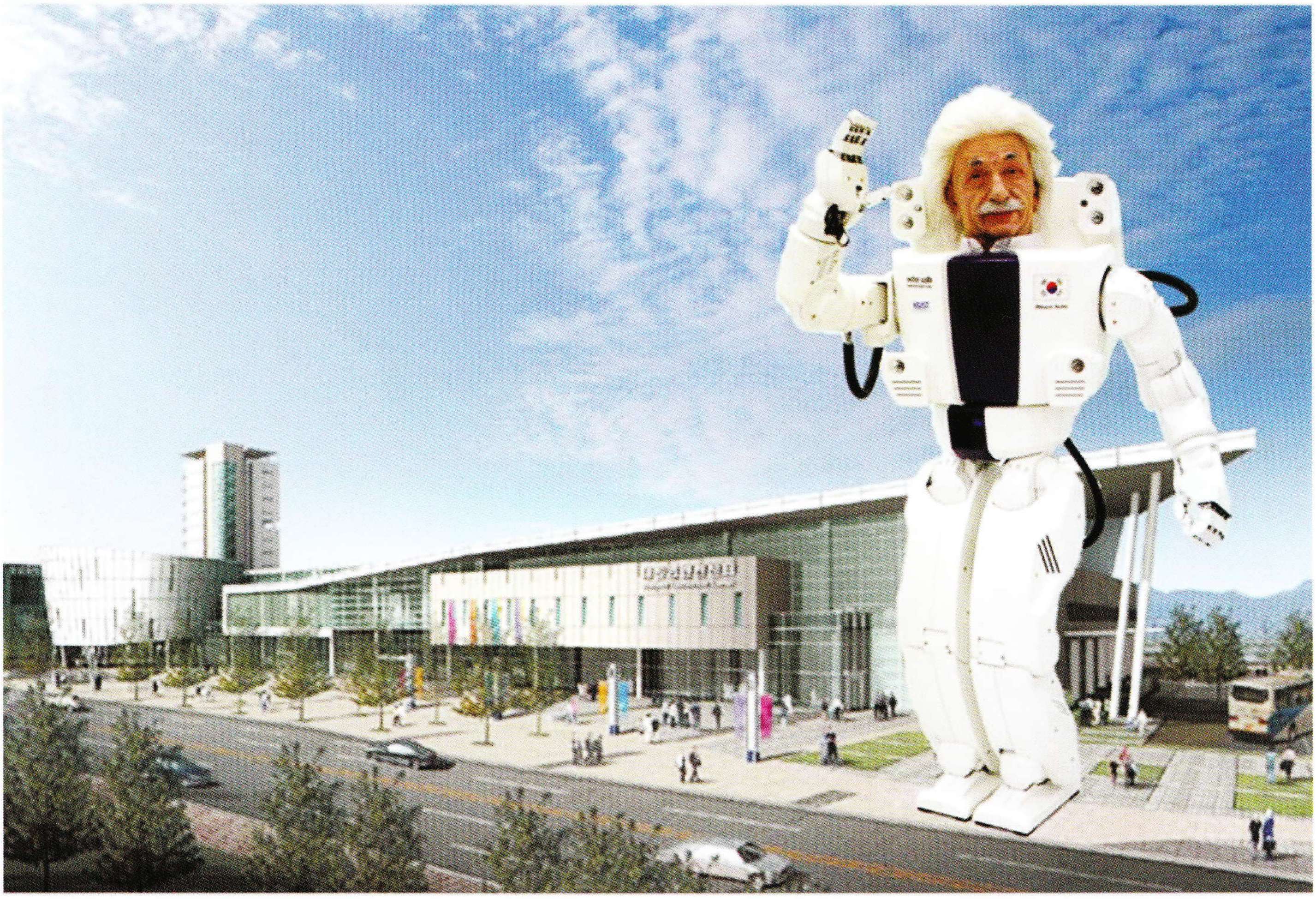
Conference Digest

IEEE INDIN 2008

6th IEEE International Conference on Industrial Informatics

July 13-16, 2008
Daejeon Convention Center
Daejeon
Korea



Sponsored by

IEEE ies o'neida KAIST RMIT University ICROS Institute of Control, Robotics and Systems

