

Lawrence Berkeley National Laboratory

LBL Publications

Title

Hardware-in-the-Loop Co-simulation of Distribution Grid for Demand Response:

Permalink

<https://escholarship.org/uc/item/402215q5>

Authors

Rotger-Griful, Sergi
Chatzivasileiadis, Spyros
Jacobsen, Rune H.
et al.

Publication Date

2016-06-20



Lawrence Berkeley National Laboratory

Hardware-in-the-Loop Co-simulation of Distribution Grid for Demand Response

Sergi Rotger-Grifol¹, Spyros Chatzivasileiadis², Rune Hylsberg Jacobsen¹, Emma M. Stewart³, Javier Matanza Domingo⁴ and Michael Wetter³

¹Department of Engineering, Aarhus University, Aarhus, Denmark

²Massachusetts Institute of Technology, Cambridge MA, United States of America

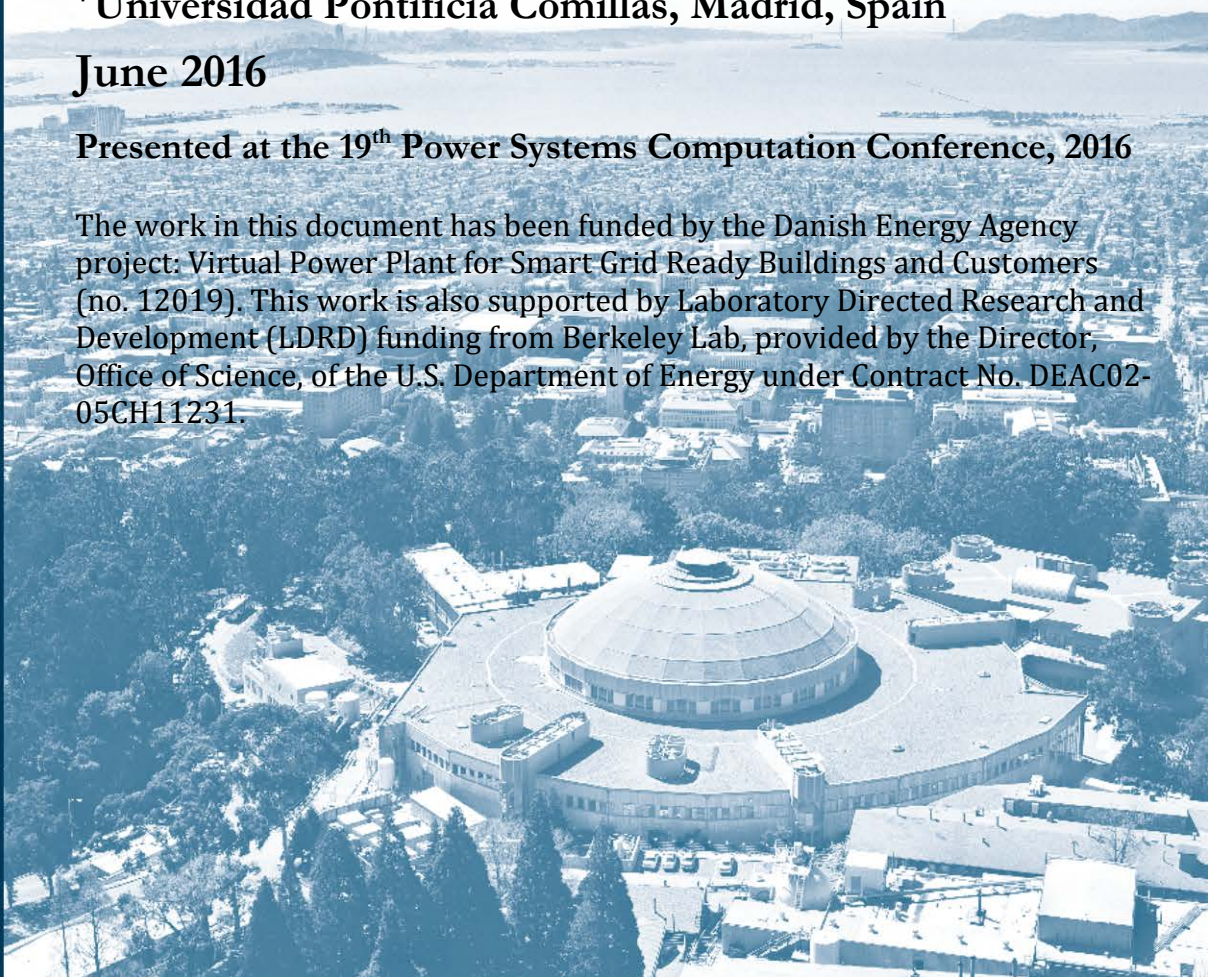
³Lawrence Berkeley National Laboratory, Berkeley CA, United States of America

⁴Universidad Pontificia Comillas, Madrid, Spain

June 2016

Presented at the 19th Power Systems Computation Conference, 2016

The work in this document has been funded by the Danish Energy Agency project: Virtual Power Plant for Smart Grid Ready Buildings and Customers (no. 12019). This work is also supported by Laboratory Directed Research and Development (LDRD) funding from Berkeley Lab, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DEAC02-05CH11231.



Disclaimer

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California.

