of the activity between components. This includes consideration for the ability to "playback" events.
- **Model management**: each component is initialized with a model of the world they are to simulate. These models must be consistent between components (e.g., the name and location of a generating unit is known to the Generation Company and the Power System Simulator). System initialization, model archive, and model retrieval need to be supported across all components.
- **Simulation time**: the speed at which the simulator runs should be able to vary from mimicking real-time to faster than real-time. This involves coordinating a simulation time clock across the system and creating rules for component development that allows them to use this time and adjust their solution steps.

C. Current Status

A design activity is presently underway to review and refine the requirements for such a software system, investigate existing system tools and services that may be able to be integrated "off the shelf" rather than internally developed, analyze the performance aspects of the system based on the demonstration, and present guidelines for well-formed component construction.

An integration prototype has demonstrated the system integration aspects of the approach. An adapter to connect the Power System Simulator component into the J2EE framework has been created and messages have successfully been exchanged with surrogates of distribution system feeder and LSE components. Initial versions of a distribution feeder equivalent, LSE, generator, and short term market are also under construction.

V. FUTURE WORK

Simulating such a complex, changing world can go many directions. The flexibility of the integration framework allows different components to be developed over time. Future focus on component development depends upon the prioritization of topics for research. In the near term, the simulation computational framework must define the basic interface contract for components to integrate into the simulation. This includes object identification, handling simulation time, archival, and the template for defining the interface of a component.

The vision for the simulation framework is to create an open source environment where independently developed software components can be shared with other people and organizations, and a variety of simulation environments can be configured to address analysis needs.

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VII. BIOGRAPHIES

Steve Widergren (M'1978, SM'1992) received his BSEE (1975) and MSEE (1978) from the University of California, Berkeley. He works at the Pacific Northwest National Laboratory, where he contributes to the research and development of new solutions for the economic and reliable operation of power systems. Prior to joining PNNL, he was with ALSTOM ESCA, a bulk transmission energy management system supplier, where he designed software solutions for system operations and championed the establishment of an integrated suite of energy management system software products. He has also held power engineering positions at American Electric Power and Pacific Gas & Electric (as an intern). He is Chair of the Richland Power Engineering Chapter, vice-chair of the PES Energy Control Center Subcommittee and a member of the IEEE SCC 21 1547.3 standards group on monitoring, information exchange, and control of distributed resources.

Joseph M. Roop received his BSc in economics from Central Missouri State University in 1963 and his Ph.D. in economics from Washington State University in 1973. He works at Pacific Northwest National Laboratory, where he manages several programs for the Department of Energy's Office of Energy Efficiency and Renewable Energy. Dr. Roop joined PNNL in 1981 after working for eight years at the University of California in Berkeley, the Economic Research Service of the U. S. Department of Agriculture, and Evans Economics Inc., in Washington, D. C. While with PNNL, he served for 17 months as a staff member in the Energy Department's Policy Office and was seconded to the International Energy Agency for nearly two years. Since joining the Laboratory he has published more than 50 technical and journal articles. He is an adjunct professor of economics at the Tri-Cities Campus of WSU and is listed in five editions of Who's Who.

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