M

N

L

The IEEE International Conference on
Industrial Informatics (INDIN 2008)
DCC, Daejeon, Korea July 13-16, 2008

A simulation platform for distributed energy optimization algorithms

Peter Palensky
Lawrence Berkeley National Laboratory, Berkeley, CA
and
University of Pretoria, Pretoria, South Africa
palensky@ieee.org

Friederich Kupzog, Adeel Abbas Zaidi, Kai Zhou
Institute of Computer Technology
Vienna University of Technology
Gusshausstrasse 27-29, A-1040 Wien, Austria
{kupzog, zaidia, zhou}@ict.tuwien.ac.at

***Abstract*—Optimizing the energy system is vital for supply safety and efficient operation. One part of such optimization efforts are demand side measures. This article discusses a simulation platform for automated demand side management, i.e. automated load management. Up to now, the strategies and algorithms that decided where and when to take influence on the loads were very primitive. The complexity of the system did not allow for intuitively designing smarter algorithms. As the energy system is a wide area distributed system, questions about system stability, SCADA (supervisory control and data acquisition), reaction times or the relation to the wider environment (customer processes, energy market, etc.) are very difficult to research. The presented prototype is intended to offer a research platform for evaluating potential algorithms for their real-world usage. All relevant parts of the overall process "intelligent grid" are modeled into the world of discrete event simulation and first implementation results are discussed.**

I. INTRODUCTION

Energy systems around the globe are rapidly moving towards critical operation. Generation and/or transport capacity hit their limits in so called emergency situations, happening almost every year in parts of Europe or USA or even weekly for instance in South Africa. The brute force answer to emergency situations is load shedding: certain regions or certain businesses are disconnected from the grid until the situation gets under control again.

The two factors that lead to this (actually unnecessary) situation are

- the tendency that consumption shows more and more "peakier" patterns, and
- increased competition among utility companies during market deregulation which lead to decreased investment in transport and generation capacity.

We can expect further investment into the energy infrastructure to solve the above problem. Such new infrastructure, however, needs many years to build, costs a tremendous amount of money and might not even be in line with national strategies or public opinion. Luckily there is one methodology that can provide a substantial part of the (although realistically seen, not the entire) desired solution that is relatively afford-able, does not involve new power lines or power stations and does not even generate additional emissions.

As the most critical detail of the demand supply balance is peak load, it helps a lot to work on these few hours a year. Instead of shedding entire districts, smart automated demand response systems selectively duty cycle, switch off or shift loads in a way that no or only a previously defined and agreed upon decrease in customer process value (e.g. thermal comfort in the case of air conditioning systems).

This soft approach implies the following prerequisites:

- Embedded load management nodes at the customer's site (e.g. an IRON box [1] or some sort of Internet relay [2]).
- Knowledge of the customer's process(es).
- An algorithm that reliably optimizes the operation of the given system.

This paper presents the structure of a simulation platform where such algorithms can be investigated. Customer processes can be represented by simple state machines or Markov models and are managed by local instances of a potentially distributed algorithm.

The remaining part of this paper is organized as follows: Section II discusses simulation techniques used in related work and draws conclusions from that. Section III presents the architecture of the proposed DAVIC platform and discusses its features. In Section IV, aspects of implementation are examined and compared to those of conventional approaches. Finally, the conclusions are drawn and an outlook on future work is given.