Hardware-in-the-Loop Co-simulation of Distribution Grid for Demand Response

Sergi Rotger-Griful*, Spyros Chatzivasileiadis[†], Rune Hylsberg Jacobsen*, Emma M. Stewart[‡],
Javier Matanza Domingo[§] and Michael Wetter[‡]

* Department of Engineering, Aarhus University, Aarhus, Denmark

[†] Massachusetts Institute of Technology, Cambridge MA, United States of America

[‡] Lawrence Berkeley National Laboratory, Berkeley CA, United States of America

[§] Universidad Pontificia Comillas, Madrid, Spain

Abstract—In modern power systems, co-simulation is proposed as an enabler for analyzing the interactions between disparate systems. This paper introduces the co-simulation platform Virtual Grid Integration Laboratory (VirGIL) including Hardware-in-the-Loop testing, and demonstrates its potential to assess demand response strategies. VirGIL is based on a modular architecture using the Functional Mock-up Interface industrial standard to integrate new simulators. VirGIL combines state-of-the-art simulators in power systems, communications, buildings, and control. In this work, VirGIL is extended with a Hardware-in-the-Loop component to control the ventilation system of a real 12-story building in Denmark. VirGIL capabilities are illustrated in three scenarios: load following, primary reserves and load following aggregation. Experimental results show that the system can track one minute changing signals and it can provide primary reserves for up-regulation. Furthermore, the potential of aggregating several ventilation systems is evaluated considering the impact at distribution grid level and the communications protocol effect.

Index Terms—Demand Response, Co-simulation, Functional Mock-up Interface, PowerFactory, Hardware-in-the-Loop.

I. INTRODUCTION

In the energy system of the future, with high penetration of Renewable Energy Sources (RES), online, dispatchable power system support services will be required to efficiently integrate RES and to provide stable grid operation. Demand response is at present utilized as a bulk power system support service, which could be a promising distribution grid support mechanism with the appropriate specificity and controls. Demand response can potentially benefit system operation, expansion, and market efficiency while reducing the overall plant and capital cost investments [1]. Furthermore, demand response can be utilized to defer the need for power grid upgrades [1].

Demand response is provided by reducing or shifting electricity usage during peak periods in response to an external

trigger and by following a predefined control strategy [2]. Recently, it has been demonstrated that this process can be automated and applied to commercial buildings to provide demand response adapted to the ancillary services market [3]. Prosumers, proactive consumers that engage in demand response, offer flexibility for certain appliances and local generation units. Flexibility is provided by trading off convenience in daily practices and comfort e.g., by relaxation of indoor climate metrics. Demand response provision requires an Information and Communications Technology platform to provide management, aggregation, and scheduling of a large number of domestic appliances with flexible consumption [4], [2].

The success of a demand response strategy at present is limited by the lack of suitable tools for assessment of its potential and detailed understanding of causality. To circumvent this, simulation techniques may be used to evaluate a targeted demand response prior to any market control actions. Specifically, co-simulation, which offers the advantage of combining domain-specific simulators, such as distribution grid planning models, and communications, enables the evaluation of demand response from a holistic and detailed perspective with a stronger foundation in building operations practices. In this paper, the co-simulation platform Virtual Grid Integration Laboratory (VirGIL) developed at Lawrence Berkeley National Laboratory is introduced and utilized to demonstrate its potential to assess demand response strategies [5]. VirGIL enables simple integration of new simulators and combines the state-of-the-art simulators in power systems, communications networks, modeling of buildings, and control engineering. Hereby, VirGIL aims at reducing the barriers of the industry to adopt new demand response programs.

The main contribution of this paper is the coupling of a co-simulation environment with a Hardware-in-the-Loop (HiL) infrastructure for demand response assessment. Demand response is evaluated by using a ventilation system of a multi-tenant residence integrated with the VirGIL co-simulation framework. The evaluation methods combine state-of-the-art tools for co-simulating power grid response with interactions of a running system of a building used as a living lab in Denmark [2]. To our knowledge, this is the first contribution to couple co-simulation with HiL to evaluate demand response in large residential buildings.

The work in this document has been funded by the Danish Energy Agency project: Virtual Power Plant for Smart Grid Ready Buildings and Customers (no. 12019). This work is also supported by Laboratory Directed Research and Development (LDRD) funding from Berkeley Lab, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Additionally, we would like to express our gratitude to NRGi for sharing distribution grid data with us.

The paper is organized as follows. Section II presents the realted work on co-simulation for power systems. Section III introduces VirGIL. The case study is described in Section IV. The experimental and simulation results are presented in Section V and Section VI concludes the paper.

II. CO-SIMULATION FOR POWER SYSTEMS

One of the first documented applications of co-simulation of power systems, EPOCHS, included a communication system component [6]. The authors advocate using existing simulation tools that excel in their respective fields, instead of creating new simulation platforms. EPOCHS simulates power systems with fixed steps using PSCAD/EMTDC for electromagnetic and PSLF for electromechanical power system simulations, and communications simulations using the discrete event simulator ns-2. These tools exchange data at pre-specified synchronization points. In [7], the authors improved the algorithm to provide a common timeline for both modules, thus reducing the accumulation of synchronization-induced inaccuracies.

Until recently, most co-simulation approaches for power systems add a communication network simulator. Examples for distribution networks are [8], [9]. The authors in [10] report a co-simulation approach for power systems and electric vehicle charging and control; this work uses Functional Mockup Interface (FMI) to interface with one of the simulation tools. Among power system tools that can operate in co-simulation environments, GridLab-D is probably one of the most widely used [11]. In addition to power systems, it incorporates load modeling, rate structure analysis, distributed generation, and distributed automation. See [12] for a comprehensive survey on tools used for co-simulation of power systems.

Concerning the co-simulation environment used in this paper, VirGIL uses a commercial software, DigSILENT PowerFactory, for power systems simulation. A co-simulation incorporating PowerFactory has also been reported in [13]; however, VirGIL is the first co-simulation platform that used an open industrial standard (FMI) to couple PowerFactory to other simulation tools, thus allowing a higher interoperability.

