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Demand response field trial experiences

Koponen, Pekka; Weiss, Robert; Ketomäki, Jaakko

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DEMAND RESPONSE FIELD TRIAL EXPERIENCES

Pekka KOPONEN Robert WEISS Jaakko KETOMÄKI
VTT Technical Research Centre of Finland – Finland
Pekka.Koponen@vtt.fi Robert.Weiss@vtt.fi Jaakko.Ketomaki@vtt.fi

ABSTRACT

This contribution summarizes the author´s experiences on many demand response field trials. It gives and overview of several field trials for modelling and control of both aggregated electric loads and individual sites. It also considers district heating in order to complete the energy balance. The tests comprise different residential houses and large industry. The paper also discusses field trial design, implementation and lessons learned.

INTRODUCTION

Knowledge on demand response (DR) field trials is scattered. Reviewing own experience and lessons learned from many DR modelling field trials aims at mitigating this problem. The trials in reverse time order include

- hybrid modelling for short term forecasting and optimizing the aggregated responses of different types of electrically heated small houses,
- aggregation of the flexibility of small houses and their appliances to electricity markets,
- aggregating distributed energy resources (DER) to the electricity markets,
- micro-grids with cogeneration of electricity, heat and cool for the provision of local back-up power and electricity market benefits,
- demand response (DR) of blockhouses,
- spot market based control of residential houses with electrical heating and related modelling,
- smart meter based power quality monitoring and Non-Intrusive Load Monitoring (NIALM),
- response modelling for emergency control of electrically heated houses to curtail the load peak of three power distribution utilities,
- market based short term energy management of large base metal industry with many distributed sites.

Many Nordic DR modelling field trials, including some mentioned above, are reviewed in [1]. The field trials and their analysis in several EU-projects spanning from 2004 to today also contribute to the experiences. In addition, International Energy Agency's Demand Side Management Implementing Agreement has collected lessons and best practices on DR trials around the world. Confidential projects and literature reviews also affect the findings.

TRIALS FOR MODELLING AGGREGATED DIRECT LOAD CONTROL RESPONSES

2.1 Combination of data from several field trials and sources

Data from several previous field tests are shown in Fig. 1. The field tests were used in the development and validation of hybrid models in the project Response (2015-2018) funded by the Academy of Finland [2]. Together these field tests spanned different types of electrical storage heating, several climate zones and spanned about 18 years. The hybrid models developed include also partly physical component models for several separately controlled groups for two types of the control responses. One type is direct load control for peak load and emergency reserves. The other is dynamic time of use (ToU) control, where the control timing varies from night to night, for example, based on the electricity market price. The developed hybrid models forecast with machine learning the residual of the physical load control models. The hybrid models performed better than the pure component modelling approaches [2].

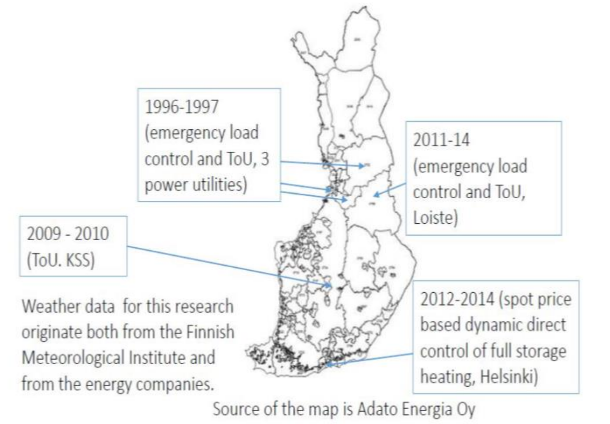


Figure 1. Several large field trials together enabled the development of hybrid models for aggregated load forecasting. Together they comprise over 16 000 controlled customers and thousands of reference customers.

Lessons learned include the following.

• Direct load control response models developed in 1996-1997 for a neighbour distribution area, and described in [3], were still valid for the field tests in 2011-2014. Only the old field trials adequately included the saturation of the loads during very cold weather (-29 C). Thus, some of the old response models were successfully validated with the new field trial data and used as such in the new hybrid models.