II. SIMULATION TOOLS AND RELATED WORK

A large variety of simulation tools is available for simulating processes in the power grid. While utility companies and grid operators have their own tailored solutions for performing simulations and estimations of operational aspects of the grid and connected entities, the most widely used tools in research might be *Matlab*, its open-source equivalent *Octave* and *DIg-SILENT Power factory* [3]. This is due to the fact that, for research purposes it is often necessary to implement components

978-1-4244-2171-8/08/$25.00 ©2008 IEEE

into grid simulations that are not available as standard components and therefore require manual modeling and model implementation. While specialized software for utilities or grid operators has fixed built-in functional models, the mentioned simulation software packages allow implementing user-defined models and functionalities. While Matlab/Octave is a very generic simulation platform, "DIgSILENT Power factory" is specialized for grid simulations.

Whenever novel ideas, techniques and technologies in the context of the power grid are to be evaluated, this is first done in simulation due to the high risks and costs of practical implementations. This section focuses on three examples where such new approaches are implemented in simulations and discusses the simulation approach used in each case.

Short et al. presents the concept of frequency response of refrigeration systems in the power grid for demand-side frequency stabilization [4]. Frequency responsive loads may not only be advantageous for stabilizing the grid in emergency situations, but also for efficiency improvement by replacing standby generation units. Short et al. studies the behavior of an isolated power system (UK) under the condition that a large part of the refrigeration load in the system reacts on grid frequency changes by according temperature setpoint changes. Their simulation approach is to model the essential parts of the power grid using basic control-theory equations for generator behavior, inertia and frequency dependency of electric machines. Also for the thermal behavior of the refrigeration loads, detailed models are derived using differential heat-flow equations. All differential equations are then discretized for a time-domain simulation with a constant time step. In order to keep the complexity of the simulation model of the grid in bounds, a lot of reasonable simplifications are introduced, such as the "copper plate" assumption for the transmission system etc. Although it is not explicitly stated in [4], the simulation (repetitive evaluation of the model equations) must have been performed with a generic tool such as Matlab or Octave. The advantage of this equation-based approach is that the performer of the simulations knows exactly how the modeling of all components looks like (no predefined "black box" model of a simulation package is used) and which effects are considered within those models and which are not. The disadvantage of the approach is that a set of equations can become very bulky as soon as the simulation becomes more detailed and therefore more complex.

A similar frequency-response concept is proposed in [5]. Here, however, the DIgSILENT Power factory software was used and similar results to [4] are achieved. While the generator and grid models used were the predefined ones of the simulation software package, the refrigeration loads had to be modeled manually and this model had to be implemented into DIgSILENT. The advantage of this approach is that the modeling process is simplified by the possibility to make use of predefined models for standard grid components. However, this comes along with a loss of detail knowledge about the actual implantation of the standard models.

In the third example, the "DG DemoNet" project [6][7], both Matlab and DIgSILENT are used. Within the project, novel approaches for on-line voltage control in medium-voltage grids performed by generators (reactive power management) and on-load tab changers are examined. The grid simulation is done in DIgSILENT due to the above stated advantages of this approach. Also, existing grid segments are studied, so DIgSILENT was chosen since it is conceptually closer to the specialized tools used by the grid operators who provided the base data for simulations. Nevertheless, the new control techniques were implemented in Matlab because the control algorithms are too complex to be implemented with the restricted description language provided by DIgSILENT. This results in very time-consuming data exchange between the two simulation programs during runtime in each simulation step. At a time step of 6 s, simulations of a medium voltage grid with a few hundred nodes can take several hours on up-to-date computer hardware. This simulation approach can be classified as an engineering solution which serves the purpose but is not the most elegant solution.

Alternatives are generic and cross-domain simulation platforms like Modelica[1] or platforms from similar domains like Ptolemy[2]. As the final focus of this project is on the communications part and the distributed algorithms, we finally went – for the time being – with a tool out of telecommunications research.