In order to predict how actual devices will interact in complex environments, co-simulation platforms can be enhanced with Power Hardware-in-the-Loop (PHiL). PHiL applications do not only include the controller of the device as a real piece of hardware, but rather the whole device is included, e.g., besides the thermostat controller, the ventilation system is also connected to the simulation platform. This paper reports one of the first efforts for co-simulation platforms to include PHiL, henceforth referred as HiL. A similar effort is reported in [14] where a co-simulation environment using GridLab-D was coupled with two residential-scale advanced solar inverters.

The focus of this work is on the interactions between distribution systems, buildings, and control, and introduces a HiL interface to test demand response strategies in real time.

III. VIRGIL OVERVIEW

VirGIL is a modular co-simulation platform developed at Lawrence Berkeley National Laboratory [5]. VirGIL enables

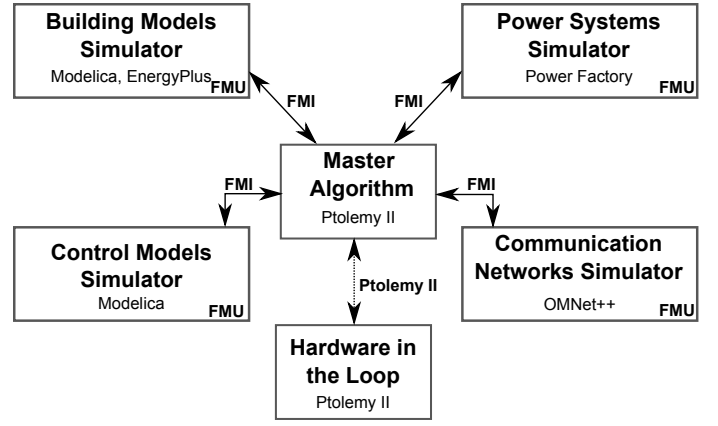


Figure 1. VirGIL Architectural Overview.

co-simulation using different simulators in power systems, communications networks, modeling of buildings, and control engineering. The modular architecture developed in VirGIL allows switching to other power system models as needed, incorporating either open source research tools or commercial tools employed by utilities like PowerFactory [15]. VirGIL can be used by different stakeholders to assess novel strategies for energy, controls and communication systems in a holistic and dynamic way. Fig. 1 shows the architectural overview of VirGIL with its different components and communications.

The communication between the different components is done using the standard FMI [16]. FMI supports both model exchange and co-simulation using C-code and XML files. Each simulation module is called a Functional Mockup Unit (FMU). Each FMU consists of a zip file containing source code to run the simulations and a XML file with general information of the unit (e.g., inputs and outputs). One main advantage of using FMI is that it is an international standard, supported by more than 70 tools, that enables the integration with any FMI compliant software (EnergyPlus, Modelica, and others).

The master algorithm that coordinates the data exchange between all components is developed in Ptolemy II [17]. For the co-simulation of cyber-physical systems such as encountered by VirGIL, Ptolemy II has been extended. These extensions are available in a special Ptolemy II configuration called CyPhySim [18]. Ptolemy II is a Java-based modular software where the different modules are actors communicating with each other using ports. Each of the simulators labeled with FMU in Fig. 1 is encapsulated as a FMU actor. The data exchange between all the modules is managed by a director. Using Ptolemy II for the master algorithm eases the assessment of adding new modules. An example of this is the actor used to communicate with real hardware in a HiL simulation. In this work, this integration has been done directly in Ptolemy II.

The current version of VirGIL uses PowerFactory as power system simulator, OMNeT++ for the communications network simulator, and Modelica for the building model and control. To enable HiL simulation, Ptolemy II environment is used. See [5] for a more detailed description of VirGIL.

IV. CASE STUDY DESCRIPTION

VirGIL is used here to analyze the demand response potential of controlling a ventilation system on a large residential building located in Aarhus, Denmark. The test bed is Grundfos Dormitory Lab (GDL) and is a 12-story building that hosts 180 students living in small apartments (i.e., maximum 40 m^2). The building is equipped with 3,400 sensors reporting data on electricity consumption, water usage, indoor climate conditions, and many others [2].

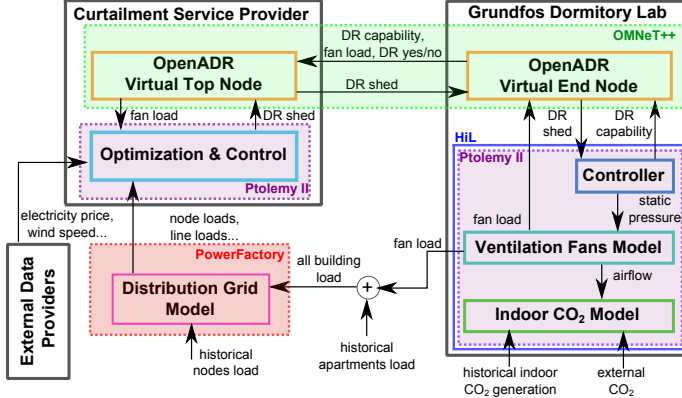


Figure 2. Overview of Grundfos Dormitory Lab Case Study for Demand Response (DR) Assessment with VirGIL.

Fig. 2 shows an overview of the different components of the VirGIL case study. The *Optimization & Control* module of the *Curtailment Service Provider* gathers data from *External Data Providers* (e.g., electricity prices) and from the *Distribution Grid Model* simulated in PowerFactory. These data is used to trigger demand response strategies transmitted to GDL using OpenADR protocol simulated in OMNeT++. OpenADR messages are then processed by the *Controller* and translated into control commands to regulate the *Ventilation Fans Model* simulated in Ptolemy II. The operation point of the ventilation system affects the *Indoor CO₂ Model* developed in Ptolemy II. In the HiL simulation, all the models encapsulated in the blue-solid line are replaced by real hardware components of GDL.