•Now, new technologies change the load behaviour of the network customers rapidly. Thus, the developed models need new data and field trials for updating. The models should preferably be such that 1) the changes are explicit and transparent, and 2) the models include capabilities to adapt to the changes. Purely black box models need many years of learning data to get good performance, but still fail in modelling exceptional situations and dynamic active demand. Hybrid models are much better in these respects.

• It is useful and often necessary to use data from many different sources. In the above field tests, the modelling used hourly interval data from smart meters, 3-minute interval power measurements from the substations, and temperature measurements in the area. In addition, climate zone dependent building requirements defined parameter constraints for identification of the model dynamics and saturation.

• Different communication system technologies and configurations sent the direct load control signals to the billing meters. The old power line ripple control systems reached within 3 seconds practically all the meters, while the mobile phone network based technologies in the field test could do the same within 30 minutes or 2 hour depending on the number of data concentrators in the communication network. Thus, new even better communication technologies are needed to replace the old ripple control systems and the existing smart metering systems in the provision of fast reserves for the system and local grid.

• Customer acceptance has not been a problem. Small compensations have been enough to keep them in the programs as very few of them noticed any inconvenience due to the control actions. For example in 1996-97, the number of complaints was only five and all of them stemmed from the house being in a wrong control group for its heat storage performance. Moving those houses in their right groups was enough to solve the problems.

• Very many individual customers had small or even non-significant load control responses, although the aggregate responses of the groups have a good size. Thus, there remain needs to automatically identify and analyse exceptionally behaving and non-responsive customers.

2.2 Direct load control

The field tests of the DSO Loiste in Kainuu in 2011-2014 and overviewed in [4] comprised:

• Hourly interval measurements from each smart meter and ambient temperatures of the areas.

• 3 min interval power measurements from substations.

Direct load control provides both system peak reserve and emergency control for the grids. All the houses have also time of use control (ToU). In Fig. 2, the emergency control is at 9:00-10:00 and the two load peaks in the evening are the ToU control responses. About 7000 emergency controlled houses were divided in groups with different communication latency stemming from different technologies. The field test included an additional customer group that was not controlled, but its load behaviour turned out to be too different to be useful as a reference group. The load control tests were in different outdoor temperatures. We used these tests to develop hybrid forecasting models.

Tampere University of Technology provided smart metering data from KSS, a DSO, for aggregated load modelling of residential ToU controlled electrically heated houses. The data complement the load control field tests by providing an additional climate zone and increasing the number of measured customers. The additional data are useful for modelling the load responses to the outdoor temperature variations and validating the models developed from the field test data from the other areas. The main limitation of this data is that there are no direct nor dynamic load control actions. Thus, this data alone do not enable modelling control saturation and dynamic control.

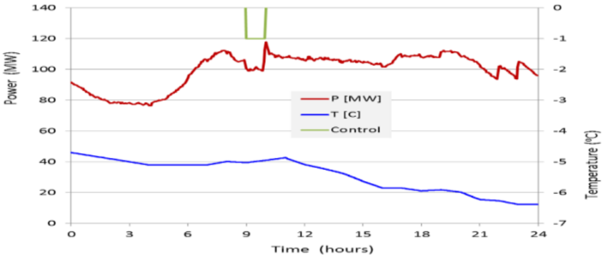


Fig. 2. Load control response in 3 min interval power of the distribution area and the direct load control signal in Feb 2014. [4]

2.3 Spot price based dynamic direct load control of full storage heated houses

Field trials of dynamic smart metering based DR for full storage heated houses in Helsinki were implemented in 2012-2014. See [5] and [4] for further information. The trial comprised about 700 houses and about 16 MW of controllable power during night time. Helen, the energy company of Helsinki, controlled the loads by calculating the daily heating energy demand from the outdoor temperature and then selected for heating the hours that with the smallest cost met the energy demand. Some additional constraints were needed. For example, too long periods without any heating were not allowed. Such a control method was used in Fig. 3. A hybrid forecasting method developed forecasts day ahead the load during this dynamic load control.