The following lessons are learned:

- Simulation tools differ in there specialization and support different levels of model complexity on one hand and number of interconnected models on the other.
- The concept of object orientation (as it is used by more specialized tools like DIgSILENT) is very advantageous as model hierarchies become more complex.
- None of the currently available mainstream simulation tools offers the object orientation feature combined with enough flexibility that is needed for realizing novel and elaborated research-level concepts for grid operation in a simulation environment.

III. Simulation Platform Architecture

The need of a new research-oriented and object-oriented simulation platform is identified by the authors as an outcome of previous work of which some examples are presented in section II. This platform should allow not only to simulate conventional power grid issues (energy flows), but also com-

[1] www.openmodelica.org
[2] ptolemy.eecs.berkeley.edu

munication processes (information flows) and in future even economic problems (money flows).

A. Needs for communication in power grid

The rapidly increasing electricity demand leads to the need for building new generation facilities, which is a capital intensive and time consuming process. The gap between increasing demand and limited generation of electricity will become critical soon. That will lead to collapse of reliability in the power system as a whole and consistent supply for a consumer will be at high risk [1]. In the light of these facts, efficient use of electrical energy and an increased flow of information between participants of the grid are essential. With a communication infrastructure in place, every member of the grid (distributed generation, end customer, etc.) is able to participate actively in the energy business. At present, large power plants can communicate to each other and coordinate their behaviors according to the market situation while on the other hand, at the customers' end, there is no infrastructure to optimize the utilization of energy. The increasing mismatch of energy supply and demand reveals the need of having a robust IT and communication solution in the energy sector. Consumers have always been considered as passive players. The inclusion of communication technologies in the power system will enable consumers to react on grid parameters like frequency and power in terms of their energy consumption, which will maintain the reduction of demand during peak load hours and will increase the security of supply.

B. DAVIC architecture

This paper presents the design of a simulation platform "Distributed Automation Via Implicit Channels" (DAVIC) using OmNet++ as underlying tool. Motivation of DAVIC is to provide a fast and reliable simulation platform that can simulate and compare different energy management algorithms like frequency-response algorithms and peak-demand reduction algorithms, etc. Fig. 1 shows the DAVIC modeling approach.

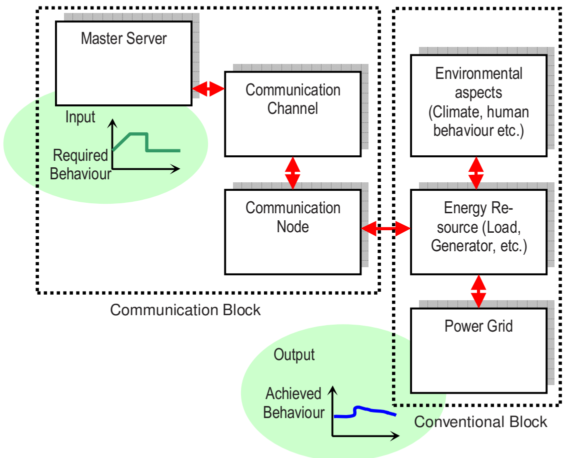


Fig. 1. DAVIC Component Modeling Approach

Fig. 1 shows two blocks represented by dotted lines. The conventional part represents the power system modules that are usually considered during the simulation of any traditional power system problem. An additional module "environmental aspects" is also utilized in this block in order to integrate the possible effect of environment like climate conditions, special events or human behavior, etc. on the energy consumption. It is evident that energy utilization is affect by the weather conditions or a live broadcast of soccer match between Austria and Germany.

The communication block contains the management and communication modules, which are responsible for the interaction among the participants of a power system. The communication node is responsible of collecting local information from the attached energy resource and takes some real-time decisions based on the control algorithm which is tested in the simulation. Every communication node has to get registered to the master server, which can serve as a central node for data exchange and might also be a system of multiple servers for scalability reasons. The node sends its information to the master server through diverse communication channels, like internet connectivity via Wi-Fi, WiMAX or GPRS etc. The master server keeps track of the whole system by registering every communication node and monitoring its status.