A. Distribution Grid Model

The distribution grid is simulated by using PowerFactory from DigSILENT, a commercial power system software. While the rest of FMUs run on Linux, PowerFactory can only run on Windows. In order to solve this incompatibility, the Windows machine with PowerFactory uses a web server that, through socket communication, interacts with the power FMU located in the Linux machine. The web server controls PowerFactory using the Python Application Programming Interface (API) provided by DigSILENT.

The distribution grid is modeled up to the first transformer substation as shown in Fig. 3. This transformer has a rated power of 630 kVA and provides electricity to 9 feeders, that correspond to 5 large residential buildings, GDL being one of them. All the grid data has been provided by the Danish Distribution System Operator (DSO) NRGi. The

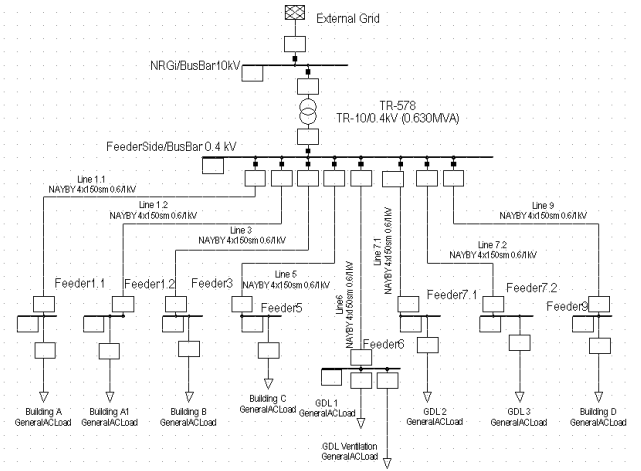


Figure 3. Grundfos Dormitory Lab Distribution Grid Model.

actual electricity consumption in GDL is available from its monitoring infrastructure. It has been assumed that the other buildings have a similar daily load profiles having their peak consumption at 18:00 Central European Time (CET).

B. Communications Network Model

The open-source software simulator OMNeT++ was chosen to model the communication of demand response messages. OMNeT++ is composed of C++ files that model the behavior of the different modules that are later instantiated and linked using Network Description Language files (OMNeT++ specific language). OpenADR has been chosen as protocol for the exchange of demand response messages between different stakeholders [19]. This protocol is widely used by industries in the United States of America. OpenADR is a client-server protocol composed by two node types: Virtual Top Nodes (VTNs) and Virtual End Nodes (VENs). VTNs send messages about events to other nodes while VENs are able to respond to these messages. Since OpenADR messages relies on the Internet Protocol stack, this communication has been modeled using the INET module in OMNeT++. INET is a module suited for network modeling that includes protocols like Ethernet, IPv4, IPv6, TCP, UDP, and HTTP among others.

In this case study, the model is composed by one OpenADR VTN (server) and one OpenADR VEN (client). The server can send load shed requests to the client while the client can send its current demand response capabilities, the load consumed and respond to the load request from the server. However, these messages are not delivered instantaneously. Therefore, the purpose of this FMU is to emulate the delay in real communication networks when transmitting these signals.

C. Controller, Ventilation Fan, and Indoor CO₂ Models

The fan *Controller* is modeled in Ptolemy II and translates load shed messages to control signals (static pressure setpoints). The *Ventilation Fan Model* is simulated using Ptolemy II. This model is developed and reported in previous work of the authors and is based on ideal equations that relate

two different operating points of a fan [20]. The equation describing the power consumption as a function of the static pressure is shown in Eq. 1. P_{fan} is the power consumption, p_s is the static pressure, $p_{s,ref}$ is the static pressure reference point for the fan, P_{ref} is the power consumption reference for the fan, and n_1 is an exponent that in ideal conditions is $\frac{3}{2}$. The ventilation system in GDL is composed by two fans: supply and exhaust. The exponents n_1 of both fans have been determined from measurements, leading to values of 1.21 for supply fan and 0.81 for exhaust fan.

$$P_{fan}(p_s) = \left[\frac{p_s}{p_{s,ref}} \right]^{n_1} P_{ref} \quad (1)$$

The airflow is obtained as shown in Eq. 2. Q is the airflow, p_s is the static pressure, Q_{ref} is the reference airflow for the fan, $p_{s,ref}$ is the reference static pressure for the fan, and n_2 is an exponent that in ideal conditions is $\frac{1}{2}$. The exponent n_2 has been determined for the supply fan as done for n_1 , leading to a value of 0.63. This is also modeled in Ptolemy II.

$$Q(p_s) = Q_{ref} \left[\frac{p_s}{p_{s,ref}} \right]^{n_2} \quad (2)$$

The indoor CO_2 level is modeled with the differential equation Eq. 3. V is the volume analyzed, C is the indoor CO_2 concentration, Q is the airflow, C_{out} is the outdoor CO_2 concentration, and G is the CO_2 generated indoors from human activity. For GDL everything is known but the indoor CO_2 generation G . A time series of the evolution of G has been obtained from measurements from CO_2 sensors in all apartments. The indoor CO_2 level is modeled in Ptolemy II. See [20] for further details on these models.

$$V \frac{dC}{dt} = Q(C_{out} - C) + G \quad (3)$$

D. Hardware-in-the-Loop

To enable the HiL simulation the ventilation system in GDL has been developed and integrated with components for remote control and monitoring over the Internet. The fans can be regulated and monitored through a secured RESTful API, which translates HTTPS messages into Modbus messages and sends them to the Air Handling Unit (AHU) of the ventilation system. Details on this installation are available in [20]. The *SystemCommand* actor in Ptolemy II has been used to execute a Python code to communicate with the real system by sending control actions using HTTPS POST messages and retrieving system status using HTTPS GET messages as shown in Fig. 4. The sequence starts by setting pressure setpoints in both fans and continues by reading power consumption, airflow and static pressure in the fans. This solution is interoperable and can be applied to enable co-simulation with HiL coupling to varied systems anywhere in the world.