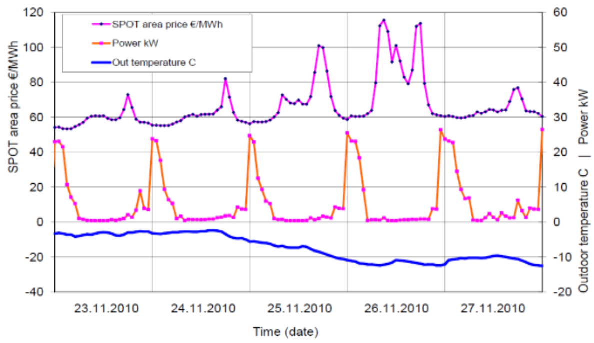


Figure 3. Storage heating was allowed during low spot prices.

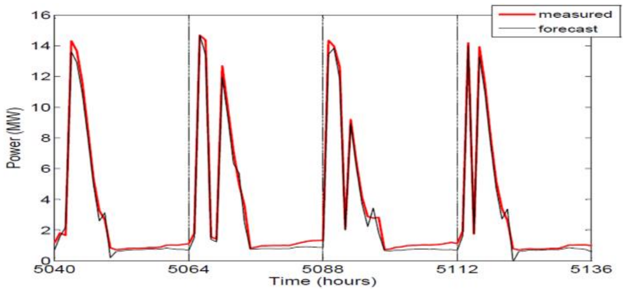


Figure 4. A hybrid forecasting model was developed based the field tests; measured and forecasted load per customer.

The main findings include the following.

• Some customers were changing to heat pumps thus either leaving the program or changing their load behaviour significantly. The number of such changes is growing.

• We found out that models that can forecast dynamic control responses are necessary. Otherwise, the balancing costs of the electricity retailer or the DR aggregator cancel the benefits of the dynamic controls.

• The hybrid model developed forecasts the dynamic load control responses accurately [2].

• The number of full storage heating customers is reducing, decreasing the relevance of this customer group. Consequently, the electricity retailer did not implement the forecasting in its online system and abandoned the spot price based dynamic load control of the full storage heated customers.

MODELLING AND CONTROL OF INDIVIDUAL HOUSES AND APARTMENTS

Field tests of market price based control were in southern Finland in 2004-2006 [6]. They included controllable electrical heat storing floor heating and water heaters in five small houses and four row house apartments. In addition, two blockhouses that were connected to district heating and together had, as controllable loads, electrical convenience floor heating in all 57 apartments and two cool storages. The load control signals in the tests were sent to the building users by mobile phone and the control actions were then manually implemented. House energy automation based price control was studied with simulations using the model of the houses identified in the field tests. Selected findings are the following. The field tests and literature demonstrated that manual actions in the control loop bring too much uncertainty and are difficult to model without extremely many test customers. Where the building automation control loops were not readily working reasonably well and reliably, it was too expensive to implement DR. The readily existing communication for remote building management had adequate performance and availability for the price control signals. The cost benefit case for DR was better in the bigger houses. Automated price control and related modelling needed, in addition to interval billing metering, real time power measurement with good time resolution (e.g. 1 minute) from the billing meter to the customer's automation system. Integration of several building management and DR functionalities to the same devices offered opportunities to reduce costs.

Long, high time resolution, measurement time series data have been collected from an electrically heated house [7]. Earlier it had a heat storage tank dimensioned for night heating, but a ground source heat pump replaced it later. The same house was also used in the development and testing of a Non-Intrusive Appliance Load Monitoring (NIALM) system described in [7]. Long high resolution time series and identified sub-loads enabled development and validation of accurate and reliable models of the thermal dynamics and the control responses of the house in later research, such as described in [4], [5] and [6].