C. OmNet++

As a discrete event simulation tool, the primary application area of OmNet++ is the simulation of communication networks. Due to the requirements of communication in power grid, we propose to introduce a network simulator into grid simulation. OmNet++ is a very advisable selection on account of its generic and flexible architecture, which makes it easy to be used in power grid simulations. Potentially continuous processes, however must be translated in discrete ones for increased simulation performance (although OmNet++ is actually capable of dealing with continuous models).

In this work, the simulation kernel and utility classes of OmNet++ are utilized to create a testbed, which will serve as a platform for experimenting with large electric power systems.

IV. SIMULATION

A. Conventional Approach

The conventional approach in power grid simulation uses aggregate models for generators and loads and describes the behavior of these (preferably few) components by differential equations.

On the generation side, base-load generators can be aggregated as well as generators for primary and secondary response can be aggregated to a single generation model, as long as the grid is assumed to be ideally conducting. Typically, the primary response capability of generators is modeled using a 4% "droop" characteristic [9]. This means relative to a 4% drop in frequency, the output of generator will increase by 100%. Similar simplifications can be done for secondary response.

Load modeling is more complex. Since there are no restrictions for consumers when to switch on or off their electric loads, the modeling and forecasting of the demand side of the electric power grid is traditionally a wide-reaching discipline that has to take into account a number of different influences namely social behavior, climate, special public events, etc. One conventional approach for modeling the demand side is the use of so-called "synthetic load profiles" [8]. Synthetic load profiles are mainly used (and were initiated) by the power supplying industry and serve as reference load profiles for consumers who do not have on-site load management. Synthetic load profiles are the result of a statistical analysis based on representative samples from different consumer groups: households, shops (different groups for different opening hours) and industry (different groups for different working hours).

Having modeled the generated power and the load Power, the balance between supply and demand, *PB* is then calculated as:

$$PB = PG - PL \tag{1}$$

where the total generated power is *PG* and *PL* is the total demand of power. When the value of *PB* is negative, this means supply is less than demand, and thus grid frequency will drop, and vice-versa.

In the simulation, a model of the grid's inertial energy store can be utilized to simulate the complex multi-generators system and all the inertia can be assumed to be accumulated in a simple flywheel module, *I*, swiveling in terms of grid frequency, $\omega = 2\pi f$ rad s^{-1}. Consequently, the sum of energy stored is:

$$Energy = \frac{1}{2} \cdot I \cdot (2\pi f)^2 \tag{2}$$

For calculation of *I*, an inertial time constant *H* is used to measure the capacity of energy storage in a power system. The constancy of this number is provided by [9] and also used to calculate the frequency by [4]. For this study, this constant is assumed to be 4 s throughout as [4] and *I* is therefore calculated as:

$$I = \frac{2 \cdot PG \cdot H}{\omega_{normal}^2} \tag{3}$$

An iterative formula provides the update of grid frequency with the inertial energy storage. Supposed that for each simulation time step, *dT*, energy is conserved, then

$$Energy_{t+dT} = Energy_t + PB \cdot dT \tag{4}$$

accordingly

$$f_{t+dT} = \frac{1}{2\pi} \cdot \sqrt{(2\pi f_t)^2 + \frac{2 \cdot PB \cdot dT}{I}} \tag{5}$$

B. Event-based DAVIC Approach

Since the system is designed as a distributed automatic network, an array of controllable loads is used instead of aggregated simulation model. Each load is accessed and controlled by a demand side governor (communication node) which is connected to a supporting communication network. The total power demand is described as:

$$PL = \sum_{i}^{n} P_i + PL_{fixed} + PL_{released} \tag{6}$$

$$P_i = \begin{cases} Pel_i & if\ switch-on \\ 0 & if\ switch-off \end{cases} \tag{7}$$

Where Pel_i is the electric power consumed by load i. This parameter is randomized within ±5% at the initialization step of the simulation.