The average CO_2 level in the building is extracted from the indoor climate sensors located inside the building. This is calculated by querying a MongoDB containing real time data using the *SystemCommand* actor to execute a Python code.

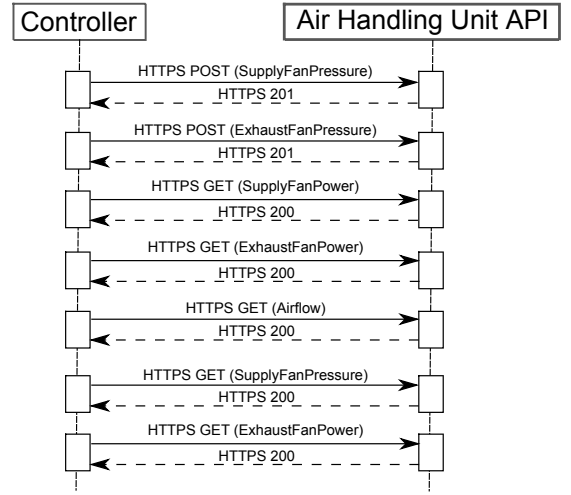


Figure 4. Ordered Sequence of Controller Interacting with API of AHU.

E. Optimization & Control and Master Algorithm

The *Optimization & Control* modules within the *Curtailment Service Provider* are modeled using Ptolemy II. These are different depending on the demand response strategy under assessment and are described in the following section.

The master algorithm is described in Ptolemy II and is responsible of coordinating the message exchange between the different actors. The *DiscreteEvent Director* has been chosen to orchestrate this data exchange (Eq. 3 has been discretized). In the HiL simulation, the real time and simulated time synchronization is handled by the *SynchronizeToRealTime* actor. In this case, it is important to identify the execution time of the different tasks to find a suitable sampling time between events so that simulation time is shorter than real time.

V. RESULTS AND DISCUSSION

The three demand response strategies presented here are evaluated using VirGIL in two different manners. The first is using HiL of the ventilation system and the building, henceforth called HiL simulation. The second is using the *Ventilation Fans Models* and *Indoor CO_2 Model*, henceforth called model simulation. In all simulations (HiL and model), the load profiles of the buildings are varied every one hour and the aggregated electricity load has been multiplied by a factor of three to emulate a more dense neighborhood. The HiL simulations were done with the building occupied notifying the janitor in advance: operating at high pressure setpoints can lead to complaints from the residents due to excessive noise.

A. Case 1: Load Following for On-site Renewable Integration

The goal of this use case is to analyze the demand response potential of the ventilation system in GDL to support on-site renewable production. The ventilation fans are set to run in normal operation ($P_{normal} = 2kW$) while the load in the transformer substation in PowerFactory is lower or equal than 70%. When the load exceeds 70%, the *Curtailment Service Provider* triggers a load following scenario. The load following

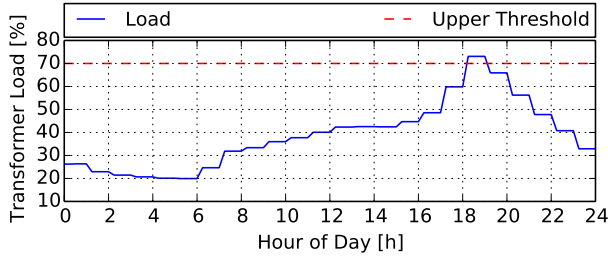


Figure 5. Transformer substation (TR-578 in Fig. 3) Load on the 27-08-2015 for the Load Following Case for the Model Simulations with the Buildings Load Multiplied by a Factor of Three.

is one minute signal based on the wind speed v provided by an anemometer located on the roof of GDL. This signal varies as shown in Eq. 4 so that when wind speed v increases in time k so does the signal to track P_{follow} . An analysis we carried out showed that the wind speed measurements are highly correlated (0.75) with the wind production in West Denmark (DK 1) thus being a good renewable production indicator.

$$P_{follow}[kW] = P_{normal} \left(\frac{v_k - v_{k-1}}{v_k} + 1 \right) \quad (4)$$

A first model simulation is done for a full day using data from Thursday 27-08-2015 with a sampling time of one second and running the Power FMU every 15 simulation minutes. This leads to the transformer substation load shown in Fig. 5, thus triggering load following from 18:00-19:00 CET. The load following signal is generated from real wind speed measurements from the weather station in GDL. Real time data of this sensor is not available and wind profile of this day has been used for all HiL and model simulations.

Prior to further simulations, it is important to do a time analysis to determine a sampling time for the HiL simulation so that the simulation time is shorter than the real time. The results of this analysis are shown in Tab. I. The most time consuming tasks are: Controller-API communication and Power FMU execution. VirGIL runs in a computer in Berkeley (CA, United States of America) while the API is hosted in Aarhus (Denmark). The average time to send all messages in Fig. 4 is 5.18 seconds with a standard deviation of 0.40 seconds. The HTTPS POST presents a larger standard deviation than a HTTPS GET because the first message of the sequence in Fig. 4 is a HTTPS POST and the server needs to authenticate the client. The average time to run the Power FMU for the given model is 3.34 seconds while the standard deviation is 0.29 seconds. This time depends on the complexity of the power model and the data exchange between the Windows server and the Linux client. This has led to choose 10 seconds sampling time and running the Power FMU every 20 seconds.