The experiences from International Energy Agency, Demand Side management Agreement, Task 2 in 1993-2002 and EU ADDRESS project 2008-2013 on home automation based DR showed how the lack of adequately standardized protocols had a tendency to increase the implementation cost too much compared to the benefits of DR. In the former one, the attempted solution was integrating multiple applications and developing a low cost gateway for protocol conversions. In the later one, the need for tailoring due to the mutual incompatibility of the different ZigBee profiles of the appliances was identified [8]. It made the utilization of the developed system as such too expensive in commercial exploitation. Australia has managed to solve this challenge by defining their own compulsory DR protocol for appliances. New Zealand has adopted the Australian requirement. Europe has been slower in requiring a common compulsory interface protocol for DR.

Home automation and electricity spot market price based DR is becoming increasingly popular and systems are now commercially available in Finland from IT-providers and electricity retailers acting as DR aggregators. Water heaters, storage heating and fuel switching are their main sources of demand flexibility. Thus, the challenges identified in the old field trials have been at the least mitigated.

BLOCKHOUSE DISTRICT HEATING DEMAND RESPONSE SIMULATIONS

We simulated heating flexibility actions for high-rise buildings according to a district heating DR control as proposed from field trial experience in Sweden [10] and [11]. In the simulated actions performed at the district-heating substation, we manipulated the outdoor temperature signal with the proposed maximum +- 7ºC as show in Fig. 5, with the aim to temporarily change the heating power need accordingly.

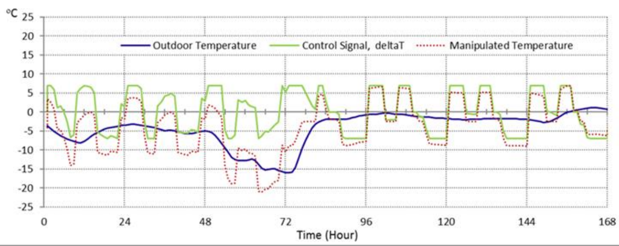


Fig 5. District heat demand response (DR) control applied in the simulation.

In Finland, a very large part of the residential blockhouse building stock is younger than in the Swedish case and built mainly in 1960-1980 in suburbs during urbanization booms. Many envelope renovation projects are now ongoing or upcoming in these suburbs, because of the large renovation needs of the old concrete envelopes.

The energy flexibility and impact on indoor temperatures were analysed with a detailed energy simulation model of a representative 7-floor blockhouse, see Fig. 6, using IDA-ICE building simulation software (IDA-ICE 2015). We modelled and analysed both the original envelope from 1980 and the renovated envelope according to Finnish 2015 building standards.

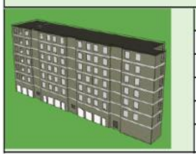
Building envelope of the Case Building		Area [m²]	Original envelope Prior renovations (Version 1980)	Renovated envelope After renovations (Version 2015)
			U [W/(K m²)]	U [W/(K m²)]
	External walls	1829.53	0.35	0.17
	Roof	610.93	0.23	0.09
	External floor	611.17	0.18	0.11
	Windows	507.25	2.09	1.10
	External doors	163.88	1.01	1.01

Fig. 6. The blockhouse studied.

DR impacts were analysed with results obtained from these energy simulations. For the blockhouse with original envelope (1980) and old slow thermostats, the proposed DR control resulted in indoor temperature variations that stayed within acceptable +-0.7 °C in the original building (1980), slightly more than the +-0.4 °C presented in [10]. For the very same DR activity, indoor temperature variations were flattened out in the envelope renovated building (2015) with new faster thermostats, see Fig. 7. The DR activity did not practically affect the room average temperatures, and there was no significant change in the yearly energy consumption for space heating. Consequently, more aggressive flexibility actions are now possible. Verification of the results and the simulation models requires new field trials in typical renovated Finnish suburb blockhouses. The simulations and tests should include whole energy balance, including also electricity and its DR potential as in [6].

The flexibility potential is strongly dependent on the building energy efficiency and renovation type. For DR field trials, detailed building modelling is a cost-efficient way to perform virtual tests as well as do more efficient planning of field tests.