With the intention of this event-based and distributed study, 1000 independent refrigerators are simulated. Their behaviors, such as switching, frequency measurement, temperature setting and even open door, all can be realized as the events in OmNet++ through message transmission. No significant difference was found in the experiments using more than 1000 individual models (maximum 10000 models were conducted).

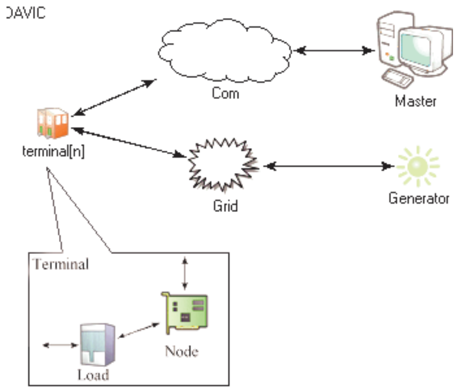


Fig. 2. Layout of the simulation models in OmNet++

As illustrated in Fig 2, models are connected into a simulation network. During each simulation cycle, the temperature of each refrigerator is recalculated. If the value of temperature is out of set point range, then a switching message is generated by load model (fridge) and sent to the grid model. Please note that the refrigerator is just a dummy for all thermostat controlled processes (e.g. heating and air conditioning or large office buildings) or other processes with thermal mass or inertia. The grid model calculates total demand using all the switching messages which are received from load model in the same cycle. Generator model creates and sends the supply message which is mutated by sudden loss event. Statistics of total supply is also implemented by grid model. Frequency is calculated using the imbalance between supply and demand, the frequency message is generated and broadcasted to every terminal. Due to the discreteness of OmNet++, the frequency message broadcast is periodically implemented to simulate frequency measurement behavior. Loads and generator respond to these frequency messages and after the process of themselves, switching messages and supply message are sent again. The process of simulation is construed as follows:

1. Initialization: Load models randomize their power consumption and temperature set point. Generator model initializes its supply power.
2. Message dispatch: Switching and supply messages are sent respectively from load models and generator model.
3. Frequency update: Grid model gathers all switching and supply messages, calculates imbalance and frequency and periodically broadcasts.
4. Generator response: Generator responds to the frequency message, recalculates power generation and sends supply message.
5. Loads response: Loads respond according to the frequency message, recalculate temperature, change the status and send switching message if necessary.
6. Goto step 3.

Terminal models, communication model and master model compose a non-real-time network, where the control and register messages are scheduled and transmitted. Since OmNet++ is designed for such kind of communication networks, detail characteristics (such as latency, packet loss rate and collision probability etc) are easy to be realized and controlled.

In this early stage of the DAVIC project, only very simple models are used for each of the modules shown in Fig. 1. As mentioned before, [4] is used as a reference scenario. Consequently, no communication is needed, so the modules of master server and communication channel are empty. A basic frequency response algorithm is implemented for testing purpose. Every load's set point of temperature is linearly changed according to the grid frequency. This leads to a reduction in dynamic demand when the grid frequency drops. The simulation results of a single refrigerator are shown in Fig. 3, where the power consumption, temperature difference between inside and outside are simulated.

The results of system frequency and total loads are shown in Fig. 4. Fig. 5 depicts the influence of sudden power loss and recovery events on a single refrigerator over time (given in seconds).