In the HiL simulations, all experiments have always been made on Thursdays 18:00-19:00 CET to have similar environmental conditions (e.g., similar amount of people in the building). The *Controller* to regulate the power of the ventilation fans uses the power error as input and returns the

TABLE I. EXECUTION TIME ANALYSIS. ALL UNITS IN SECONDS.

Task	Mean	Standard Deviation	Minimum	Maximum
HTTPS POST	0.77	0.28	0.71	3.78
HTTPS GET	0.73	0.02	0.68	1.13
2 POSTs + 5 GETs	5.18	0.40	4.99	8.18
Power FMU	3.34	0.29	2.20	6.05

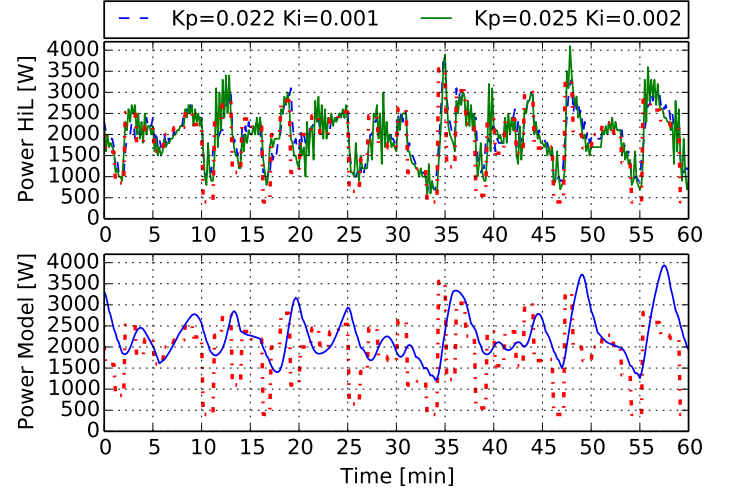


Figure 6. Comparison Load Following for On-site Renewable Integration of HiL Co-simulation and Co-simulation Using Fan Models. The Red-dashed Line is the Power Reference.

static pressure to the supply fan. The exhaust fan is always set with constant offset with respect to the supply fan. Both fans have inner controllers to track pressure setpoints and ramp up/down limits to avoid sudden changes. These mechanisms have not been tuned and have been represented in the model simulation by adding one inner PI controller in each fan model.

The top plot in Fig. 6 shows the results of the load following for the HiL simulation with two different PI controllers. The green-solid line shows the system performance with proportional ($K_p = 0.025$) and integral ($K_i = 0.002$) gains obtained using the Ziegler-Nichols-Method [21]. The blue-dashed line displays the performance with lower gains manually tuned. The performance of the controllers can be assessed both visually and numerically by using the Integral of Absolute Error (IAE) [21]. The second controller is preferred for having less oscillations and presenting a IAE 0.1% smaller. It can be observed that the chosen controller is capable of following the reference signal (red-dashed line) quite accurately. The tracking performance is worse for sudden down regulations because the controller hits the lower limit setpoint in pressure (negative pressures cannot be set). The tracking performance could be improved if the inner pressure controllers and ramp up/down settings of both fans are tuned. During the HiL simulations, the indoor CO_2 level was kept low and the residents comfort was not jeopardized [20]. Fig. 7 compares the model simulations with the HiL simulation CO_2 values. It can be observed that the accuracy of the model is good: it tracks well the tendency

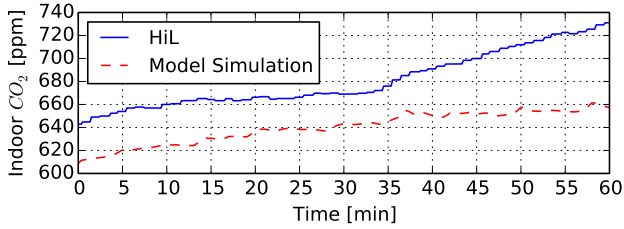


Figure 7. Comparison of the Indoor CO₂ Level for Load Following between HiL and Model Simulations.

but presents an offset of approximately 30 ppm. This offset is due to a higher human activity than modeled.

The bottom plot in Fig. 6 shows the results of the model simulation with the chosen controller ($K_p = 0.022$ and $K_i = 0.001$) using the same time settings as in the HiL simulation. The ventilation system model follows the red-dashed reference signal with delay due to OpenADR communication (the VEN polls load shed request from VTN every 10 seconds). It can be observed that the dynamics of the model are slightly slower than the real system because of the difficult process of manual tuning the inner static pressure controllers in the fan models. A more accurate tuning and model would lead to more accurate results but there would still be differences with the HiL simulation for several reasons (model mismatch, noise in measurements, etc.). HiL co-simulation provides a simulation closer to reality and therefore helps in the design and deployment of new demand response strategies.

B. Case 2: Ancillary Services Provision - Primary Reserves

In this case, the capabilities of the ventilation system in GDL to provide ancillary services are analyzed. We focus on primary reserves provision for up-regulation, that for consumers means to reduce power consumption. According to the Energinet.dk (Danish Transmission System Operator), in primary reserves 50% of the agreed power has to be provided within 15 seconds, 100% within 30 seconds and power must be held up to 15 minutes [22]. The *Curtailment Service Provider* triggers a 15 minutes power reduction to the minimum possible (without shutting down) when the prices for up-regulation in the regulating power market are 50% higher than the prices of the day-ahead market (*Elsport*). Afterwards the system returns to normal operation. Electricity prices have been obtained from Nord Pool Spot for West Denmark (region DK 1) for the day 27-08-2015. In that day, primary reserves would have been called three times: 4:00-5:00, 5:00-6:00 and 7:00-8:00 CET.

