GridLAB-D: An Open-source Power Systems Modeling and Simulation Environment

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***Abstract*—GridLAB-D is a new power system modeling and simulation environment developed by the US Department of Energy. This paper describes its basic design concept, method of solution, and the initial suite of models that it supports.**

***Index Terms*—power simulation, power modeling, high-performance computing.**

I. Introduction

GridLAB-D is the first of a new generation power distribution system simulation technology developed by the US Department of Energy at Pacific Northwest National Laboratory in collaboration with industry and academia. GridLAB-D incorporates the most advanced modeling techniques, with high-performance algorithms to deliver the best in end-use modeling, coupled with distribution automation models, and software integration tools for users of many power system analysis tools. The most important new capabilities slated for GridLAB-D include

- extended quasi-steady state time-series solutions;
- end-use models including appliances and equipment models, consumer models, all implemented with the latest agent-based simulation methods;
- distributed energy resource models, including appliance-based load shedding technology and distributed generator and storage models;
- retail market modeling tools, including contract selection, business and operations simulation tools, models of SCADA controls, and metering technologies;
- external links to Matlab™, MySQL™, Microsoft™ Excel™ and Access™, and text-based tools, as well as SynerGEE's power distribution modeling system; and
- the ability to run efficiently on multicore and multiprocessor machines.

GridLAB-D has been validated with both existing end-use simulation and standard distribution analysis tools. In addition, the coupling to many other tools will offer unparalleled analysis capabilities: with GridLAB-D we will be able to study rate cases to determine whether the price differentials are sufficient to encourage customer adoption; we can study the potential and benefit of deploying distributed energy resources, such as Grid-Friendly appliances; or we can study the business cases for technologies like automated meter reading, distribution automation, retail markets, or other late-breaking technologies. GridLAB-D will even allow you to study the interactions between multiple technologies, such as how underfrequency load-shedding remedial action strategies might interact with appliance-based load-relief systems.

GridLAB-D is capable of studying distribution utility system behavior ranging from a few seconds to decades, simulating the interaction between physical phenomena, business systems, markets and regional economics, and consumer behaviors. The results will include many power system statistics, such as reliability metrics (e.g., CAIDI, SAIDI, SAIFI), and business metrics such a profitability, revenue rates of return, and per customer or per line-mile cost metrics.

II. The GridLAB-D System

A. *What is GridLAB-D?*

GridLAB-D is a flexible simulation environment that can be integrated with a variety of third-party data management and analysis tools. At its core, GridLAB-D has an advanced algorithm that can determine the simultaneous state of millions of independent devices, each of which is described by multiple differential equations solved only locally for both state and time. The advantages of this algorithm over traditional finite difference-based simulators are: 1) it is much more accurate; 2) it can handle widely disparate time scales, ranging from sub-second to many years; and 3) it is very easy to integrate with new modules and third-party systems. The advantage over tradition differential-based solvers is that it is not necessary to integrate all the device's behaviors into a single set of equations that must be solved. The GridLAB-D system also includes modules to perform the following system simulation functions:

- Power flow and controls, including distributed generation and storage
- End-use appliance technologies, equipment and

Development of GridLAB-D is funded by the US Department of Energy and managed by Pacific Northwest National Laboratory, which is operated by Battelle Memorial Institute for the US Department of Energy under contract DE-AC65-76RLO1830.

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978-1-4244-1904-3/08/$25.00 ©2008 IEEE

controls

- Data collection on every property of every object in the system, and boundary condition management including weather and electrical boundaries.

Additional planned modules are being developed to provide additional functionality, including:

- Consumer behavior including daily, weekly, and seasonal demand profiles, price response, and contract choice
- Energy operations such as distribution automation, load-shedding programs, and emergency operations.
- Business operations such as retail rate, billing, and market-based incentive programs.