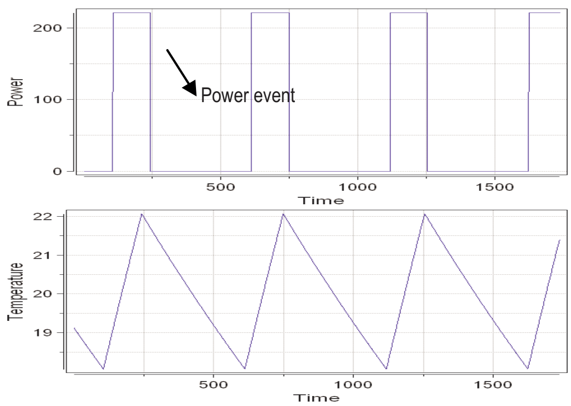


Fig. 3. Single refrigerator simulation results of power and temperature

Traditional spinning reserves are not provided in the simulation, as the replacement, every dynamic demand changed its consumption of energy, endeavoring to stabilize grid frequency. Thus, power generation in DAVIC simulation is invariant except that the sudden-loss event happens.

C. Discussion

For performing a cross platform comparison, an example power system according to the discussions in [4] has been simulated in Matlab and using the DAVIC platform. These details of the simulation are provided in table 1. The system of simulation is subjected to a sudden-loss event that is launched by the generator model. Responses to this sudden loss of generation are investigated in terms of grid frequency and dynamic load.

TABLE I. PARAMETERS OF SIMULATION

Parameter	Value
Fixed generation	3.732×10^{10}W
Sudden loss	1.32×10^{9}W
Fixed loads	3.6×10^{10}W
Spinning reserve	1.32×10^{9}W
Total average dynamic loads	1.32×10^{9}W

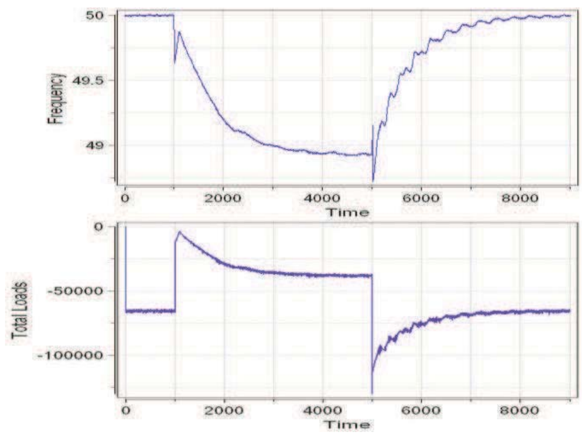


Fig. 4. Simulated system frequency and total loads with a sudden loss of 1320 MW of generation which is then recovered at Time = 5000s

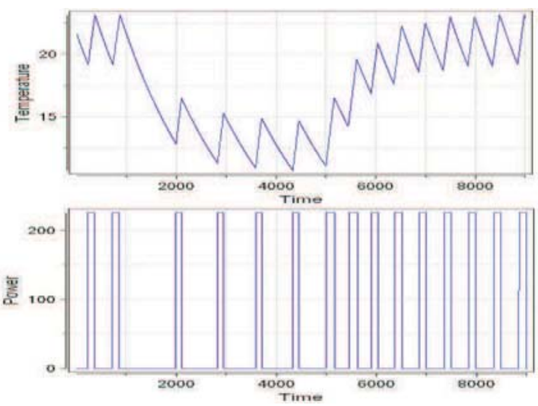


Fig. 5. Single refrigerator simulation results of power and temperature resulting from a sudden loss of 1320 MW of generation which is then recovered at Time = 5000s

While there is no difference of simulation *results* between two approaches, a number of differences in the way how these results were obtained have become obvious. The conventional approach runs much faster and the memory requirement of the program is also less than that of DAVIC approach. However, the significant contribution of DAVIC is, that it is not only an object oriented, reusable, flexible and modular platform but its most important feature is that it uses events to enable interaction of simulation modules. It is also based on a communication network simulation tool. Hence, the distributed control algorithms can be plugged into it, very easily in future.

V. Conclusion and Outlooks

A new platform for developing, testing and investigating distributed energy systems is presented. The platform is not a solution to given optimization or control problems, it is a means of researching potential solutions. Up to now, there is no such tool available, which is one reason why demand response automation is still done very conservatively. This tool is intended to shed light onto the unknown mechanisms of this complex system.