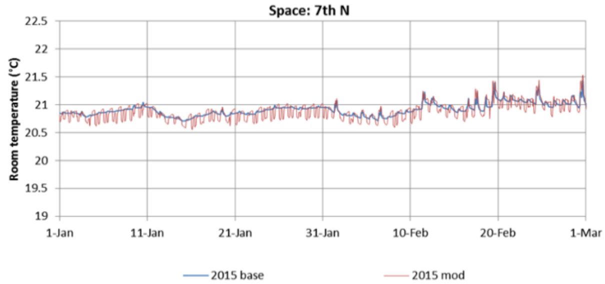


Fig. 7. Simulated temperature during the energy flexibility actions in the room that had the highest variability in the renovated blockhouse.

FIELD TRIAL OF ENERGY MANAGENT IN BASE METAL INDUSTRY

A prototype for modelling the energy management and trading of a large base metal company was developed and tested in real on-line operation [9]. It covered mines and base metal processing at several locations. The responsive electricity consuming processes included a FeCr-plant, a steel melt shop, hot-rolling, cold rolling, two electrolysis plants, and in the mines large pumps etc. The prototype predicted the loads based on the production plans of the plants and traded electricity between the different plants and with external actors. Thus, the prototype included an internal electricity market. The market cleared simultaneously with the next time steps ahead also preliminary some (e.g. 3) time steps ahead. After a long testing period, the base metal company had a production software developed and implemented based on the prototype and its experiences.

The lessons learned include the following:

- Rapid software prototyping methods and tools helped the development of the system very much. In the field tests, they enabled fast capture of the knowledge of domain experts.
- The rapid prototyping tools available at that time (1992) required disciplined and competent software development.
- Allocating much time and effort to modelling, specification, design, prototyping and field tests made it possible to develop a good novel solution to the large and uncharted problem.
- The artificial intelligence hype flooded the software business with developers that lacked the necessary competence and discipline required by efficient development with fast prototyping tools. The rapid prototyping tools were expensive and far from being mature then in 1992, but efficient with competent users.

SUMMARY

The main findings include the following.

• When electricity retail and distribution were not unbundled and the competitive electricity markets not established DR was very profitable.

• The unbundling and opening the electricity markets to competition reduced the incentives to DR and blocked the customers from incentives to be flexible. However, further development of the electricity and reserve markets is gradually improving the access of active customers to the flexibility markets. In addition, the needs to engage demand side flexibility are getting stronger.

• The potential for fast reacting flexibility in the demand side is abundant and increasing. The development and standardization of interfaces and related requirements is removing barriers.

• Machine learning methods, model based nonlinear constrained optimal control and market based distributed optimal scheduling where economically feasible only for large demand side flexibilities, but they can now be profitable with small consumptions, too.

• Customers have accepted the DR offerings. The compensations required have been reasonable.

• Connecting customer surveys to field trials is useful in many ways.

• Automation is necessary in order to have predictable and fast responses. Manual responses tend to be too slow and unpredictable to be profitable.

• Field test design is essential. The objectives should be feasible with respect to the field test size, time span and the load control signals. Statistical and practical relevance should be considered before implementing tests and drawing conclusions. Using non-controlled and differently controlled reference groups is recommend. Use of carefully designed test signals is often necessary in order to get necessary information for modelling load saturation and control responses.

• Combining rapid software prototyping with field trials was efficient, but it seems too seldom used nowadays.

• Detailed models of the buildings and processes are very useful to support the field test.

• Simulations are needed to help field test design and result analysis. Identification, calibration and verification of the simulation models needs field tests. Simulations enable testing field test design thus saving time and costs. Typically, only a small subset of possible situations can be implemented in the field tests due to time, cost and safety constraints and simulations must be used to fill in the remaining gaps. Adequate analysis of the results is seldom possible without simulations.

• Using data and other results from earlier field trials is often necessary. Otherwise, the data does not describe adequately all relevant situations, climate zones, and time resolutions.

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