B. How does GridLAB-D work?

GridLAB-D includes an extensive suite of tools to build and manage studies, and analyze results. Existing and planned tools include:

- Agent-based and information-based modeling tools that allow you to create detailed models of how new end-use technologies, distributed energy resources, distribution automation, and retail markets interact and evolve over time.
- Tools to create and validate rate structures, examine consumer reaction, and verify the interaction and dependence of programs with other technologies and wholesale markets.
- Interfaces to industry-standard power systems tools and analysis systems.
- Extensive data collection tools to permit a wide variety of analyses.

At its simplest GridLAB-D can examine in detail the interplay of every part of a distribution system with every other. GridLAB-D does not require the use of reduced-order models, so the danger of erroneous assumption is averted. GridLAB-D is more likely to find problems with programs and business strategies than any other tool available. It is therefore an essential tool for industry and government planners.

C. Who uses GridLAB-D?

Today's power systems simulation tools don't provide the analysis capabilities needed to study the forces driving change in the energy industry. The combined influence of fast-changing information technology, novel and cost-effective distributed energy resources, multiple and overlapping energy markets, and new business strategies result in very high uncertainty about the success of these important innovations. Concerns expressed by utility engineers, regulators, various stakeholders, and consumers can be addressed by GridLAB-D. Some example uses included:

- **Rate structure analysis**. Multiple differentiated energy products based on new rate structure offerings to consumers is very attractive to utilities because it creates the opportunity to reveal demand elasticity and gives utilities the ability to balance supplier market power in the wholesale markets. The challenge is designing rate structures that are both profitable and attractive to consumers. GridLAB-D provides the ability to model consumer choice behavior in response to multiple rate offerings (including fixed rates, demand rates, time-of-day rates, and real-time rates) to determine whether a suite of rate offerings is likely to succeed.
- **Distributed resources**. The advent of new distributed energy resource DER technologies, such as on-site distributed generation, BCHP and Grid-FriendlyTM appliance controls creates a number of technology opportunities and challenges. GridLAB-D permits utility manager to better evaluate the cost/benefit trade-off between infrastructure expansion investments and distributed resources investments by including the other economic benefits of DER (e.g., increase wholesale purchasing elasticity, improved reliability metrics, ancillary services products to sell in wholesale markets).
- **Peak load management**. Many peak-shaving programs and emergency curtailment programs have failed to deliver the expected benefits. GridLAB-D can be calibrated to observed consumer behavior to understand its interaction with various peak shaving strategies. The impact of consumer satisfaction on the available of peak-shaving resources can be evaluated and a more accurate forecast of the true available resources can be determined. GridLAB-D can even evaluate the consumer rebound effect following one or more curtailment or load-shed events in a single day.
- **Distribution automation design**. GridLAB-D offers capabilities that support the design and analysis of distribution automation technology, to allow utilities to offer heterogeneous reliability within the same system but managing power closer to the point of use.

GridLAB-D offers many other analysis capabilities to assist in the design and operation of distribution systems, and it is an essential tool for utilities that wish to take advantage of latest energy technology.

III. Power Flow Modeling

The power flow component of GridLAB-D is separated into a distribution module and a transmission module. While the distribution systems are the primary focus of GridLAB-D, the transmission module is included so that the interactions between the two systems can be examined. When the integration of these two modules is complete it will be possible to examine how "smart loads" on the distribution system affect the transmission system. Traditionally the ability to examine interactions on this level has been limited by computational power; the use of multiple processors is how this is addressed in GridLAB-D.

A. Transmission Systems Component models

As previously stated, the transmission system is not the primary focus of GridLAB-D. The primary purpose of including a transmission module is to allow for the interconnection of multiple distribution feeders. If a transmission module was not included each distribution feeder could only be solved independent of other feeders. While distribution feeders can be solved independently, as is common in current commercial software packages, GridLAB-D will also have the ability to generate a power flow solution for multiple distributions feeders interconnected via a transmission or sub-transmission network.

In the current version of GridLAB-D the power flow algorithm used for the transmission system is the Gauss-Seidel (GS) method. There are 2 primary reasons why the GS method was selected over other algorithms for the initial transmission module. The first was that GS method is able to solve a single power flow iteration more efficiently that other methods such as the Newton Raphson (NR) method. This is especially important since GridLAB-D will only start from a "flat start" at the first time step and all other solutions will use the solution from the previous synchronous update. This is one of the key differences in GridLAB-D; it is not designed to solve only a single power flow but instead to solve a series of power flow solutions that approximate a time varying condition.