In the HiL simulations, we have used the same time intervals as in the previous case. All experiments have been done during week days between 4:00 and 6:00 CET. The PI controller has been exchanged with a look-up table with steady state values of static pressure and power consumption. This smooths transitions between operating points and avoids disturbing the residents with noise during night time.

The top plot in Fig. 8 shows three power profiles for the first two minutes after the regulation is called. The red-dashed lines

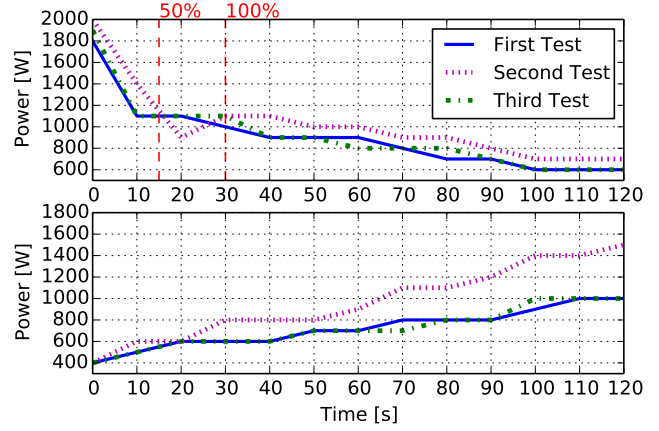


Figure 8. Primary Reserves Provision for HiL Simulation. Top-plot: First Two Minutes After Starting Intervention. Bottom-plot: First Two Minutes After Ending Intervention. The Two Red-dashed Vertical Lines Correspond to Times Where 50% and 100% of Power Reduction Shall be Delivered.

show the time where 50% and 100% of the regulation should be deployed. In the first 15 seconds, 700 W are provided for the first test and 800 W for the other two. In the first 30 seconds, 800 W are provided for all test. In conclusion, the ventilation fans in GDL can provide up to 800 W of primary reserves for up-regulation. The bottom plot in Fig. 8 shows how the system returns to normal operation after the intervention. It can be observed that the system returns slowly to normal operation point, taking around 5 minutes for all tests. If we used the PI controller from the previous section, the power reduction phase at the beginning of the intervention would not have been faster. However, the PI controller could indeed lead to faster restoration of power to normal, but at the cost of power oscillations that could disturb the residents. The comfort of the residents in terms of CO₂ is not compromised since CO₂ increase never exceeds 30 ppm over normal levels. This increase is delayed with respect to the power reduction due to the slow dynamics of the CO₂ concentration build up.

With the results above and the current market regulations (minimum bid 300 kW) it does not seem feasible to provide primary reserves for up-regulation with the GDL system alone. However, in concert with a distribution system feeder working to provide services via an aggregator, this would be a feasible service requiring 375 similar systems. The transient behavior observed in Fig. 8 is hard to capture with a model. In these cases, it is important to use more accurate solutions to assess a demand response strategy like the co-simulation with HiL.

C. Case 3: Ventilation System Aggregation for Load Following

Danish buildings use little electricity in ventilation systems due to the high penetration of district heating and low presence of air conditioning. It is then required to pool several ventilation systems to produce a demand response comparable to an American/Southern European system. Here VirGIL is used to assess the impact of changing the polling time of load shed requests of the OpenADR client on the distribution grid. The

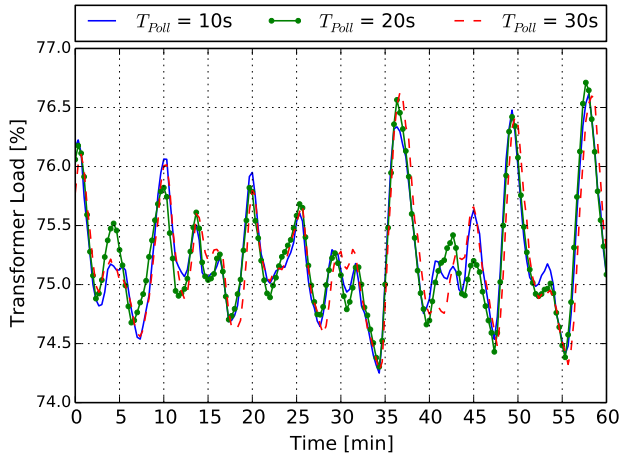


Figure 9. Transformer Load from Power FMU for Aggregation 15 Ventilation Systems with Different Time Between Polling Load Shed Requests.

Curtailment Service Provider controls 15 ventilation systems (*Ventilation Fan Models*) similar to GDL following one minute load following signal. However, in order to emulate different systems, a normally distributed noise (mean model output and standard deviation 5% of mean) has been added to the power output of each model.

Fig. 9 shows how the load of the transformer substation is affected by the load shed request frequency for 15 ventilation systems. It can be observed that the load in the transformer can change more than 2% in a few seconds. Furthermore, we can see how different polling times lead to different load profiles. This difference is caused by different load references that let the models evolve differently on time. It is therefore important to assess the configuration of the communication protocol used to get a holistic assessment of a demand response strategy.

VI. CONCLUSIONS

There is a growing market for load-based services at the distribution level, but their widespread implementation has been limited by the lack of visibility of such services from an operator angle, as well as by the lack of appropriate tools for their assessment. To reduce these barriers, we propose the co-simulation platform VirGIL and extend it with Hardware-in-the-Loop (HiL) of a ventilation system of a 12-story building. Demand response co-simulation with HiL in VirGIL has been demonstrated for three services: load following, primary reserves and load following aggregation. It is demonstrated that the ventilation system can follow one minute signals and it is shown how HiL co-simulation can capture behaviors hard to model and interactions with other systems (e.g., communication networks). While the control of a single building is unlikely to meet the needs of an up-regulation market, these techniques could be applied to multiple buildings and a full substation, providing a wide range of services.