After setting up the platform it will be the task to model all existing client processes as well as the grid and generation characteristics. For this paper, first and simplified models were chosen, later these will be refined and extended if necessary. During the next months more realistic models of commercial, industrial and residential loads will be implemented. Another category of components that will be added is distributed generation like photo voltaics or wind power.

The platform itself has up to now proved its usefulness. One unknown factor is, however, scalability. If the given platform does not scale well if the number of nodes goes into hundreds of thousands, the simulation platform might be re-implemented on an alternative system (e.g. Ptolemey) or a dedicated and specialized platform must be developed from scratch. A possible alternative would be to utilize cluster computing to simply increase the computational power of the hardware.

The chosen path of discrete event simulation might not be ideal for every detail that needs to be investigated. Some loads might for instance need dynamic/continuous simulations to be correctly represented in a simulation environment. The strategy within DAVIC is to transfer all that behavior into as-simple-as possible models, ideally based on paradigms suitable for and fast in discrete event programming (e.g. state machines, lookup tables), since it is not the customer process which is the focus of the research but rather the behavior of the distributed system under special circumstances.

The typical, envisioned, usage of DAVIC is the case when a new optimization idea (i.e. algorithm) is supposed to be analyzed for its performance (timing, costs, stability, etc.). All performance parameters are evaluated by a set of standard tests that expose the algorithm to a variety of challenges or stimuli like grid failure,

- grid overload,
- communication failure or
- oscillating demand.

Especially the case when a previous design reason changes (e.g. the costs for GPRS based communication change or a previously unknown technology is now available), algorithms and entire systems might need a substantial redesign for optimal performance. These redesigns can easily be evaluated with DAVIC. Another aspect of communication that can easily be studied with this platform is the reliability and costs of communication (dial-up connections might need minutes to connect, might fail at all and if they work they cause costs).

The next steps for DAVIC are the extension of the client processes, scalability investigations and potential extensions of the grid sub process towards load flow analysis.

References

[1] C. Roesener, P. Palensky, M. Weihs, B. Lorenz M. Stadler, “Integral Resource Optimazation Network – a new solution on power markets”, 3rd IEEE International Conference on Industrial information, August 2005.

[2] Piette, M.A., Watson, D. S., Motegi, N., Kiliccote, S., Linkugel, E.: „Participation through Automation: Fully Automated Critical Peak Pricing in Commercial Buildings“; Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August 13-18, 2006.

[3] DIgSILENT, “Power Factory Version 13 .2 User Manual”, 2006.

[4] Short, J. A., Infield, D. G., Freris L. L.: Stabilization of Grid Frequency Through Dynamic Demand Control, IEEE Transactions on Power Systems, Vol. 22, No. 3, August 2007.

[5] Xu, Z.;, Ostergaard, J., Togeby, M., Marcus-Moller, C.: Design and Modelling of Thermostatically Controlled Loads as Frequency Controlled Reserve, IEEE Power Engineering Society General Meeting, June 2007.

[6] Lugmaier A., Brunner A., Bletterie B., Kupzog F., Abart A.: Intelligent Distribution Grids in respect of a growing share of Distributed Generation, 19th International Conference on Electricity Distribution (CIRED 2007), Vienna, Austria, May 2007.

[7] Kupzog F., Brunner H., Prüggler W., Pfajfar T., Lugmaier A.: DG DemoNet-Concept - A new Algorithm for active Distribution Grid Operation facilitating high DG penetration, 5th International IEEE Conference on Industrial Informatics (INDIN 2007), Vienna, Austria, July 2007.

[8] Fünfgeld, C.: Repräsentative VDEW-Lastprofile, EUROFORUM Fachkonferenz Netznutzungs- und Bilanzkreismanagement, Berlin, Jul. 2000

[9] P.Kundur, *Power System Stability and Control*. New York: McGraw-Hill, 1993, pp. 581–592.