The second reason for the use of the GS solver is that it has many desirable characteristics when implemented in an object orient environment on multiple processors. For example, NR solvers do not lend themselves to parallelization because of the need to invert the Jacobian, which is not an intrinsically parallel process. The GS method, while converging linearly, does so in an intrinsically parallel way [1]. Because GridLAB-D solves a time-series of quasi-steady solution, the number of iteration for either solver is generally very low, and the convergence performance advantage of NR is lost when compared with the high degree of parallelism possible with GS. In addition, the GS solver is more robust when solving from a poor initial "guess" solution. This means that when a large disturbance is evaluated, the solver is more likely to find a solution, even if it takes more iterations.

In the current version of GridLAB-D, the transmission module is capable of solving balanced 3-phase models. Future modules will be capable of solving unbalanced conditions allowing integration of the transmission model with unbalanced distribution models.

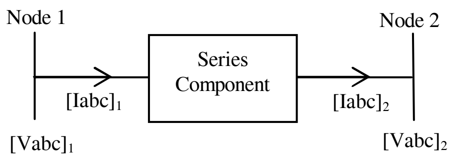
B. Distribution Systems Component models

In order to accurately represent the distribution system the individual feeders are expressed in terms of conductor types, conductor placement on poles, underground conductor orientation, phasing, and grounding [3]. GridLAB-D does *not* simplify the component models of the distribution system.

The distribution module of GridLAB-D utilizes the traditional forward and backward sweep method for solving the power flow problem. This method was selected in lieu of newer methods such as the current injection methods of [2] for the same reasons that the GS method was selected for the transmission module; converging in the fewest number of iterations is not the primary goal. Just as with the transmission module the distribution modules will only start with a "flat start" at initialization and all subsequent solutions will be from the previous time step.

Even thought the forward and backward sweep was chosen as the initial power flow algorithm, the modular nature of GridLAB-D does not prevent the creation of a power flow module that implements other algorithms, as in the case of the transmission module. In fact, in the future it is planned to develop distribution modules with algorithms that are more suited to the analysis of networked distribution systems such as those found in dense urban cores.

The forward and backward sweep use the methods outlined by Kersting et al. [3]. Equations for the forward and backward sweep are shown below:



Backward Sweep

$$[V_{abc}]_1 = [a]\cdot[V_{abc}]_2 + [b]\cdot[I_{abc}]_2 \tag{1}$$

$$[I_{abc}]_1 = [c]\cdot[V_{abc}]_2 + [d]\cdot[I_{abc}]_2 \tag{2}$$

Forward Sweep

$$[V_{abc}]_2 = [A]\cdot[V_{abc}]_1 - [B]\cdot[I_{abc}]_2 \tag{3}$$

The [a], [b], [c], [d], [A], and [B] generalized matrices are developed using characteristics of the individual series components. The matrices are 3x3 and represent three-phase components, but can also represent two-phase and single-phase components by filling in the usused rows and columns with zeroes.

At this time the following components are modeled and available for use:

- **Overhead and Underground Lines**. Multiple configurations, bare conductor, concentric neutral or tape shielded cables.
- **Transformers.** Single-phase or three-phase in most common configurations.
- **Voltage Regulators**. Three-phase Load Tap Changer (LTC) type, 3 - single-phase in Wye and Delta configurations, support for Line Drop Compensation (LDC).
- **Fuses**. Simplified over-current model.
- **Switch**es. Single-phase and three-phase ganged.
- **Shunt Capacitor Banks**. Modeled similar to a load; static, switched, and automatic control are supported.

Metering is supported for both single/split phase and three phase customers. Support for reclosers, islanding, distributed generation models, and overbuilt lines are anticipated in coming versions.