Future work is proposed to tune the inner fan controllers to respond faster and more accurately, and to apply the techniques to a full distribution substation model using VirGIL. VirGIL will also be extended to simulate electrical vehicles.

REFERENCES

- [1] P. Siano, "Demand response and smart grids—A survey," *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 461–478, Feb. 2014.
- [2] S. Rotger-Grifol and R. H. Jacobsen, "Control of Smart Grid Residential Buildings with Demand Response," in *Chaos Modeling and Control Systems Design*, ser. Studies in Computational Intelligence, A. T. Azar and S. Vaidyanathan, Eds. Springer Int. Publishing, 2015, vol. 581.
- [3] S. Kiliccote, M. A. Piette, E. Koch, and D. Hennage, "Utilizing Automated Demand Response in commercial buildings as non-spinning reserve product for ancillary services markets," in *IEEE Conference on CDC-ECC*. IEEE, Dec. 2011, pp. 4354–4360.
- [4] A. G. Azar, R. H. Jacobsen, and Q. Zhang, "Aggregated load scheduling for residential multi-class appliances: Peak demand reduction," in *12th International Conference on EMM*. IEEE, May 2015, pp. 1–6.
- [5] S. Chatzivasileiadis, M. Bonvini, J. Matanza, R. Yin, T. Noudui, E. C. Kara, R. Parmar, D. Lorenzetti, M. Wetter, and S. Kiliccote, "Cyber physical modeling of distributed resources for distribution system operations," *Proceedings of the IEEE*, pp. 1–15, 2015.
- [6] K. Hopkinson, X. Wang, R. Giovanini, J. Thorp, K. Birman, and D. Coury, "EPOCHS: a platform for agent-based electric power and communication simulation built from commercial off-the-shelf components," *Power Systems, IEEE Transactions on*, vol. 21, no. 2, pp. 548–558, May 2006.
- [7] Hua Lin, S. Sambamoorthy, S. Shukla, J. Thorp, and L. Mili, "Power system and communication network co-simulation for smart grid applications," in *ISGT 2011*. IEEE, Jan. 2011, pp. 1–6.
- [8] M. Lévesque, D. Q. Xu, G. Joós, and M. Maier, "Communications and power distribution network co-simulation for multidisciplinary smart grid experimentations," *SCS/ACM Spring Simul. Multi-Conf.*, no. 413427, pp. 1–7, 2012.
- [9] R. Bottura, D. Babazadeh, K. Zhu, A. Borghetti, L. Nordstrom, and C. Nucci, "SITL and HLA co-simulation platforms: Tools for analysis of the integrated ICT and electric power system," in *EUROCON, 2013 IEEE*, July 2013, pp. 918–925.
- [10] P. Palensky, E. Widl, M. Stifter, and A. Els Sheikh, "Modeling intelligent energy systems: Co-simulation platform for validating flexible-demand EV charging management," *Smart Grid, IEEE Transactions on*, vol. 4, no. 4, pp. 1939–1947, Dec 2013.
- [11] D. P. Chassin, K. Schneider, and C. Gerkensmeyer, "GridLAB-D: An open-source power systems modeling and simulation environment," in *2008 IEEE/PES Transmission and Distribution Conference and Exposition*. IEEE, Apr. 2008, pp. 1–5.
- [12] P. Palensky, E. Widl, and A. Els Sheikh, "Simulating cyber-physical energy systems: Challenges, tools and methods," *Systems, Man, and Cybernetics: Systems, IEEE Transactions on*, vol. 44, no. 3, pp. 318–326, Mar. 2014.
- [13] S. C. Muller, H. Georg, C. Rehtanz, and C. Wietfeld, "Hybrid simulation of power systems and ICT for real-time applications," in *2012 3rd IEEE PES ISGT Europe*. IEEE, Oct. 2012, pp. 1–7.
- [14] B. Palmintier, B. Lundstrom, S. Chakraborty, T. Williams, K. Schneider, and D. Chassin, "A power hardware-in-the-loop platform with remote distribution circuit cosimulation," *Industrial Electronics, IEEE Transactions on*, vol. 62, no. 4, pp. 2236–2245, April 2015.
- [15] E. M. Stewart, S. Kiliccote, and C. McParland, "Software-Based Challenges of Developing the Future Distribution Grid," Tech. Rep. LBNL 6708E, 2014.
- [16] Modelica Association Project "FMI", "Functional Mock-up Interface for Model Exchange and Co-Simulation," Tech. Rep. 2.0, 2014.
- [17] C. Ptolemaeus, *System Design, Modeling, and Simulation. Using Ptolemy II*, 2014.
- [18] E. A. Lee, M. Niknam, T. S. Noudui, and M. Wetter, "Modeling and simulating cyber-physical systems using cyphsim," in *EMSOFT*, Oct. 2015.
- [19] R. Bienert, J. Zuber, and U. Herberg, "OpenADR 2.0 Profile Specification B Profile," Tech. Rep. 20120912-1, 2013.
- [20] S. Rotger-Grifol, R. H. Jacobsen, D. Nguyen, and G. Sørensen, "Demand Response Potential of Ventilation Systems in Residential Buildings," *Energy and Buildings*, 2016. Under Review.
- [21] W. Tan, J. Liu, T. Chen, and H. J. Marquez, "Comparison of some well-known PID tuning formulas," *Computers & Chemical Engineering*, vol. 30, no. 9, pp. 1416–1423, Jul. 2006.
- [22] Energinet.dk, "Ancillary services to be delivered in Denmark Tender conditions," Tech. Rep. 8871/11, 2012.