Additionally the ability to model "overbuilt lines" will be included in coming versions. This will be essential in simulations where multiple feeders originate from a single substation. When multiple feeders originate from a single substation it is common for them to share the same support structures, resulting in mutual coupling. The mutual coupling means that the simulation of two feeders, sharing a support structure, cannot be completely decoupled. This result is the necessity to be able to model an n-phase system.

IV. End-Use Load Modeling

Commercial and residential end-uses are implemented using the Equivalent Thermal Parameters model [5]. These are differential models solved for both time as a function of state and state as a function of time. Currently supported residential end-uses are heat-pumps, resistance heating, electric hotwater heaters, washer and dryers, cooking (range and microwave), electronic plugs and lights. Commercial loads are simulated using an aggregate multi-zone ETP model that will be enhanced with more detailed end-use behavior in coming versions.

V. Testing and Validation

Testing on the power system components of GridLAB-D will be done in 2 steps; unit tests, and integrated tests. The unit tests are designed to ensure that the objects that represent individual components, such as a line section, are properly implementing their functions. This is especially important since the distribution system is modeled with in accordance with [3] which give a complete representation of the system.

The second step in testing and validation utilizes the IEEE Distribution Test Feeders [4]. In particular the 4 node, 13 node, and 37 node test feeders were used. By using the IEEE Distribution Test Feeders we confirmed that both the solution method and implementation are functioning correctly in GridLAB-D.

VI. Open Source Distribution

GridLAB-D will be released as an open-source system to a limited group of charter developers in December 2007. This release will be the basis for these selected partners to develop modules they propose in response to a Program Opportunity Notice issue by PNNL on behalf of the US DOE.

A release is planned for October 2008, which will be available under open-source licensing. Industry partners and collaborators are invited to examine and test the system. Modules may be added and submitted to the open-source library. When modules are vetted by the partners, they will be added to the standard release. Unvetted modules will be available as add-ons from the open-source repository, but will not be installed as a part of the standard download available from the repository.

Developers will be permitted to create proprietary modules, however they will be required to distribute required GridLAB-D components free of charge, and provide prominent acknowledgement of the authors and funding used to create those modules. Any changes made to the open-source modules comprising the GridLAB-D system must be resubmitted to the open-source library for distribution.

VII. Conclusion

We have described an open-source system that provides the next generation of power system simulation integrated with end-use modeling and high-performance computing capabilities. This system is to be released to a limited distribution in December 2007 and become widely available after October 2008. The open-source strategy is expected to provide the widest possible user-base for the system and allow for the fast growth of tools that utilize these new capabilities.

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IX. Biographies

David P. Chassin (M'2003, SM'05) received his BS of Building Science from Rensselaer Polytechnic Institute in Troy, New York. He is a staff scientist with the Energy Science and Technology Division at Pacific Northwest National Laboratory where he has worked since 1992. He was Vice-President of Development for Image Systems Technology from 1987 to 1992, where he pioneered a hybrid raster/vector computer aided design (CAD) technology called CAD Overlay™. He has experience in the development of building energy simulation and diagnostic systems, leading the development of Softdesk Energy and DOE's Whole Building Diagnostician. His recent research focuses on emerging theories of complexity as they relate to high-performance simulation and modeling in building controls and power systems and is currently responsible for the design and development of DOE's GridLAB-D simulator.

Kevin Schneider (M'2006) received his B.S. degree in Physics and his M.S. and Ph.D. degrees in Electrical Engineering from the University of Washington. His main areas of research are power system operations and infrastructure interdependencies. He is currently a research engineer at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington. He is also an Adjunct Faculty member at the Washington State University Tri-Cities campus and a licensed Professional Engineer in Washington State.

Clint Gerkensmeyer (M'1999) received the B.S.E. degree in electrical engineering from Arizona State University, Tempe. Currently, he is a power systems research engineer with the Energy Science and Technology Division, Pacific Northwest National Laboratory, Richland, WA. Prior to joining PNNL, he was with Franklin County PUD No.1 and Bonneville Power Administration. He is a licensed Professional Engineer in the State of Washington.